International Journal of Agricultural Technology 2026 Vol. 22(1):195-218
DOI: https://doi.org/10.63369/ijat.2026.22.1.195-218
Available online http://www.ijat-aatsea.com
ISSN 2630-0192 (Online)

Impact of iron and zinc fertilization on Maize (*Zea mays* L.) yield and quality traits under integrated nutrient management practices

Kumar. R. S. A., Augustine, R.*, Dhivyalakshmi, T. and Abisankar, R. S.

Division of Agronomy, School of Agricultural Sciences, KITS, Karunya University, Coimbatore, Tamil Nadu, India.

Kumar, R. S. A., Augustine, R., Dhivyalakshmi, T. and Abisankar, R. S. (2026). Impact of iron and zinc fertilization on Maize (*Zea mays* L.) yield and quality traits under integrated nutrient management practices. International Journal of Agricultural Technology 22(1):195-218.

Abstract The results showed the most significant improvement: dry matter yield increased by 38.5%, grain yield by 30.47%, Fe content by 73.31%, and Zn content by 91.74% over the control (F_1). Foliar application of Fe and Zn substantially enhanced maize growth, yield, and grain quality, including crude protein levels. This study demonstrated that applying 75% RDF with FYM, combined with foliar sprays of Fe and Zn at 45 and 60 days after sowing (DAS), significantly boosts maize productivity and grain micronutrient content. Such strategies offer a sustainable approach to improve human and livestock nutrition through enhanced grain quality.

Keywords: Agronomic biofortification, Foliar application, Maize grain yield, Micronutrients (Fe, Zn), Soil fertility management

Introduction

Deficits are prevalent in developed nations, especially among working men, pregnant and lactating women, and children. Over 2 billion people, or one in three, worldwide suffer from micronutrient deficiencies, also known as "hidden hunger" (Prom-u-thai *et al.*, 2020). Zinc (Zn) and iron (Fe) are the two micronutrients most frequently linked to malnutrition worldwide. According to an estimate, 151 million children under the age of five are "stunted," of which 51 million fall into the reversible group, meaning that their weight is out of proportion to their height (Ramdas *et al.*, 2020).

In India, the percentage of anaemia is 56.2% and 79.1% in married women aged 15-49 and children aged 3-6, respectively (Krishnaswamy, 2009). This is because most of the soil is degraded because of alkalinity and salt problems, and large amounts of cereal grains, viz., Wheat, rice, and maize, are commonly consumed as staple foods despite their naturally low contents of zinc and iron (Beal *et al.*, 2017; Cakmak and Kutman, 2018).

*Corresponding Author: Augustine, R.; **Email:** augustiner@karunya.edu

Dietary diversity and insufficient consumption are thought to be the main causes of human micronutrient deficits. Due to their metabolic functions, micronutrient deficiencies impair growth and development. They also have an adverse effect on the immune system's ability to fight off hazardous pathogens, increasing the body's susceptibility to illnesses and ultimately decreasing productivity (Read *et al*., 2019).

Micronutrients are essential for maintaining and affecting the immune response at every stage. Malnutrition in micronutrients can impair innate and adaptive immunity, resulting in immunological suppression and heightened vulnerability to infections (Gorji and Ghadiri, 2021). Infections and inadequate nutrition work together synergistically. An illness raises the body's need for micronutrients and exacerbates its state of nutritional insufficiency (Sayah *et al*., 2021).

Deficits in micronutrients affect food quality, metabolic processes such as flowering and seed production, and crop productivity. In order to meet the micronutrient requirements of human diets and enhance crop nutritional quality, micronutrient fertilization, often referred to as agronomic biofortification, may be required. Biofortification requires increased micronutrient intake, improved plant translocation, and increased edible portion accumulation for effective results. Plant-based micronutrient supply faces challenges in synthesizing essential minerals for human survival and uneven distribution of nutrients across different plant portions. (Zhu *et al*., 2007). For women and children, biofortified crops can offer the biggest nutritional complement when added to regular diets. In food crops including wheat, rice, and maize, agronomic biofortification, a fertilizer-based technique, significantly increases grain concentrations of specific micronutrients like iron, zinc, selenium and iodine (Mao *et al*., 2014 and Cakmak *et al*., 2017).

Maize, one of the world's oldest cereals, and is a crucial staple food crop grown in various agro-ecological zones and farming systems. In affluent nations, maize is mostly grown for animal feed, biofuel, and other commercial uses; nevertheless, in many other nations, it is consumed by humans (Ranum *et al*., 2014). Twenty per cent of calories and fifteen per cent of its protein globally come from maize, a staple grain for more than 200 million people (Nuss and Tanumihardjo, 2010). People with a wide range of socioeconomic backgrounds and culinary preferences usually eat maize. According to the FAO, more than 150 million tons of corn are consumed directly for food each year worldwide. Increasing maize yield in a sustainable farming setting can provide food security for a growing population. In 2022-23, maize production reached over 1,218 million hectares globally, spanning over 207 million hectares. India produced 34.6 million tonnes of maize in 2023-24, with the potential to double the production to meet supply-demand gaps cost-effectively and sustainably. Increasing yield to feed seven billion people and enhancing plant edible portions with minerals for optimal health are the current priorities (Graham *et al*., 2007).

The concentrations of micronutrients in food and feed made from plants considerably improve the health and welfare of both humans and animals (Grujcic *et al*., 2018). As a result, for maximum crop output and nutritional value, maize plants need appropriate micronutrient concentrations. When added to soil, micronutrients frequently become fixed and are difficult to translocate to the edible plant sections. It is advised to provide micronutrients via foliar sprays in soluble form rather than using conventional techniques. When fertilizer form, application technique, and application time are properly taken into account, agronomic biofortification can be a simple and affordable strategy.

The 60% lower Fe concentration in maize, which is less than the necessary nutritional impact because of Fe bioavailability inhibitors in processed maize, limits efforts to biofortify maize with iron (Chakraborti *et al*., 2011; Keigler *et al*., 2023). Corn typically has a Fe level of 16 mg kg^{-1}, while high-zinc corn has been shown to have a little increase in Fe content, up to 22 mg kg^{-1}. Pleiotropic influences can impact the absorption and mobilization of zinc and iron in kernels; these effects vary based on the properties of the soil (Maqbool and Beshir, 2019). The biofortification of zinc may potentially affect the Fe content in maize. Thus, the effects of foliar application of chelated Fe and ZnO fertilizers (e.g., $FeSO_4$ and ZnO) and their bioavailability in kernel maize must be evaluated to quantify the fertilizer potential under field conditions. Given this context, the study aimed to evaluate the effectiveness of agronomic biofortification, to compare the response of biofortified and non-biofortified maize hybrids and to determine the optimal combination of fertilizer treatments.

Materials and methods

Study location

A field experiment was conducted during 2022 and 2023 of the *kharif* and *rabi* seasons at the South Farm, KITS, Karunya University, Coimbatore, located at 10.9362° N latitude, 76.7441° E longitude at 400m above mean sea level. The experimental site is medium black soil, with a clayey texture, belongs to the vertisol order and the sub-group of typic chromusterts of the peelamedu series. The experimental site collected composite soil samples from 0 to 15cm depth before sowing and analyzed for physical and chemical properties. The experimental site is of clayey in texture (10.40 % sand, 30.0% silt, 59.37 % clay) with pH 7.3, E.C 0.34 dsm^{-1}, low organic carbon (4.8 g kg^{-1}) and available nitrogen (216.6 kg ha^{-1}), high in available phosphorus (29.5 kg ha^{-1}) and available potassium (334.3 kg ha^{-1}), medium in available zinc (0.81ppm) and available iron (4.22 ppm) respectively. The experimental site is located in Tamil Nadu's western ghat, which is part of the semi-arid tropics of India's Agro-climatic zone X. The experiment had mean temperatures of 28-39°C during the day and 22-19°C at night. The relative humidity ranged from 55 to 65 per cent, and the total rainfall received was 298.8 mm and 680 mm in 2022 and 2023, respectively, over 19 and 25 rainy days (Figure 1).

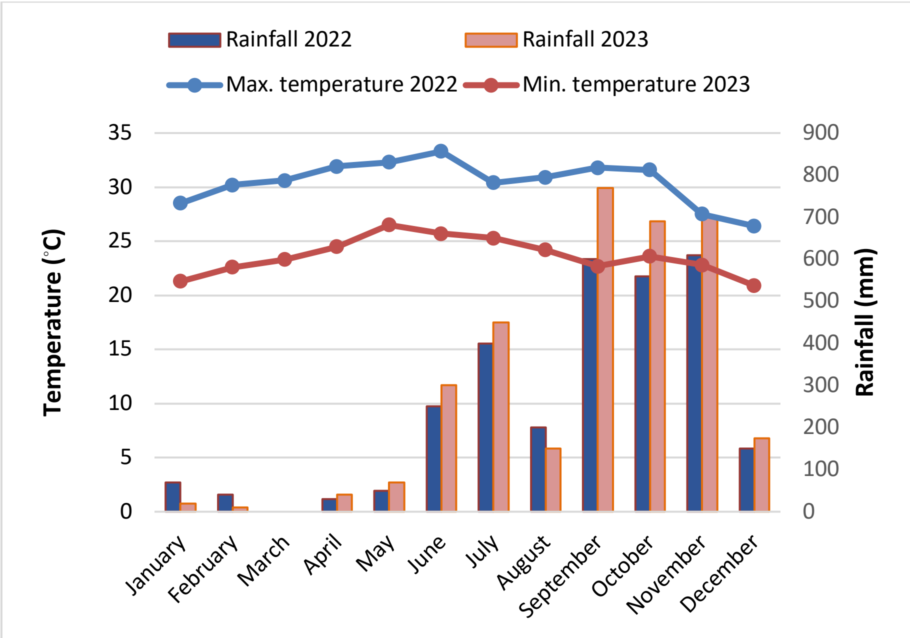

Figure 1. Weather prevailed during the field experiment

The experiment was conducted using a split-plot design, replicated three times, with two main treatments and six sub-plot treatments, viz., non-biofortified hybrid (M_1) and biofortified hybrid (M_2) are the two main plot categories and sub plots as 100 per cent Recommended Dose of Fertilizers (RDF) alone (F_1), 100 per cent RDF + Farmyard Manure (FYM) (F_2), 75 per cent RDF + FYM (F_3), F_1+ Foliar application of chelated iron @ 0.2 per cent conc., + zinc oxide (ZnO) @ 0.5 per cent conc. (F_4), F_2 + Foliar application of chelated iron @ 0.2 per cent conc., + Zinc @ 0.5 per cent conc. (F_5), F_3 + Foliar application of chelated iron + zinc @ 0.5 per cent conc. (F_6). The M_1 (commercial hybrid S6668) from the Syngenta group (seed division) and M_2, Quality protein maize (QPM) biofortified hybrid (HQPM8) from the International Maize and Wheat Improvement Center (CIMMYT), Hyderabad, for maize were used in this experiment. The F_1, F_2, and F_3 treatments are supplied with RDF of 250:75:75 kg ha^{-1} (N: P_2O_5: K_2O) and FYM of 12.5 t ha^{-1} for maize. Similarly, treatments F_4, F_5, and F6 received $FeSO_4$ in chelated form @ 0.2 per cent concentration (conc.) and ZnO (36% Zinc Conc.) @ 0.5 per cent conc., respectively.

Crop management and data collection

The biofortified maize hybrid (HQPM8) was used in both seasons of experimentation. This QPM maize hybrid was planted with a 60 x 20 cm spacing and is high in protein, lysine, and tryptophan. The recommended dose of fertilizer (RDF) for maize (N: P_2O_5: K_2O) was applied @ 250:75:75 kg ha^{-1}, respectively. For F_1 to F_3 treatment, the entire phosphorus and potassium were applied as basal, and N was applied in two equal splits at basal and 30 and 45 DAS. Irrespective of treatments, viz., irrigation, weed management, and plant protection measures were followed in accordance with the standard package of practices.

Observations were recorded on various morphological growth stages, viz., plant height (cm), leaf area index, and the samples were collected for estimation of dry matter (dried in a hot air oven at 80˚C ± 5 ˚C) from the gross plot area. Five plants were analyzed for leaf area using a leaf area meter (Model LI-COR 3100), and the leaf area index was calculated by dividing the total leaf area by the total ground area. The yield attributes viz., cob length, cob weight, hundred test weight, and shelling % were recorded treatment-wise, and were recorded from the tagged plants in each treatment. The grain and stover yield was noted separately. The Fe, Zn, crude protein, and starch content in grains were analysed from the treatments.

Economic returns

The economics of treatments were done by calculating variable costs (VC) on seeds, chemicals, and micro-nutrient fertilizers, and labour separately. The gross return (GR) was worked out by multiplying the economic output (maize grain) by the current market price. The net income (NR) was calculated as per Equation (1) and expressed in US$/day (the average exchange rate in 2022 and 2023 was 84.50 and 85.12, respectively. The benefit-cost ratio was calculated by dividing net income by the variable cost. (Equation 2).

Net income (US$) = Gross returns (US$) – Variable cost (US$) ……… (1)

BCR = Net return / Variable cost ………………………………………. (2)

Statistical analysis

The data were examined using the analysis of variance (ANOVA) for split plot design, as per the guidelines of Gomez and Gomez (1984). The F-test was used to assess the significance of the treatment effect, and least significant differences (LSD) were used to examine treatment means at a 5% probability level. The pearson correlation and principal component analysis (PCA) were performed by using R Studio.

Results

Growth and yield attributes of maize

The experiment showed significant differences (p=0.05) among treatments, with the highest plant height at harvest was recorded in M_1 (non-biofortified hybrid) + F_6 (F_3+ foliar sprays of chelated Fe @ 0.2% conc., + ZnO @ 0.5 % conc.) and was statistically at par with F_5 (194.27 cm) (Table 1). The F_1 treatment (Control) reported shorter plant height at harvest stages (164.24 cm), followed by F_2 (100% RDF with FYM), and was at par with F_3 (75% RDF + FYM).

The two-year experimental study revealed that the application of chelated Fe and ZnO significantly increased the leaf area index, regardless of the combination. The study found that, 75 per cent RDF with FYM + foliar sprays of chelated Fe @ 0.2% and ZnO @ 0.5 % conc., (F_6) reported a higher leaf area index (5.25) compared to F_2 + foliar sprays of chelated Fe @ 0.2% and ZnO @ 0.5 % conc., (F_5) and F_1 + foliar sprays of chelated Fe @ 0.2% and ZnO @ 0.5 % conc., (F_4). In both years, the lowest LAI was reported in Control (F_1). The study revealed a positive correlation between leaf area index (LAI) and dry matter, suggesting LAI as a crucial indicator of photosynthesis and translocation in maize crops. Higher radiation levels are linked to higher LAI, which has been shown to enhance dry matter production. The dry matter production on pooled basis is substantially increased by the 75 per cent RDF with FYM + (F_6) foliar sprays of chelated Fe @ 0.2% and ZnO @ 0.5% conc., (1.88 t ha^{-1}) at harvest, and it remained competitive with 75 per cent RDF with FYM (F_5) (1.73 t ha^{-1}). The lowest dry matter production was noted under 100% RDF (F_1). There was a 21.56 % per cent increase in dry matter production due to 75 per cent RDF with FYM + foliar sprays of chelated Fe @ 0.2% and ZnO @ 0.5% conc., (F_6) as compared to 100% RDF with FYM (F_3). Soil application of 75 per cent RDF with FYM (F_3) increased DMP by 19.6% and 6.42% compared to 100% RDF (F_1) and 100% RDF with FYM (F_2), respectively. Overall, at harvest, the foliar spray treatments F_6, F_5, and F_4 recorded 38.51%, 27.2%, and 19.18% DMP, respectively, over the control.

The response of yield contributing characters like cob length, cob weight, test weight, and shelling% % at harvest was significantly improved by both conventional and chelated Fe and ZnO foliar applications (Table 1). Combined application of 75 per cent RDF with FYM + foliar sprays of chelated Fe @ 0.2% and ZnO @ 0.5 % had a maximum cob length (21.23 cm), cob weight (102.18 g), test weight (259.31g) and shelling (77.09%), it was closely followed by other foliar applications (F_5 & F_4). The least cob length, cob weight, test weight, shelling was recorded in 100% RDF (F_1) (14.07 cm, 74.60 g, 201.15 g and 71.66%), and have shown a decreased levels by 12.44%, 18.86% in cob length, 2.94%, 6.68% in cob weight, 6.32%, 10.23% in test weight, 0.61%, 1.54% in shelling%, respectively with 100% RDF with FYM (F_2) and 75% RDF with FYM (F_3) indicating among soil applications and 24.03%, 25.83%, 33.73 in cob length, 12.37%, 15.37%, 26.99% in cob weight, 18.11%, 20.41%, 22.43% in test weight, 4.71%, 6.00%, 7.04% in shelling%, respectively with F_4, F_5 and F_6, indicating by foliar applications. Although a maximum number of cob length, cob weight, test weight, and shelling% was found under F_6, the average was statistically significant with soil application treatments (F_3, F_2 & F_1).

Yield and quality attributes of maize

Significant variation across the year in a pooled mean of maize yield was noted in the experiment (Table 2 and Figure 2). The average maize yield in the field experiment was 7.96 t ha^{-1}, 7.46 t ha^{-1}, and 8.46 t ha^{-1} under cultivars, soil application, and foliar treatments, respectively. The maximum yield was found with the application of (F_6) 75 per cent RDF with FYM + foliar sprays of chelated Fe @ 0.2% and ZnO @ 0.5 % conc., (8.82 t ha^{-1}) reported significantly superior over F_3, F_2, and F_1, however, it was statistically equivalent to (F_5)100 per cent RDF with FYM + foliar sprays of chelated Fe @ 0.2% and ZnO @ 0.5 % conc., at 8.53 t ha^{-1}. The maize yield responded linearly with a decrease in RDF levels and increased yield in both soil (F_3 & F_2) and chelated Fe & ZnO foliar (F_6 & F_5) treatments. The difference in the maize yield due to chelated Fe & ZnO foliar and soil application was 10.53%, while that of with control was 30.47%. Application of 75 per cent RDF with FYM + foliar sprays of chelated Fe @ 0.2% and ZnO @ 0.5 % (F_6) has shown a per cent age increase by 30.35% compared to the control (100% RDF).

The response of quality contributing characters viz., protein, starch, iron, and zinc of maize grain significantly increased by both foliar and soil applications (Table 2). Combined application of 75 per cent RDF with FYM + foliar sprays of chelated Fe @ 0.2% and ZnO @ 0.5 % had a maximum protein (16.13 %) and starch (66.97 mg g^{-1}), iron content (38.77 mg kg^{-1}) and zinc content (32.50 mg kg^{-1}), and it was at par with F_5 treatment. The least content of protein, starch, iron and zinc, was recorded in control (F_1) (11.45%, 57.15 mg g^{-1}, 22.37 and 16.95 mg kg^{-1}), respectively and it was at par with 100% RDF with FYM (F_2), indicating fertilizer and soil application affect the quality attributes. Although the maximum content of quality attributes (iron, zinc, protein, and starch) was found under integrated nutrients + chelated Fe & ZnO (F_6), the average was statistically significant with conventional soil and foliar treatments (F_1, F_2, F_3, F_4, and F_5). Significant variation in iron, zinc content, protein, and starch content was noted in our field experiment (Figure 3), both in soil and foliar sources.

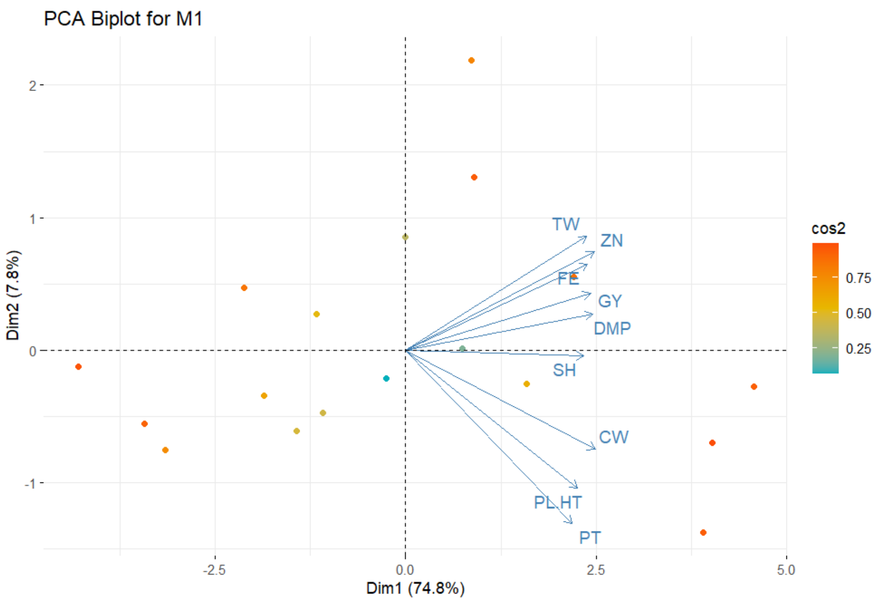

Figure 2. Using PCA technique for non-biofortified hybrid (M_1)

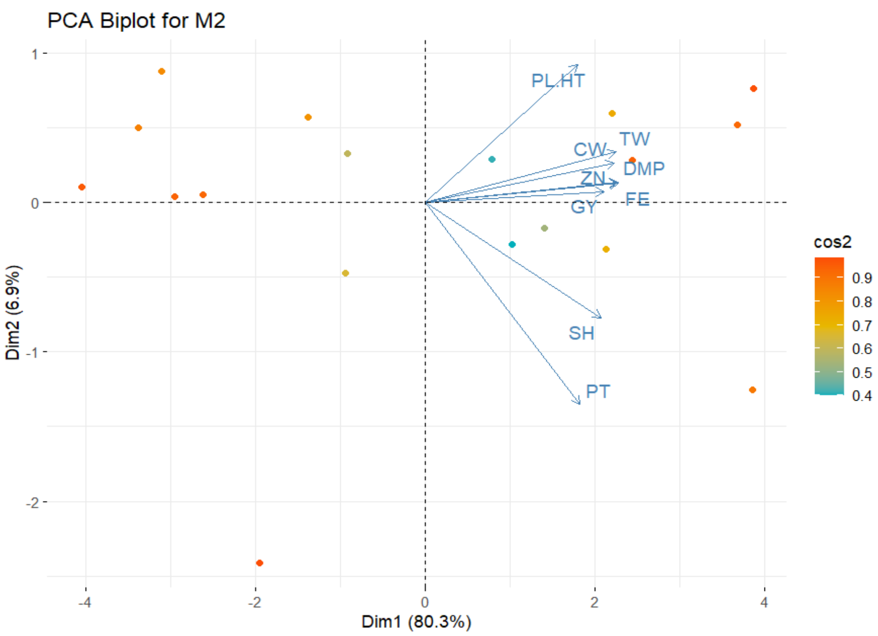

Figure 3. Using PCA technique for biofortified hybrid (M_2)

Data interpretation using pearson correlation and PCA

The correlation analysis recorded significant ($p < 0.05$) or highly significant correlations ($p < 0.01$) between maize growth parameters, dry matter yield, yield attributes, and quality attributes (Table 3). The study revealed a significant correlation between the amount of zinc and iron in plants and their height (0.614**and 0.617**), leaf area index (0.758**and 0.724**), dry matter production (0.534**and 0.508**), Cob length (0.730**and 0.707**), Cob weight (0.724** and 0.734**), test weight (0.606**and 0.570**) and shelling (0.625** and 0.605**). Also, significant correlations between zinc and iron content were found (0.548** and 0.541**) with protein and (0.667** and 0.624**) with starch in the grain (Table 3). The study found a significant ($p<0.01$) positive correlation between maize grain yield and growth and yield parameters such as plant height (0.627**), leaf area index (0.846**), and dry matter production (0.869**), cob length (0.848**), cob weight (0.726**), test weight (0.862**) and shelling (0.626**). In regard to the correlation with yield in maize with other quality parameters, a non-significant correlation with GY-PN and GY-SH content in grain was found (-0.035^{NS} and 0.220^{NS}), whereas a significant positive correlation (0.596** and 0.628**, $p < 0.01$) with GY-Fe and GY-Zn content was observed (Table 3).

In Principal component analysis (PCA), the grain yield (GY) has a very strong positive influence on DMP, Fe, Zn, TW, and SH. But Cob weight, Plant height, and Protein do contribute to the grain weight, but they don’t directly contribute compared to other parameters. This analysis can be compared with pearson to understand more about their contributions. Cos2 represents the quality of the representation (clusters) in the dataset. The higher the cos2 (red), the more captured by the dimensions (Figure 2 and Figure 3). For both M_1 and M_2, the common factors influencing the grain Yield (GY) (t/ha) are strongly influenced by DMP, Fe, Zn, and TW. Both starch, protein, cob weight, and plant height have distinct differences in their influencers for both M_1 and M_2.

There exists a considerable positive correlation between the yield and the iron and zinc concentrations ($r = 0.48^*$ and $r = 0.56^*$; $r = 0.78^*$ and $r = 0.75^*$) in M_1 and M_2 cultivars, respectively, illustrating that yield has a direct function with foliar Fe & Zn application (Figure 4 & 5).

Economic returns

The monetary analysis of maize cultivation showed that treatments receiving chelated Fe & ZnO showed higher gross returns, net returns, and BC ratio over time. The highest BC ratio (3.14 & 2.77) with net profit (959.9 & 809.6 US\$ ha^{-1}) was obtained in the year 2022 & 2023 respectively by the application of 75% NPK+FYM and foliar applied chelated Fe 0.2% & ZnO 0.5% (F_6), it was followed by F_3 (75 per cent RDF with FYM) and F_2 (100 per cent RDF + FYM) applications. The control (RDF) treatment resulted in the lowest gross returns, net returns, and BC ratio (1379.5 & 1203.3; 896.4 & 716.6 and 2.86 & 2.47) in both years, respectively (Table 4).

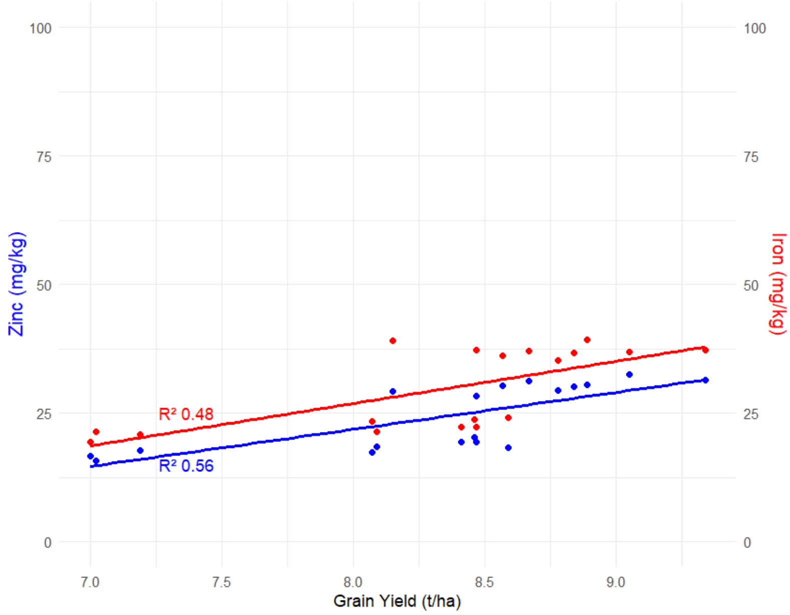

Figure 4. Relationship between iron and zinc concentration to maize grain yield by non-biofortified hybrid (M_1)

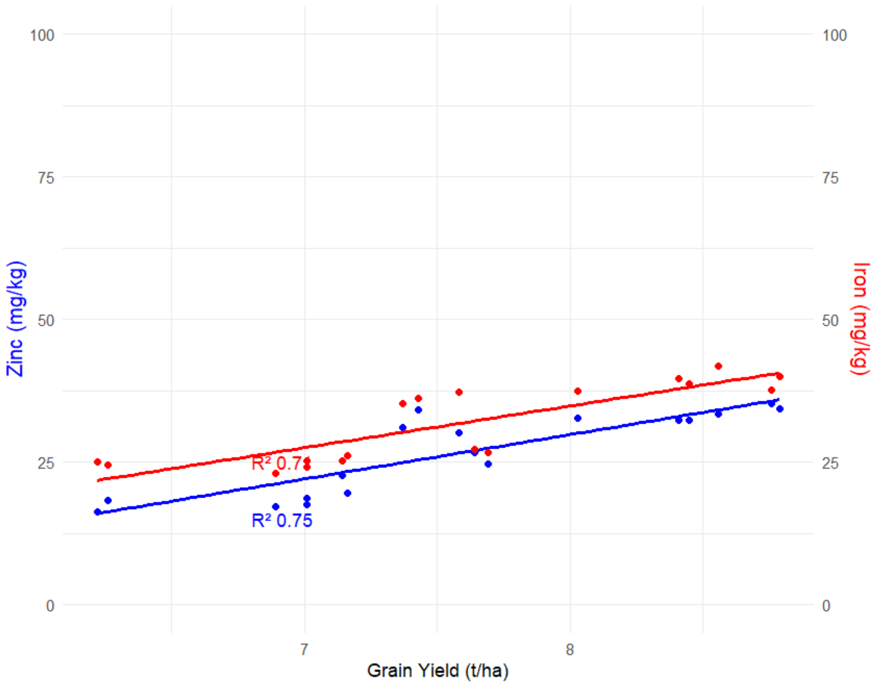

Figure 5. Relationship between iron and zinc concentration to maize grain yield by biofortified hybrid (M_2)

Table 1. Effect of iron and zinc fertilization on growth and yield attributes of maize cultivars (Pooled data of two years)

Treatments		PH (cm)	LAI	DMP (t ha^{-1})	Cob length (cm)	Cob weight (g)	Test weight (g)	Shelling (%)
Hybrid								
M$_1$: Non-biofortified		188.19^a ± 4.30	4.55^a ± 0.11	1.74^a ± 0.02	18.58^a ± 0.64	86.48^a ± 2.52	250.46^a ± 4.34	74.91^a ± 0.69
M$_2$: Biofortified		182.62^b ± 3.79	4.07^b ± 0.18	1.45^b ± 0.06	16.82^b± 0.53	82.47^b± 2.2	215.42^b ± 6.77	73.45^b ± 0.77
SE(d)		1.53	0.05	0.09	0.18	0.87	3.28	0.21
CD at 5%		NS	0.22	0.45	0.83	4.01	15.19	0.96
Soil application								
F$_1$: Control (100% RDF only)		164.24^d ± 2.64	3.52^e ± 0.04	1.36^e ± 0.04	14.07^c ± 0.11	74.6^d ± 0.61	201.15^d ± 4.33	71.66^b ± 0.48
F$_2$: 100 per cent RDF with FYM		175.5^c ± 2.74	3.79^d ± 0.06	1.46^d ± 0.02	16.07^d ± 0.15	76.86^c ± 0.55	214.72^c ± 2.46	72.10^b ± 0.38
F$_3$: 75 per cent RDF with FYM		181.98^c ± 3.00	4.08^c ± 0.13	1.57^c ± 0.05	17.34^c ± 0.31	79.94^c ± 0.98	224.08^c ± 6.93	72.78^b ± 0.54
Foliar application								
F$_4$: F$_1$+ Chelated Fe @ 0.2% + ZnO @ (		185.00^{bc} ± 3.45	4.51^b ± 0.11	1.62b^c ± 0.05	18.52^b ± 0.22	85.13^b ± 1.11	245.65^b ± 7.01	75.2^{ab} ± 0.72
F$_5$: F$_2$+ Chelated Fe @ 0.2% + ZnO @ 0.5 %		194.27^b ± 1.05	4.69^b ± 0.07	1.73^b ± 0.05	18.97^b ± 0.20	88.15^b ± 0.85	252.72^a ± 5.12	76.24^a ± 0.44
F$_6$: F$_3$+ Chelated Fe @ 0.2% + ZnO @ 0.5 %		211.43^a ± 1.49	5.25^a ± 0.06	1.88^a ± 0.01	21.23^a ± 0.63	102.18^a ± 1.59	259.31^a ± 4.25	77.09^a ± 0.55
SE(d)		5.03	0.09	0.03	0.45	1.86	5.36	1.29
CD at 5%		10.56	0.20	0.08	0.94	3.89	11.26	2.71
M at S	SE(d)	6.67	0.13	0.05	0.60	2.55	7.66	1.68
	CD at 5%	NS	0.32	0.11	1.40	6.09	19.64	NS
S at M	SE(d)	7.11	0.14	0.05	0.63	2.63	7.58	1.83
	CD at 5%	14.83	0.33	0.11	1.47	6.28	19.45	NS

DMP – Dry matter production; Fe – iron; FYM- Farm yard manure; LAI – Leaf area index; PH – Plant height; RDF – Recommended dose of fertilizer; ZnO- Zinc oxide

S: significant at P≤ 0.05; NS: Non-significant at P> 0.05; Means of the identical case letter do not show significant differences at p ≤ 0.05

Table 2. Effect of iron and zinc fertilization on yield and quality parameters of maize cultivars (pooled data of two years)

Treatments		Grain yield (t ha^{-1})	Stover yield (t ha^{-1})	Protein (%)	Starch (mg g^{-1})	Iron (mg kg^{-1})	Zinc (mg kg^{-1})
Hybrid							
M_1: Non-biofortified		$8.34^{a} \pm 0.15$	$11.07^{a} \pm 0.18$	$11.22^{b} \pm 0.42$	58.73 ± 0.90	$29.63^{b} \pm 1.86$	$24.25^{b} \pm 1.52$
M_2: Biofortified		$7.58^{b} \pm 0.18$	$10.64^{b} \pm 0.13$	$15.47^{a} \pm 0.45$	65.01 ± 0.93	$31.73^{a} \pm 1.62$	$26.51^{a} \pm 1.67$
SE(d)		0.03	0.02	0.19	1.69	0.36	0.38
CD at 5%		0.15	0.10	0.86	NS	1.67	1.76
Soil application							
F_1: Control (100% RDF only)		$6.76^{d} \pm 0.15$	$10.19^{c} \pm 0.15$	$11.45^{c} \pm 0.76$	$57.15^{c} \pm 1.02$	$22.37^{e} \pm 0.21$	$16.95^{e} \pm 0.46$
F_2: 100 per cent RDF with FYM		$7.62^{c} \pm 0.60$	$10.39^{c} \pm 0.11$	$12.37^{b} \pm 0.47$	$59.58^{c} \pm 1.23$	$23.75^{d} \pm 0.28$	$18.50^{d} \pm 0.50$
F_3: 75 per cent RDF with FYM		$7.98^{b} \pm 0.97$	$10.51^{c} \pm 0.37$	$12.75^{b} \pm 0.45$	$61.41^{b} \pm 0.82$	$24.87^{c} \pm 0.51$	$22.00^{c} \pm 0.22$
Foliar application							
F_4: F_1+ Chelated Fe @ 0.2% + ZnO @ 0.5 %		$8.02^{b} \pm 0.14$	$10.92^{b} \pm 0.20$	$13.18^{b} \pm 0.78$	$62.43^{b} \pm 1.13$	$36.20^{b} \pm 0.43$	$30.58^{ab} \pm 0.21$
F_5: F_2+ Chelated Fe @ 0.2% + ZnO @ 0.5 %		$8.53^{ab} \pm 0.13$	$11.05^{b} \pm 0.10$	$14.18^{b} \pm 0.54$	$63.67^{b} \pm 0.78$	$38.13^{a} \pm 0.45$	$31.75^{a} \pm 0.77$
F_6: F_3+ Chelated Fe @ 0.2% + ZnO @ 0.5 %		$8.82^{a} \pm 0.10$	$11.91^{a} \pm 0.15$	$16.13^{a} \pm 0.60$	$66.97^{a} \pm 0.84$	$38.77^{a} \pm 0.46$	$32.50^{a} \pm 0.32$
SE(d)		0.13	0.22	0.51	1.26	0.55	0.62
CD at 5%		0.29	0.46	1.07	2.64	1.16	1.31
M at S	SE(d)	0.18	0.28	0.68	2.34	0.79	0.89
	CD at 5%	0.40	NS	NS	NS	2.09	2.28
S at M	SE(d)	0.19	0.31	0.72	1.78	0.78	0.88
	CD at 5%	0.43	NS	NS	NS	2.04	2.26

FYM- Farmyard manure; Fe- iron; RDF – Recommended dose of fertilizer; ZnO- Zinc oxide;
S: significant at P≤ 0.05; NS: Non-significant at P> 0.05; Means of the identical case letter do not differ significantly at p ≤ 0.05

Table 3. Study of Pearson correlation coefficient and significance level between growth, dry matter, yield, yield attributes and quality parameters on maize (pooled data of two years)

	PH	**LAI**	**DMP**	**CL**	**CW**	**TW**	**SH**	**GY**	**SY**	**PN**	**SH**	**Fe**	**Zn**
PH	1												
LAI	0.705**												
DMP	0.609**	0.901**											
CL	0.702**	0.903**	0.776**										
CW	0.777**	0.871**	0.754**	0.879**									
TW	0.567**	0.885**	0.907**	0.825**	0.743**								
SH	0.552**	0.733**	0.644**	0.672**	0.691**	0.632**							
GY	0.627**	0.846**	0.869**	0.848**	0.726**	0.862**	0.626**						
SY	0.702**	0.737**	0.680**	0.814**	0.768**	0.645**	0.545**	0.693**					
PN	0.253^{NS}	0.187^{NS}	-0.124^{NS}	0.170^{NS}	0.335*	- 0.155^{NS}	0.245^{NS}	- 0.035^{NS}	0.151^{NS}				
SH	0.367*	0.348*	0.077^{NS}	0.344*	0.427**	0.068^{NS}	0.378*	0.220^{NS}	0.303^{NS}	0.848**			
Fe	0.617**	0.724**	0.507**	0.707**	0.734**	0.570**	0.605**	0.596**	0.650**	0.541**	0.624**		
Zn	0.614**	0.758**	0.534**	0.730**	0.724**	0.606**	0.625**	0.628**	0.612**	0.548**	0.667**	0.951**	1

CL: Cob length; CW: Cob weight; DMP: Dry matter production; Fe: Iron content; GY: Grain yield; LAI: Leaf area index; PH: Plant height; PN: Protein SH: Shelling; SH: Starch; SY: Stover yield; TW: Test weight; Zn: Zinc content;
**: significant at 0.01 probability level; NS: Non-significant.

Table 4. Effect of iron and zinc fertilization on the economics of maize cultivars (Pooled data of two years)

Hybrid	Treatments	Gross return (x $ ha^{-1})		Net return (x $ ha^{-1})		BC ratio	
		2022	2023	2022	2023	2022	2023
M_1	F_1: Control (100% RDF only)	1379.5	1203.3	896.4	716.6	2.84	2.47
	F_2: 100 per cent RDF with FYM	1388.9	1219.5	900.0	727.0	2.86	2.48
	F_3: 75 per cent RDF with FYM	1398.3	1235.7	944.6	778.7	3.04	2.70
	F_4: F_1+ Chelated Fe @ 0.2% + ZnO @ 0.5 %	1407.7	1251.9	951.5	795.1	3.04	2.70
	F_5: F_2+ Chelated Fe @ 0.2% + ZnO @ 0.5 %	1417.0	1264.0	959.8	800.7	3.08	2.71
	F_6: F_3+ Chelated Fe @ 0.2% + ZnO @ 0.5 %	1431.1	1284.3	959.9	809.6	3.14	2.77
M_2	F_1: Control (100% RDF only)	1243.4	1053.3	754.6	566.7	2.54	2.16
	F_2: 100 per cent RDF with FYM	1260.6	1073.6	807.0	581.2	2.68	2.18
	F_3: 75 per cent RDF with FYM	1280.9	1085.8	812.0	628.8	2.74	2.38
	F_4: F_1+ Chelated Fe @ 0.2% + ZnO @ 0.5 %	1290.3	1101.9	815.4	645.2	2.75	2.38
	F_5: F_2+ Chelated Fe @ 0.2% + ZnO @ 0.5 %	1295.0	1114.1	819.1	650.8	2.78	2.40
	F_6: F_3+ Chelated Fe @ 0.2% + ZnO @ 0.5 %	1338.8	1134.4	891.0	659.7	2.99	2.44

Average exchange rate of US $ during 2022 and 2023 was 84.50 and 85.12, respectively

Discussion

Growth attributes

The study revealed that 75% NPK with FYM and foliar application of iron and zinc significantly impacts maize growth, yield, attributes, and quality. Our results corroborated the findings of Potarzycki and Grzebisz (2009). The growth parameters of maize cultivars have been observed to increase in terms of plant height, leaf area of index, dry matter accumulation were significantly higher under 75 per cent RDF with FYM + foliar sprays of chelated Fe @ 0.2% and ZnO @ 0.5 % at 45 and 60 DAS (F_6) treatment, which can be attributed to improved vegetative growth owing to improvement of the solubilization and mobilization.

Foliar spray expedited the absorption of Zn and Fe nutrients through leaves, enhanced cell division, stem elongation, chlorophyll content, and photosynthesis. The use of foliar micronutrients can enhance the transition of dry matter from the store to the sink parts (Singaraval *et al*., 1996). This study was confirmed by Blindauer and Schmid (2010) that foliar fertilizer application accumulates in the phloem, through the leaf's cuticle and stomata, entering the leaf surface. This application method was found to be more efficient and shorter than root uptake, as Fe and Zn moved in chelated forms in the phloem stream.

The synergistic effect of both soils applied NPK with FYM and foliar application of iron and zinc, accentuated vegetative growth. Precision NPK and foliar application promote growth by synthesizing plant growth hormones like IAA and auxins, which aid in cell elongation and enlargement. An increase in cell division and chlorophyll content may be the cause of the observed increase in plant height over the control treatment, as reported by Anees *et al.* (2016). Similarly, lower plant height in maize was noticed in 100 per cent RDF (F_1) treatment, due to low availability of nutrients and minimum nutrient uptake, which reduces the dry matter and plant growth characteristics in maize. Similar findings with results were recorded by Lakhwinder *et al.* (2017) and Hasan *et al.* (2018).

The leaf area index (LAI) and dry matter were shown to positively correlate in the study, suggesting that the LAI is a good indication of photosynthesis and translocation in maize crops. Among the main treatments evaluated, the non-biofortified hybrid recorded significantly higher growth parameters than the biofortified (QPM) hybrid. Our findings are supported by Singh *et al.* (2001), who found that the highest dry matter accumulation and leaf area index at harvest were higher in the non-QPM hybrid than the QPM hybrid (HQPM1). The continuous slow release of nutrients by the application of 75 per cent RDF + FYM with chelated Fe @ 0.2 per cent conc., + ZnO @ 0.5 per cent conc., (F_6) has enabled leaf area increase, promoting photosynthetic rate and higher dry matter accumulation in plants, as confirmed by Shivanand Patil *et al.* (2017).

Yield attributes

The application of foliar iron and zinc fertilizers with 75% NPK+FYM improved yield owing to penetration and solubility. The synergistic effect of both soil-applied NPK+FYM and foliar-applied chelated Fe & ZnO accentuated yield attributes, which provided higher yield (F_6). Singh *et al.* (1995) found that zinc and iron are necessary for photosynthesis, assimilation, and the movement of photosynthates from the source, leaves to the sink, cobs.

Increased cob length and cob weight are due to the simulation effect of the combined application of 75% RDF + FYM with chelated Fe @ 0.2 per cent conc., + Zn @ 0.5 per cent conc., (F_6) on cell division and expansion. The results were in conformity with Vijay *et al.* (2015). Qian *et al.* (2016) noted that the yield parameters were decreased due to maize density and the competition among plants for nutrient uptake from the soil. Interaction of 75% RDF, FYM, and chelated Fe + ZnO had a positive response on yield attributes, consistent with the study by Hasan *et al.* (2018), which reported that adequate integrated nutrient supply enhances the grain size, which increases the cob weight. Increased cob weight is due to higher concentration of macro and micronutrients, enhanced and steady nutrient release from the application of 75 per cent RDF + FYM with chelated Fe @ 0.2 per cent conc, + ZnO @ 0.5 per cent conc., (F_6) when compared to the application of control. The reason for the cob's increased weight is that it can hold more nourishment from the green sections of plants (Hasan *et al.,* 2018).

Test weight (100-grain weight) suggested a positive correlation between the quantity of grain produced and its overall yield (Vijay *et al.,* 2015). Combined fertilizers with 75% RDF with FYM and Fe + Zn foliar spray, for better growth and grain filling of maize have directly influenced the 100 seed weight content. Admas *et al.*'s (2015) findings were in agreement with this, who concluded that the combined application of N and compost has a significant impact on 100 seed weight content.

Maximum shelling per cent age was recorded in the non-QPM hybrid and was found to be significantly superior to other hybrids. Similar results corroborated with Hargilas *et al.* (2017). Masuka *et al.* (2017**)** reported that there was a positive correlation between grain production and the shelling %, which is impacted by various factors such as location, agro-climatic conditions, genotypes, cultural methods, and kernel moisture content.

Yield

Higher yield attributes in the maize crop were stimulated, with foliar sprays with Zn or Fe generally increasing crop yields more than grain concentrations. Crop growth is significantly influenced by their role in photosynthesis, respiration, and other biochemical and physiological activities, contributing to higher yields (Zeidan *et al*., 2010). The decline in yield in the absence of these micronutrients is due to nutrient imbalance as reported by Kanwal *et al.* (2010).

Results showed that the non-QPM hybrid was significantly higher in yield than the QPM hybrid. These results were found to be in line with the findings of Hargilas *et al.* (2017) that HQPM1 significantly lowered the yield attributes and grain yield. This was due to better partitioning of photosynthetic activity and source-sink relationship, which has led to higher growth and yield attributes in non-QPM hybrids. The variation in grain yield may be influenced by factors such as rainfall, distribution pattern, and temperature variations during the crop growing season. Our findings are supported by Rajesh *et al.* (2018). The translocation of Fe and Zn in reproductive parts has led to increased total dry matter, which is influenced by Fe and Zn foliar application coupled with higher grain yield. The minimum grain yield was due to minimum available nutrients and poor yield attributing characters. Similar reports were recorded by Zaremanesh *et al.* (2017).

Quality attributes

The utilization of NPK+FYM and foliar applied chelated Fe & ZnO favoured quality improvement, resulting in enhanced iron, zinc, including protein and starch. The study revealed that QPM maize showed higher accumulation of kernel Fe and Zn compared to normal maize. The opaque2 (O2) mutation in QPM genotypes alters the endosperm protein's amino acid profile, increasing lysine and tryptophan levels 2-3 times compared to non-QPM genotypes (Prasanna *et al*., 2001). QPM genotypes, besides their superior protein quality, also exhibit higher concentrations of kernel micronutrients, particularly zinc (Welch *et al*., 1993 and Chakraborti *et al*., 2009b).

Appropriate application and availability of foliar applications at 45 and 60 DAS have improved the iron, zinc, and protein content. The higher content may be attributed to the combination of microelements and appropriate macro element fertilization (NPK). The nitrogen status of a plant significantly impacts the increase in zinc and iron levels in vegetative tissue. The results of the investigation showed a strong relationship between wheat (Montoya *et al*., 2020) and chickpea (Pal *et al*., 2019) Zn and Fe grain concentration and urea application. Increased nitrogen application improves the nutritional status of plants and encourages the grain to accumulate zinc and iron. Our results are confirmed by the findings of Cakmak *et al.* (2010); White and Broadley (2011); Murgia *et al*. (2012) and Sperotto *et al*. (2012). Thus, FYM with NPK balances the nutrients of the crop and improves the yields. Our results are in line with Manzeke *et al*. (2014) and Manzeke-Kangara *et al*. (2021), who reported a maize grain Zn increase of up to 67% when a combination of Zn fertilizer, mineral fertilizers, and locally available organic resources was applied.

Applications of foliar zinc considerably raised grain Zn and Fe contents by 8% and 99%, respectively (Pahlavan-Rad and Pessarakli 2009 and Niyigaba *et al*., 2019). Similarly, Phattarakul *et al*. (2012), Saha *et al*. (2017) and Meena and Fathima (2017) reported a significant increase in grain mineral content from 25 to 100% due to the application of combined soil and foliar fertilization.

The foliar application of chelated Fe & ZnO along with RDF+FYM has increased the iron and zinc content noted by Pahlavan-Rad and Pessarakli (2009) and Ibiang *et al.* (2018) for wheat and soyabean. Overall, we observed that application of 0.2% chelated Fe and 0.5% ZnO foliar spray, along with 75% RDF with FYM, respectively, could enhance the quality of maize grain compared to conventional RDF. Nandita *et al*. (2022) in Mosambi verified similar results, showing that foliar spraying Zn @ 0.5% + Fe @ 0.2% + B @ 0.3% + Cu @ 0.1% from May to July can improve fruit quality and output. Interaction of RDF + FYM with Fe and Zn had a positive response on quality contents, consistent with Niyigaba *et al*. (2019) reported that combined application of Zn and Fe fertilizer increases grain Zn, Fe, crude fibre, and protein content, whereas grain Fe content is increased by Fe fertilizer alone. Khattak *et al.* (2015) and Melash *et al.* (2016) corroborate our findings. Fe and Zn contents in transgenic rice were enhanced by 3.4 and 1.3 folds, respectively, by increased expression of Fe transport and storage proteins (Aung *et al*., 2013). Several researchers have found that non-QPM hybrids have significantly lower kernel Fe and Zn concentrations (Chakraborti *et al*., 2009a and Chen *et al.,* 2007). Increased use of nitrogen fertilizer enhanced the nutritional status of plants, resulting in a greater concentration of zinc and iron in grain (Cakmak *et al.,* 2010, White and Broadley 2011).

Economics and profitability of maize

On average, 14.55% and 23.98% higher net returns and 9.095 & 13.79% higher BC ratio were obtained by non-biofortified hybrid (H_1) with 75% NPK+FYM and foliar applied chelated Fe @ 0.2% conc., & ZnO @ 0.5% conc., (F_6) than the biofortified hybrid (H_2), which confirms the findings of Hargilas *et al.* (2017) that a minimum support price added to a better yield resulted in better economics.

In summary, the study is demonstrated that INM with Fe-Zn foliar application increased the grain yield of the tested maize hybrids grown on the respective soil conditions. The combined treatment during the two growing seasons had a beneficial effect on growth, grain yield, and nutritional quality in the season with favourable conditions. It appeared that Fe-Zn foliar application promoted plant growth and DMP, which led to an increase in grain yield components, and in some cases, grain Fe and Zn concentration. Therefore, Fe and Zn delivery to crops through foliar can be used as an effective technique to improve grain yield and nutritional quality of maize on soils with limited Zn available to plants.

Acknowledgements

The authors are grateful to the academic department officials and management for their assistance and cooperation in this research work.

Conflicts of interest

The authors declare no conflict of interest.

References

Admas, H., Gebrekidan, H., Bedadi, B. and Adgo, E. (2015). Effects of organic and inorganic fertilizers on yield and yield components of maize at Wujiraba Watershed, Northwestern Highlands of Ethiopia. American Journal of Plant Nutrition and Fertilization, 5:1-15.

Anees, M., Ali, A., Shakoor, U., Ahmed, F., Hasnain, Z. and Hussain, A. (2016). Foliar Applied Potassium and Zinc Enhances Growth and Yield Performance of Maize under Rainfed Conditions. International Journal of Agriculture and Biology, 18:1025-1032.

Aung, M. S., Masuda, H., Kobayashi, T., Nakanishi, H., Yamakawa, T. and Nishizawa, N. K. (2013) Iron biofortification of Myanmar rice. Frontier Plant Science, 4:158.

Beal, T., Massiot, E., Arsenault, J. E., Smith, M. R. and Hijmans, R. J. (2017). Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. PloS One, 12:e0175554.

Blindauer, A. C. and Schmid, R. (2010). Cytosolic metal handling in plants: Determinants for zinc specificity in metal transporters and metallothioneins. Metallomics, 2:510-29.

Cakmak, I., Pfeiffer, W. H. and Mcclafferty, B. (2010). Biofortification of durum wheat with zinc and iron. Cereal Chemistry, 87:10-20.

Cakmak, I. and Kutman, U. B. (2018). Agronomic biofortification of cereals with zinc: a review. European Journal of Soil Science, 69:172-180.

Cakmak, I., McLaughlin, M. J. and White, P. (2017). Zinc for Better Crop Production and Human Health. Plant and Soil, 411:1-4.

Chakraborti M., Hossain F., Kumar R., Gupta H. S. and Prasanna B. M. (2009a). Genetic evaluation of grain yield and kernel micronutrient traits in maize. Pusa Agricultural Science, 32:11-16.

Chakraborti, M., Prasanna, B. M., Hossain, F., Singh, A. M. and Guleria S. K. (2009b). Genetic evaluation of kernel Fe and Zn concentrations and yield performance of selected maize (*Zea mays* L.) genotypes. Range Management and Agroforestry, 30: 109-114.

Chakraborti, M., Prasanna, B. M., Hossain, F., Mazumdar, S., Singh, A. M., Guleria, S. and Gupta, H. S. (2011). Identification of Kernel Iron and Zinc-Rich Maize Inbreds and Analysis of Genetic Diversity Using Microsatellite Markers. Journal of Plant Biochemistry and Biotechnology, 20:224-233.

Chen F., Chun L., Song J. and Mi, G. (2007). Heterosis and genetic analysis of iron concentration in grains and leaves of maize. Plant Breeding, 126:107-109.

Gomez, K. A. and Gomez, A. A. (1984) Statistical Procedures for Agricultural Research. 2nd Edition, John Wiley and Sons, New York, 680 p.

Gorji, A. and Ghadiri, M. K. (2021). Potential roles of micronutrient deficiency and immune system dysfunction in the coronavirus disease (COVID-19) pandemic. Nutrition, 82:111047.

Graham, R. D., Welch, R. M., Saunders, D. A., Ortiz-Monasterio, I., Bouis, H. E. and Bonierbale, M. (2007). Nutritious subsistence food systems. Advances in Agronomy, 92:1-74.

Grujcic, D., Drinic, M., Zivanovic, I., Cakmak, I. and Singh, B. R. (2018). Micronutrient availability in soils of Northwest Bosnia and Herzegovina in relation to silage maize production. Acta Agriculturae Scandinavica, Section B – Soil & Plant Science, 68:301-310.

Hasan, M. M., Ray, T. K., Manirul Islam, K. M., Younus Ali, S. M., Muhammad, N., Rahman, M. A. and Barman, N. C. (2018). Growth and yield of hybrid maize as influenced by fertilizer management. Turkish Journal of Agriculture – Food Science and Technology, 6912:1727-1733.

Ibiang, Y. B., Innami, H. and Sakamoto, K. (2018). Effect of excess zinc and arbuscular mycorrhizal fungus on bioproduction and trace element nutrition of tomato (*Solanum lycopersicum* L. cv. Micro-Tom). Soil Science and Plant Nutrition, 3:342-351.

Kanwal, S., Rahmatullah, Ranjha, A. M. and Ahmad, R. (2010). Zinc partitioning in maize grain after soil fertilization with zinc sulphate. International Journal of Agriculture Biology*,* 12:299-302.

Keigler, J. I., Wiesinger, J. A., Flint-Garcia, S. A. and Glahn, R. P. (2023). Iron Bioavailability of Maize (*Zea mays* L.) after Removing the Germ Fraction. Frontiers in Plant Science*,* 14:1114760.

Khattak, S. G., Dominy, P. J. and Ahmad, W. (2015). Effect of Zn as soil addition and foliar application on yield and protein content of wheat in alkaline soil. Journal of the National Science Foundation of Sri Lanka*,* 43:303-312.

Krishnaswamy, K. (2009). The problem and consequences of the double burden—A brief overview. Programme and abstracts. In: Symposium on Nutritional Security for India-Issues and Way Forward. New Delhi: Indian National Science Academy*,* pp. 5-7.

Lakhwinder, S., Santhosh, K., Kuldeep, S. and Dalwinder, S. (2017). Effect of integrated nutrient management on growth and yield attributes of maize under winter season (*Zea mays* L.). Journal of Pharmacognosy and Phytochemistry*,* 6:1625-1628.

Manzeke, G. M., Mtambanengwe, F., Nezomba, H. and Mapfumo, P. (2014). Zinc fertilization influence on maize productivity and grain nutritional quality under integrated soil fertility management in Zimbabwe. Field Crops Research, 166:128-136.

Manzeke-Kangara, G. M., Joy, E. J. M., Mtambanengwe, F., Chopera, P., Watts, M. J., Broadley, M. R. and Mapfumo, P. (2021). Good soil management can reduce dietary zinc deficiency in Zimbabwe. CABI Agriculture and Bioscience*,* 2:36.

Mao, H., Wang, J., Wang, Z., Zan, Y. and Zou, C. (2014). Using agronomic biofortification to boost zinc, selenium, and iodine concentrations of food crops grown on the loess plateau in China. Journal of Soil Science and Plant Nutrition, 14:459-470.

Maqbool, M. A. and Beshir, A. R. (2019). Zinc Biofortification of Maize (*Zea mays* L.): Status and Challenges. Plant Breeding, 138:1-28.

Masuka, B., Atlin, G. N., Olsen, M., Magorokosho, C., Labuschagne, M., Crossa, J., Banziger, M., Pixley, K. V., Vivek, B. S. and Von Biljion, A. (2017). Grains in genetic improvement in Eastern and Southern Africa: I. CIMMYT hybrid breeding pipeline. Crop Science, 57:180-191.

Melash, A. A., Mengistu, D. K. and Aberra, D. A. (2016). Linking agriculture with health through genetic and agronomic biofortification. Agricultural Sciences*,* 7:295-307.

Meena, N. and Fathima, P. S. (2017). Nutrient uptake of rice as influenced by agronomic biofortification of Zn and Fe under methods of rice cultivation. International Journal of Pure and Applied Bioscience*,* 5:456-459.

Montoya, M., Vallejo, A., Recio, J., Guardia, G. and Alvarez, J. M. (2020) Zinc–nitrogen interaction effect on wheat biofortification and nutrient use efficiency. Journal of Plant Nutrition and Soil Science, 183:169-179.

Murgia, I., Arosio, P., Tarantino, D. and Soave, C. (2012). Biofortification for combating 'hidden hunger' for iron. Trends in Plant Science, 17:47-55.

Nandita, K., Manoj, K., Rajiv, R. and Sareeta, N. (2022). Effects of foliar application of micronutrients on growth, yield and quality of sweet orange (*Citrus sinensis* L. osbeck)". Bangladesh Journal of Botany, 51:57-63.

Niyigaba, E., Twizerimana, A., Mugenzi, I., Ngnadong, W. A., Ye, Y.P., Wu, B. M. and Hai, J. B. (2019). Winter wheat grain quality, zinc and iron concentration affected by a combined foliar spray of zinc and iron fertilizers. Agronomy, 9:250.

Nuss, T. E. and Tanumihardjo, A. S. (2010). A Paramount Staple Crop in the Context of Global Nutrition. Comprehensive Reviews in Food Science and Food Safety, 9:417-436.

Pahlavan-Rad, M. R. and Pessarakli, M. (2009). Response of wheat plants to zinc, iron, and manganese applications and uptake and concentration of zinc, iron, and manganese in wheat grains. Communication of Soil Science and Plant Analysis*,* 40:1322-1332.

Pal, V., Singh, G. and Dhaliwal, S. S. (2019). Agronomic biofortification of chickpea with zinc and iron through application of zinc and urea. Communication of Soil Science and Plant Analysis*,* 50:1864-1877.

Patil, S., Girijesh, G. K., Nandini, K. M., Kiran Kumar, L. S., Pradeep and Ranjith Kumar, T. M. (2017). Effect of zinc application through soil and foliar means on bio-fortification of zinc in rainfed maize (*Zea mays* L.). International Journal of Pure and Applied Bio Science, 5:246-253.

Phattarakul, N., Rerkasem, B., Li, L. J., Wu, L. H., Zou, C. Q., Ram, H., Sohu, V. S., Kang, B. S., Surek, H. and Kalayci, M. (2012). Biofortification of rice grain with zinc through zinc fertilization in different countries. Plant Soil, 361:131-141.

Potarzycki, J. and Grzebisz, W. Ranjan (2009). Effect of zinc foliar application on grain yield of maize and its yielding components. Plant Soil and Environment*,* 55:519-527.

Prasanna, B. M., Vasal, S. K., Kassahun, B. and Singh, N. N. (2001). Quality protein maize. Current Science, 81:1308-1319.

Prom-u-thai, C., Rashid, A. and Ram, H. (2020). Simultaneous biofortification of rice with zinc, iodine, iron and selenium through foliar treatment of a micronutrient cocktail in five countries. Frontiers in Plant Science, 11:589835.

Qian, C., Yu, Y., Gong, X., Jiang, Y., Zhao, Y., Yang, Z., Hao, Y., Li, L., Song, Z. and Zhang, W. (2016). Response of grain yield to plant density and nitrogen rate in spring maize hybrids released from 1970 to 2010 in Northeast China. Crop Journal, 4:459-467.

Rajesh, R. K, Neeraj, K., Rana, J. B. and Rai, K. N. (2018). Effect of integrated nutrient management on yield of maize crop under rainfed condition in eastern part of UttarPradesh, India. International Journal of Current Microbiology and Applied Sciences, 7:2134.

Ramadas, S., Vellaichamy, S., Ramasundaram, P., Kumar, A. and Singh, S. (2020). Biofortification for Enhancing Nutritional Outcomes and Policy Imperatives. Elsevier, 310-312.

Ranum, P., Rosas, J. P. P. and Casal, M. N. G. (2014). Global maize production, utilization, and consumption. Annals of the New York Academy of Sciences, 1312:105-112.

Read, S. A., Obeid, S., Ahlenstiel, C. and Ahlenstiel, G. (2019). The role of zinc in antiviral immunity. Advances in Nutrition, 10:696-710.

Saha, S., Chakraborty, M., Padhan, D., Saha, B., Murmu, S., Batabyal, K., Seth, A., Hazra, G. C., Mandal, B. and Bell, R. W. (2017). Agronomic biofortification of zinc in rice: Influence of cultivars and zinc application methods on grain yield and zinc bioavailability. Field Crops Research, 210:52-60.

Sayah, AI. F., McAlister, F. A., Ohinmaa, A., Majumdar, S. R. and Johnson, J. A. (2021). The predictive ability of EQ-5D-3L compared to the LACE index and its association with 30-day post-hospitalization outcomes. Quality of Life Research, 30:2583-2590.

Singh, A. K. H., Jat, S. L., Rakodia, P. K. and Arvid Kumar. (2001). Response of maize (*Zea mays*) hybrids to nutrient management practices for enhancing productivity and profitability under sub-humid condition of Southern Rajasthan. Indian Journal of Agronomy, 62:326-331.

Singh, J. P., Dahiya, D. J. and Vinod, K. (1995). Effect of nitrogen and iron supply on growth and nutrient uptake of maize on sandy soil. Crop Research, 10:271-276.

Singaraval, R., Parasath, V. and Elayaraja, D. (1996). Effect of organics and micronutrients on the growth, yield of groundnut in coastal soil. International Journal of Agricultural Science, 2:401-402.

Sperotto, R. A., Ricachenevsky, F. K., Waldow, V. A. and Fett, J. P. (2012). Iron biofortification in rice: It's a long way to the top. Plant Science, 190:24-39.

Vijay, K. Singh, S. K., Bhati, P. K., Amita, S., Sharma, S. K. and Vinay, M. (2015). Correlation, path and genetic diversity analysis in maize (*Zea mays* L.). Environment and Ecology, 33:971-975.

Welch, R. M., Smith, M. E., Van-Campen, D. R. and Schaeffer, S. C. (1993). Improving the mineral reserves and protein quality of maize (*Zea mays* L.) kernels using unique genes. Plant and Soil, 155-156:215-218.

White, P. J. and Broadley, M. R. (2011). Physiological limits to zinc biofortification of edible crops. Frontiers in Plant Science, 2:80.

Zaremanesh, H., Nasiri, B. and Amiri, A. (2017). The effect of vermicompost biological fertilizer on corn yield. Journal of Material and Environment Science, 8:154-159.

Zeidan, M. S., Manal, F. Mohamed. and Hamouda, H. A. (2010). Effect of Foliar Fertilization of Fe, Mn and Zn on Wheat Yield and Quality in Low Sandy Soils Fertility. World Journal of Agricultural Sciences, 6:696-699.

Zhu, C., Naqvi, S., Gomez-Galera, S., Pelacho, A. M., Capell, T. and Christou, P. (2007). Transgenic strategies for the nutritional enhancement of plants. Trends in Plant Science, 12:548-555.

(Received: 25 September 2024, Revised: 25 May 2025, Accepted: 1 July 2025)