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Agronomic biofortification with iron and zinc for enhancement in yield and quality of maize (*Zea mays L.*)

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Abstract
A field experiment was conducted during the kharif season of 2024 at the Agricultural Research Farm, Vivekananda Global University, Jaipur, Rajasthan, to evaluate the impact of agronomic biofortification with iron (Fe) and zinc (Zn) on maize (*Zea mays L.*) hybrid DHM 117. The study utilized a randomized block design with nine treatments, including control and combinations of recommended dose of fertilizers (RDF) with soil and foliar applications of $ZnSO_4$ and $FeSO_4$. Results showed that the treatment RDF + soil application of $ZnSO_4$ @ 20 kg/ha + 0.5% $FeSO_4$ foliar spray at 45 days after sowing (DAS) significantly enhanced plant population (8.28 plants/m row at 30 DAS), plant height (up to 55.9% increase at harvest), dry matter accumulation (up to 67.12% increase), yield attributes (e.g., 57.85% more grains/cob), grain yield (87.85% increase to 74.84 q/ha), nutrient content and uptake (N, P, K increases of 108%, 154%, and 144% in grain), protein content (11.58% increase), and economic returns (net return of ₹102,715/ha, B:C ratio 1.77). This integrated approach proved effective for improving maize productivity, nutritional quality, and profitability under semi-arid conditions.

Keywords: Maize, agronomic biofortification, iron, zinc, yield, nutrient uptake, economics

Introduction

Maize (*Zea mays L.*) is a vital cereal crop globally, serving as a staple food, animal feed, and industrial raw material. In India, it ranks third after rice and wheat, with an area of 11.24 million ha, production of 37.66 million tons, and productivity of 3.35 t/ha (Anonymous, 2024) [1]. In Rajasthan, maize covers 0.94 million ha with a production of 2.28 million tons and productivity of 2.4 t/ha (Anonymous, 2024) [1]. Nutritionally, maize provides essential macronutrients and micronutrients, but deficiencies in iron (Fe) and zinc (Zn) in soils and crops contribute to hidden hunger affecting human health.

Agronomic biofortification involves enhancing crop nutrient density through fertilizer applications, differing from genetic methods by improving nutrient uptake via soil and foliar means. Micronutrient deficiencies, such as Zn (47% in Indian soils) and Fe (13%), limit crop productivity (Sakal and Singh, 2001) [13]. Zn aids in enzyme activation, auxin synthesis, and stress resistance, while Fe is crucial for chlorophyll synthesis and metabolic processes. Combined Fe and Zn applications have shown promise in boosting growth, yield, and quality (Bhardwaj *et al*., 2022) [5].

This study aimed to: (1) investigate the impact of agronomic biofortification with Fe and Zn on maize growth and yield; (2) examine its influence on nutrient uptake and quality; and (3) analyze the economic implications.

3. Materials and Methods

3.1 Experimental Site

The experiment was conducted during the kharif season of 2024 at the Agricultural Research Farm, Vivekananda Global University, Jaipur, Rajasthan (agro-climatic zone III A, semi-arid Eastern Plain Zone). The climate is semi-arid with summer temperatures up to 48 °C, winter lows to 1 °C, and annual rainfall of 450–550 mm, mainly during July–August. During the crop season, maximum temperatures ranged from 30.2 °C to 40.9 °C, minimum from 14.3 °C to 25.4 °C, relative humidity 15–85%, and sunshine hours 1.8–9.3. Soil was loamy sand, alkaline (pH 8.2), low in organic carbon (0.32%), available N (185 kg/ha), and P (12.5 kg/ha), and medium in K (245 kg/ha).

3.2 Cropping History and Variety

The field had mung bean and fallow in 2023–24, with maize in kharif 2024. The variety used was DHM 117, a medium-duration hybrid (90–100 days) with high yield potential (80 q/ha), tolerant to stalk rot and foliar diseases.

3.3 Treatments and Design: Nine treatments were laid out in a randomized block design with three replications (27 plots). Treatments included: T_1 (Control), T_2 (RDF + soil $ZnSO_4$ @20 kg/ha), T_3 (RDF + soil $FeSO_4$ @25 kg/ha), T_4 (RDF + 0.5% $ZnSO_4$ foliar at 20–25 DAS), T5 (RDF + 0.5% $FeSO_4$ foliar at 20–25 DAS), T6 (RDF + soil $ZnSO_4$ @20 kg/ha + 0.5% $ZnSO_4$ foliar at 45 DAS), T_7 (RDF + soil $ZnSO_4$ @20 kg/ha + 0.5% $FeSO_4$ foliar at 45 DAS), T_8 (RDF + soil $FeSO_4$ @25 kg/ha + 0.5% $ZnSO_4$ foliar at 45 DAS), T_9 (RDF + soil $FeSO_4$ @25 kg/ha + 0.5% $FeSO_4$ foliar at 45 DAS). RDF was 120 kg N/ha, 50 kg P_2O_5/ha 40 kg K_2O/ha via DAP and MOP. Plot size was 4.2 m×6m.

S. No	Treatments	Symbol
1	Control	T_1
2	RDF + Soil application $ZnSO_4$ @20 kg/ha	T_2
3	RDF + Soil application $FeSO_4$@ 25 kg/ha	T_3
4	RDF + 0.5% $ZnSO_4$ Foliar sprat at tillering stage (20-25 DAS)	T_4
5	RDF+ 0.5% $FeSO_4$ Foliar spray at tillering stage (20-25 DAS)	T_5
6	RDF+ Soil application $ZnSO_4$ @20 kg/ha +0.5% $ZnSO_4$ Foliar spray at 45 DAS	T_6
7	RDF+Soil application $ZnSO_4$ @20 kg/ha +0.5% $FeSO_4$ Foliar spray at 45 DAS	T_7
8	RDF+ Soil application $FeSO_4$@ 25 kg/ha + 0.5% $ZnSO_4$ Foliar sprat at 45 DAS	T_8
9	RDF+ Soil application $FeSO_4$@ 25 kg/ha + 0.5% Foliar sprat at 45 DAS	T_9
RDF = Recommended dose of fertilizer (120 kg N +50 kg P_2O_5/ha+ 40 kg K_2O		

3.4 Cultural Practices

Land was prepared with two ploughings, harrowing, and planking. Seeds (25 kg/ha) were treated with Bavistin + Captan (2 g/kg) and Metalaxyl (4 g/kg), sown at 60 cm × 20 cm spacing. Thinning occurred at 15 DAS. Irrigation used check basin method during critical stages. Weeds were managed manually at 15–20 DAS and with Tembotrione (150 g a.i./ha) at 30 DAS. Pests were controlled with Chlorpyriphos (0.05%). Harvesting was manual, with grain yield adjusted to 15% moisture.

3.5 Observations

Growth parameters: Plant population (plants/m row at 30 DAS and harvest), height (cm at 30, 60, 90 DAS, harvest), dry matter (q/ha at 30, 60, 90 DAS, harvest), phenological stages (days to knee-high, tasseling, silking, maturity). Yield attributes: Cobs/plant, rows/cob, grains/cob, seed index (g), cob length/diameter (cm with/without husk), grain/stover/biological yield (q/ha), harvest index (%). Nutrient analysis: N (Kjeldahl method), P, K content/uptake in grain/stover; protein (%) = N × 6.25. Economics: Gross/net returns, B:C ratio based on market prices.

3.6 Statistical Analysis

Data were analyzed using ANOVA, with significance at $p \leq 0.05$.

4. Results and Discussion

4.1 Growth Parameters

Plant population ranged from 6.22 (T_1) to 8.28 plants/m row (T_7) at 30 DAS (32.15% increase) and 6.02 to 8.12 at harvest (34.88% increase). T_7 outperformed others due to Zn's role in auxin synthesis and Fe's in chlorophyll formation, enhancing seedling vigor (Prasad *et al.*, 2014; Anwar *et al.*, 2022) [12, 2].

Plant height increased significantly under T_7 (up to 55.9% at harvest over T_1), attributed to micronutrients' metabolic roles. Dry matter accumulation followed similar trends, with T_7 showing 67.12% increase at harvest, reflecting improved photosynthesis (Kumar and Salakinkop, 2018) [10]. Phenological stages were prolonged under T_7 (e.g., 10.74% delay to maturity), allowing extended biomass accumulation (Augustine and Kalyanasundaram, 2021).

4 Yield

4.1 Grain Yield (q/ha): According to Table, the grain yield ranged from 39.84 kg/ha (Control) to 74.84 kg/ha (RDF + Soil application ZnSO4 @20 kg/ha + 0.5% FeSO4 Foliar spray at 45 DAS), with the highest treatment increasing yield by 87.85% and the lowest (Control) at 0% increase. Other treatments showed yield increases from 37.05% (RDF + Soil application ZnSO4 @20 kg/ha) to 77.61% (RDF + Soil application ZnSO4 @20 kg/ha + 0.5% FeSO4 Foliar spray at 45 DAS) compared to the Control.

4.2 Stover Yield (q/ha)

According to Table, the stover yield ranged from 105.79 kg/ha (Control) to 176.83 kg/ha (RDF + Soil application ZnSO4 @20 kg/ha + 0.5% FeSO4 Foliar spray at 45 DAS), with the highest treatment increasing yield by 67.14% and the lowest (Control) at 0% increase. Other treatments showed yield increases from 34.06% (RDF + Soil application ZnSO4 @20 kg/ha) to 62.81% (RDF + Soil application FeSO4@ 25 kg/ha + 0.5% ZnSO4 Foliar spray at 45 DAS) compared to the Control, with treatments 4 and 9 being statistically at par.

4.3.3 Biological Yield (q/ha)

The biological yield ranged from 105.79 kg/ha (Control) to 176.83 kg/ha (RDF + Soil application ZnSO4 @20 kg/ha + 0.5% FeSO4 Foliar spray at 45 DAS), with the highest increase of 67.12% over the control for treatment 7 and the lowest increase of 33.92% for treatment 2. All treatments showed significant yield improvements over the control, with percentage increases ranging from 33.92% (treatment 2) to 67.12% (treatment 7), and treatment 9 being closest to par with a 50.21% increase.

4.3.4 Harvest Index (%)

The Harvest Index ranged from 37.65 (Control) to 42.32 (RDF + Soil application ZnSO4 @20 kg/ha + 0.5% FeSO4 Foliar spray at 45 DAS), with the highest increase of 12.35% over the control for treatment 7 and the lowest increase of 2.18% for treatment 2. All treatments improved the Harvest Index compared to the control, with percentage increases ranging from 2.18% (treatment 2) to 12.35%

(treatment 7), and treatment 9 (5.82% increase) being closest to the median improvement.

Table 1: Influence of Agronomic Biofortification with Iron and Zinc on yield

S. No.	Treatments	Seed Yield (kg/ha.)	Stover yield (kg/ha.)	Biological yield (kg/ha.)	Harvest Index
1	Control	39.84	65.95	105.79	37.65
2	RDF + Soil application ZnSO4 @20 kg/ha	54.58	87.27	141.85	38.47
3	RDF + Soil application FeSO4@ 25 kg/ha	54.96	88.15	143.11	38.4
4	RDF + 0.5% ZnSO4 Foliar sprat at tillering stage (20-25 DAS)	63.56	95.02	158.58	40.08
5	RDF+ 0.5% FeSO4 Foliar spray at tillering stage (20-25 DAS)	65.78	98.4	164.18	40.06
6	RDF+ Soil application ZnSO4 @20 kg/ha +0.5% ZnSO4 Foliar spray at 45 DAS	68.17	99.91	168.08	40.55
7	RDF+Soil application ZnSO4 @20 kg/ha +0.5% FeSO4 Foliar spray at 45 DAS	74.84	101.99	176.83	42.32
8	RDF+ Soil application FeSO4@ 25 kg/ha + 0.5% ZnSO4 Foliar sprat at 45 DAS	70.96	101.28	172.24	41.19
9	RDF+ Soil application FeSO4@ 25 kg/ha + 0.5% Foliar sprat at 45 DAS	63.32	95.59	158.91	39.84
	C.D.	2.525	3.604	8.658	2.218
	SE(m)	0.835	1.192	2.863	0.734
	C.V.	2.341	2.229	3.212	3.189

4.3 Nutrient Content, Uptake, and Quality

N content increased to 1.45% in grain (T_8, 11.54%) and 0.64% in stover (T6–T_8, 23.08%); uptake to 107.76 kg/ha grain (T_7, 108.03%) and 65.27 kg/ha stover (90.29%). P content reached 1.57% grain (T_7, 35.34%) and 0.95% stover (39.71%); uptake 117.49 kg/ha grain (154.3%) and 96.89 kg/ha stover (116.1%). K content was 0.39% grain (T_7, 30%) and 0.194% stover (27.63%); uptake 29.18 kg/ha grain (144.2%) and 19.78 kg/ha stover (97.4%). Protein content hit 9.06% (T_8, 11.58%). Synergistic Fe-Zn effects improved nutrient mobilization (Cakmak, 2008; Manzeke *et al.*, 2020) [6, 11].

Table 2: Influence of Agronomic Biofortification with Iron and Zinc on nitrogen content and uptake and protein content of maize

S. No.	Treatments	Nitrogen Content (%) in		Nitrogen uptake (kg/ha.) in		Protein Content in seed (%)
		Grain	Stover	Grain	Stover	
1	Control	1.3	0.52	51.79	34.29	8.12
2	RDF + Soil application ZnSO4 @20 kg/ha	1.42	0.62	77.5	54.1	8.87
3	RDF + Soil application FeSO4@ 25 kg/ha	1.43	0.63	78.59	55.53	8.93
4	RDF + 0.5% ZnSO4 Foliar sprat at tillering stage (20-25 DAS)	1.42	0.62	90.25	58.91	8.87
5	RDF+ 0.5% FeSO4 Foliar spray at tillering stage (20-25 DAS)	1.43	0.63	94.06	61.9	8.93
6	RDF+ Soil application ZnSO4 @20 kg/ha +0.5% ZnSO4 Foliar spray at 45 DAS	1.44	0.64	98.16	63.94	9
7	RDF+Soil application ZnSO4 @20 kg/ha +0.5% FeSO4 Foliar spray at 45 DAS	1.44	0.64	107.76	65.27	9
8	RDF+ Soil application FeSO4@ 25 kg/ha + 0.5% ZnSO4 Foliar sprat at 45 DAS	1.45	0.64	102.89	64.81	9.06
9	RDF+ Soil application FeSO4@ 25 kg/ha + 0.5% Foliar sprat at 45 DAS	1.42	0.62	89.91	59.26	8.87
	C.D.	0.067	0.026	4.436	2.541	0.434
	SE(m)	0.022	0.009	1.467	0.84	0.144
	C.V.	2.725	2.386	2.892	2.529	2.81

Table 3: Influence of Agronomic Biofortification with Iron and Zinc on phophorus content and uptake of maize.

S. No.	Treatments	Phosphorus Content (%)		Phosphorus uptake (kg/ha.)	
		Grain	Stover	Grain	Stover
1	Control	1.16	0.68	46.21	44.84
2	RDF + Soil application ZnSO4 @20 kg/ha	1.22	0.76	66.58	66.32
3	RDF + Soil application FeSO4@ 25 kg/ha	1.3	0.84	71.44	74.04
4	RDF + 0.5% ZnSO4 Foliar sprat at tillering stage (20-25 DAS)	1.34	0.86	85.17	81.71
5	RDF+ 0.5% FeSO4 Foliar spray at tillering stage (20-25 DAS)	1.32	0.9	86.82	88.56
6	RDF+ Soil application ZnSO4 @20 kg/ha +0.5% ZnSO4 Foliar spray at 45 DAS	1.34	0.94	91.34	93.91
7	RDF+Soil application ZnSO4 @20 kg/ha +0.5% FeSO4 Foliar spray at 45 DAS	1.57	0.95	117.49	96.89
8	RDF+ Soil application FeSO4@ 25 kg/ha + 0.5% ZnSO4 Foliar sprat at 45 DAS	1.55	0.94	109.98	95.2
9	RDF+ Soil application FeSO4@ 25 kg/ha + 0.5% Foliar sprat at 45 DAS	1.33	0.79	84.21	75.51
	C.D.	0.054	0.054	3.332	3.363
	SE(m)	0.018	0.018	1.102	1.112
	C.V.	2.303	3.627	2.262	2.418

Table 4: Influence of Agronomic Biofortification with Iron and Zinc on phophorus content and uptake of maize.

S. No.	Treatments	Phosphorus Content (%)		Phosphorus uptake (kg/ha.)	
		Grain	Stover	Grain	Stover
1	Control	1.16	0.68	46.21	44.84
2	RDF + Soil application ZnSO4 @20 kg/ha	1.22	0.76	66.58	66.32
3	RDF + Soil application FeSO4@ 25 kg/ha	1.3	0.84	71.44	74.04
4	RDF + 0.5% ZnSO4 Foliar sprat at tillering stage (20-25 DAS)	1.34	0.86	85.17	81.71
5	RDF+ 0.5% FeSO4 Foliar spray at tillering stage (20-25 DAS)	1.32	0.9	86.82	88.56
6	RDF+ Soil application ZnSO4 @20 kg/ha +0.5% ZnSO4 Foliar spray at 45 DAS	1.34	0.94	91.34	93.91
7	RDF+Soil application ZnSO4 @20 kg/ha +0.5% FeSO4 Foliar spray at 45 DAS	1.57	0.95	117.49	96.89
8	RDF+ Soil application FeSO4@ 25 kg/ha + 0.5% ZnSO4 Foliar sprat at 45 DAS	1.55	0.94	109.98	95.2
9	RDF+ Soil application FeSO4@ 25 kg/ha + 0.5% Foliar sprat at 45 DAS	1.33	0.79	84.21	75.51
	C.D.	0.054	0.054	3.332	3.363
	SE(m)	0.018	0.018	1.102	1.112
	C.V.	2.303	3.627	2.262	2.418

Table 5: Influence of Agronomic Biofortification with Iron and Zinc on Potassium content and uptake of maize.

S. No.	Treatments	Potassium Content (%)		Potassium uptake (kg/ha.)	
		Grain	Stover	Grain	Stover
1	Control	0.3	0.152	11.95	10.02
2	RDF + Soil application ZnSO4 @20 kg/ha	0.32	0.162	17.46	14.13
3	RDF + Soil application FeSO4@ 25 kg/ha	0.33	0.165	18.13	14.54
4	RDF + 0.5% ZnSO4 Foliar sprat at tillering stage (20-25 DAS)	0.34	0.17	21.61	16.15
5	RDF+ 0.5% FeSO4 Foliar spray at tillering stage (20-25 DAS)	0.32	0.163	21.09	16.03
6	RDF+ Soil application ZnSO4 @20 kg/ha +0.5% ZnSO4 Foliar spray at 45 DAS	0.34	0.17	23.17	16.98
7	RDF+Soil application ZnSO4 @20 kg/ha +0.5% FeSO4 Foliar spray at 45 DAS	0.39	0.194	29.18	19.78
8	RDF+ Soil application FeSO4@ 25 kg/ha + 0.5% ZnSO4 Foliar sprat at 45 DAS	0.38	0.19	26.96	19.24
9	RDF+ Soil application FeSO4@ 25 kg/ha + 0.5% Foliar sprat at 45 DAS	0.33	0.167	20.89	15.963
	C.D.	0.014	0.007	0.982	0.61
	SE(m)	0.005	0.002	0.325	0.202
	C.V.	2.365	2.48	2.658	2.201

4.4 Economics
Cost of cultivation ranged ₹52,862 (T_1) to ₹63,724.96 (T_9). Gross returns peaked at ₹160,540 (T_7, 78% over T_1), net returns ₹102,715.04 (175%), and B:C 1.77 (153%). Integrated applications maximized profitability (Goyal *et al*., 2018) [8].

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