Research Article

Synergistic Application of Zinc–Iron through Seed and Foliar Treatments for Maize Yield and Nutrition in the Western Ghats

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ABSTRACT

Agronomic biofortification through fertilizer application is an effective approach to address global malnutrition caused by deficiencies of zinc and iron. A field study was carried out on sandy clay loam soil during the rabi seasons of 2024 and 2025 at Coimbatore, Tamil Nadu, to evaluate the influence of zinc and ferrous fertilization under integrated nutrient management on maize productivity and grain quality under Western Ghats conditions. Maize was sown at a spacing of 60 × 25 cm following a split plot design, wherein the main plots consisted of two fertilizer recommended doses of fertilizers, 100% and 125%, and the sub-plots comprised nine nutrient level treatments, each replicated three times. The integrated treatment S_9-S_3 + Foliar application – $ZnSO_4$ @ 0.5% at 45th and 60th DAS recorded the highest plant height (207.50 cm), leaf area index (5.28), dry matter production (2002.96 kg ha^{-1}), cob length (23.55 cm), grain yield (9048.66 kg ha^{-1}), and stover yield (13,359.25 kg ha^{-1}), whereas the control (S_1) registered the lowest values. Compared to S_1, quality parameters were improved drastically at S_9 with crude protein (14.88%), starch (66.417mg g^{-1}), iron (36.32 mg kg^{-1}), zinc (32.15 mg kg^{-1}), higher than all previous treatments. The results of the study suggest that the application of zinc fertiliser has a significant positive effect on both vegetative growth and productivity of maize while providing improved nutritional properties of the grain; therefore, zinc fertilisation has an important role in enhancing both the performance and the quality of maize crops.

Key words: Biofortification, ferrous fertilisation, foliar application, maize, zinc fertilisation, integrated nutrient

INTRODUCTION

Hidden hunger the term is used to describe micronutrient deficiencies happens when people do not eat enough of the vitamins and minerals they need for their body to function properly or stay healthy, which causes poor growth and development, poor immune function, lower mental performance, and being more likely to get sick; this is something many people experience, especially women who are pregnant and children under 5 years of age. Maize is commonly known by two titles: “Queen of Cereals” and “King of Fodder Crops”; it has gained worldwide acclaim for being one of the most consistently productive and yield capable among all the cereals (Behera *et al*., 2019). The deficiencies constitute a major public health challenge worldwide, and have been a subject of research interest for many years. Current estimates indicate that greater than one-fourth of the global population will suffer from at least one essential micronutrient deficiency. Compared to the major cereals consumed around the world rice and wheat, maize stands out because it contains considerably more energy, as well as a unique set of nutritional properties that provide exceptional nutraceutical benefits.

Maize provides a good source of carbohydrate, essential nutrients including vitamins, minerals and bioactive compounds that are important staples in the human diet, ensuring dietary energy and health. In terms of worldwide cereal crop production, maize is ranked third, following wheat and rice. With approximately 2-3% of global maize production, India ranks among the top 10 maize producing nations (Wold Health Organization, 2023). Maize is also one of the world's largest exporters, making up almost 14% of all the world's maize exports. Maize is a staple food for a large number of people in India, it is also a primary raw material for a number of industries and it is one of the most important livestock feeds in India and other countries around the world that are based on agriculture. Maize's processed forms include corn flakes, corn syrup, and corn oil among others. The animal feed value of maize is also growing because it has a high nutritional value: the grain, leaves, and stems of maize are all good sources of nutrition for livestock. Crops are grown year round in the kharif, rabi and summer seasons in India on approximately 9.4 million hectares at an average yield of approximately 2.55 tonnes per hectare. The grain has a high nutritional value carbohydrates, protein, fat, fibre, essential minerals and carotene with an estimated 45% of total production eaten directly (Erenstein *et al*., 2022).

Maize can adapt to many growing conditions, which makes it possible to produce it several times a year. Additionally, due to

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the strong growth of processing industries and a high demand for nutrients, maize has become a cash crop, with a large portion of the maize harvested destined for poultry production over 50%, and approximately 23% for human consumption (Messias *et al*., 2013). However, maize is also used extensively in the industrial and pharmaceutical sectors for creating starches, ethanol, and biodegradable plastic products, as well as providing certain compounds that are manufactured into antibiotics. Of all of the industrial applications for maize, starch has been the most widely used and would have been produced in the past as a food commodity, but now has a significant industrial application, as was the case with dextrin, liquid glucose and starches (e.g., maltose and other modified starch products) (Ranum *et al*., 2014; Huma *et al*., 2019).

Mineral fertilization represents an effective tool for increasing levels of essential micronutrients in the edible portions of various food crops. This practice has been shown to effectively increase the level of iron in cereal grains such as wheat, rice, and maize. Increasing the level of iron biofortification through fertilisation in maize has been demonstrated to enhance the synthesis of chlorophyll, enhance the plant's ability to efficiently use photosynthesis to produce energy, and enhance the metabolic rate of plant material through the enhancement of enzyme production in plants. The increased level of iron in maize will significantly increase the nutritional quality of the maize grains that eventually end up in human diets (Mao *et al*., 2014).

Agronomic biofortification through fertilizer use has become an effective way to improve the level of particular micronutrients in cereal crops. Much evidence exists to support this, with wheat, rice and maize studies showing major increases in grain Zn and Fe levels from these practices (Cakmak *et al*., 2017). It has also been found that foliar applications of Zn and Fe increase the accumulation of these micronutrients in grains to a much greater extent than soil applications alone. Additionally, when foliar application of zinc is used together with N fertilization, zinc concentrations and its bioavailability in grain are further increased, therefore, this could be an effective means of Zinc enrichment of maize as well. Other more recent work has confirmed that using a combined foliar micronutrient solution containing both Zn and Fe increases the levels of these micronutrients in wheat and rice grains grown in different geographic locations (Naeem *et al*., 2022).

Zinc is an essential micronutrient needed by plants for many different purposes, but it is especially important for the proper functioning of many of the enzymes that are key to the formation of photosynthetic energy. Foliar application of zinc has been shown to positively affect the amount of zinc that is present in the grain of a number of cereal crops. However, the actual effectiveness of foliar application will vary with the type of chemical fertilizer being used, the source of zinc that is being used, the solubility of the material, and the particle size or shape of the material (Palacio Marquez *et al*., 2021). On a physiological level, zinc serves as both a cofactor to catalyze reactions of many enzymes and a structural component of several of the enzymes that regulate major metabolic pathways. Sufficient levels of zinc in the diet allow for optimal vegetative growth of the plant, differentiation of cells within the plant, and maximum productivity of the crop. In addition, the application of zinc has been found to improve the mechanisms that protect the plant, inhibit the uptake from the soil and transport to the plant of toxic elements, and increase the tolerance of the plant to abiotic stresses as drought and major changes in temperature (Rehman *et al*., 2018).

The objective of biofortification is to implement agricultural practice which improves the nutritional content of edible parts of crops, primarily by enhancing their limitations in mineral content, especially iron and zinc. In maize, the principle of biofortification was shown through foliar fertilization that added microminerals to the leaves of corn plants, resulting in improved fortification of the seeds with micronutrients at harvest time. While biofortification can be applied to most crops, research has demonstrated that carefully timed applications of mineral fertilisers at various stages of crop growth are the primary means of improving the translocation and deposition of nutrients from the soil to the plants within and between the plants. Therefore, biofortification will have a significant impact on the quality of the food and feed produced by crops that are biofortified, positively influencing both human and animal well-being (Graham *et al*., 2018). By enhancing essential mineral elements, such as iron and zinc, in the edible portions of crops through the process of biofortification, micronutrient deficiencies can be addressed. Biofortification represents a sustainable, economically viable and highly practical solution to eliminate micronutrient malnutrition (Bevis, 2015).

Zinc and iron deficiencies have been found to be a serious public health concern and are often cited as limitations to soil fertility. During the investigation into the spatial relationship of soils deficient in these micronutrients to populations deficient in zinc and iron, it is clear that there is a strong correlation between the two and that increasing the micronutrient density of staple food crops is necessary. There is an urgent need for effective and complementary agronomic strategies to improve the micronutrient content of food crops in a short period of time due to the widespread occurrence of zinc and iron deficiencies.

This research study was undertaken to assess the contribution of zinc and ferrous fertilization to the improvement of maize seed quality by evaluating the effects of various nitrogen levels in conjunction with treatments of the two micronutrients. The objective was to determine the effects of varying doses of nitrogen, in combination with a foliar application of zinc, on the growth, yield components, and grain quality of maize in order to identify effective nutrient management practices to improve both production and nutritional quality.

MATERIALS AND METHODS

A field experiment was conducted during the rabi seasons of 2024 and 2025 at the South Farm, KITS Campus, Karunya Institute of Technology and Sciences, Coimbatore Tamil Nadu, India 10°59′ N latitude and 76°64′ E longitude; 474 m above mean sea level in Figure 1. The experimental site is situated in the western agro-climatic zone of Tamil Nadu and is characterized by a semi-arid tropical climate with high temperatures during summer and relatively mild winters.

Fig. 1. Field location of research work.

During the cropping periods, the total rainfall received was 875.50 mm in 2024 and 925 mm in 2025. The seasonal maximum and minimum temperatures were 35.2°C and 22.8°C, respectively in Figure 2. Soil samples were classified to be sandy clay loam, the soil was alkaline (pH = 8.3) and had EC = 0.33 dS m -1 confirming non-salinity. The initial soils had low N (212.45 kg N ha -1), moderate level P (11.50 kg P ha -1) and moderate K (144.25 kg K ha -1) levels. For the micronutrient status of the soils, the Fe (5.15 mg kg -1), Cu (1.14 mg kg -1) and Mn (16.00 mg kg -1) levels were adequate, however, the soil's available Zn (0.42 mg kg -1) is below the optimum level and confirms that there is a Zn deficiency.

The experiment was carried out using a split-plot design, consisting of eighteen treatments. The main plots included M_1– 100% Recommended dose of fertilizer (NPK: 250:75:75), M_2-125% RDF, while the sub plots comprised nine micronutrient levels with three replications each of S_1- Control (No seed priming), S_2- Seed priming - $FeSO_4$ @ 0.5%, S_3- Seed priming - $ZnSO_4$ @ 0.5%, S_4- S_1 + Foliar application – $FeSO_4$ @ 0.2% at 45th and 60th DAS, S_5- S_2 + Foliar application – $FeSO_4$ @ 0.2% at 45th and 60th DAS, S_6- S_3 + Foliar application – $FeSO_4$ @ 0.2% at 45th and 60th DAS, S_7- S_1 + Foliar application – $ZnSO_4$ @ 0.5% at 45th and 60th DAS, S_8- S2 + Foliar application – $ZnSO_4$ @ 0.5% at 45th and 60th DAS, S_9- S_3 + Foliar application – $ZnSO_4$ @ 0.5% at 45th and 60th DAS.

The Mahyco (MRM 4065) maize hybrid was used in the study, with a growing season of around 100-110 days. The maize crops were planted at an optimal spacing of 60 cm × 25 cm to maximize the number of seeds planted and produce even growth of plants. In order to adhere to treatment for the experiment, fertilisation was performed using 250:75:75 kg ha^{-1} of N:P:K.

At 40 days and 60 days after sowing, foliar application of 0.5% $ZnSO_4$ and 0.5% $FeSO_4$ were used to boost plant nutrition at critical growth stages. Knapsack sprayers were used to apply these nutrient solutions evenly to the crop canopies. Application of agronomic procedures other than those described recommendations, thereby ensuring that crop growth and development occurred normally throughout the trial period.

The observations recorded for different parameters during the experimental period were subjected to statistical analysis using the analysis of variance (ANOVA) appropriate for a split-plot design, as outlined by Gomez and Gomez (1984). Whenever the calculated F-test indicated significant treatment effects, the critical difference was computed at the 5 % level of significance to compare treatment means. In cases where the differences were not statistically significant, the results were denoted as "NS".

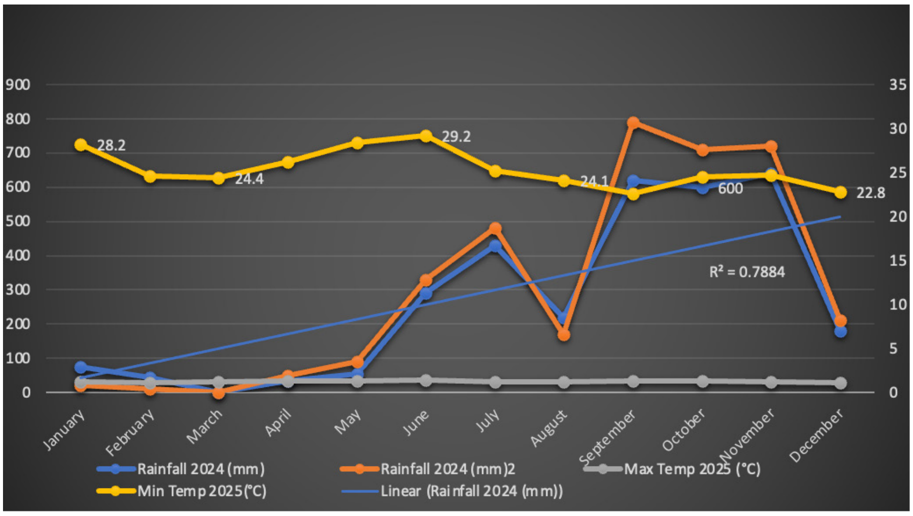

Fig. 2. Weather prevailed during the field experiment.

RESULTS AND DISCUSSION

Growth parameters

A critical evaluation of the data presented in Table 1 indicates that growth attributes, particularly plant height and leaf length of spring sown fodder maize at various developmental stages, were significantly affected by different levels of zinc and iron application. It showed that the maximum plant height (207.50cm) at harvest was observed under treatment S_9-S_3 + Foliar application – $ZnSO_4$ @ 0.5% at 45th and 60th DAS (Figure 3). When compared to the other nutrient levels. The lowest plant height was recorded under the treatment S_1 Control (183.73 cm). The combined use of foliar nutrient sprays along with integrated nutrient management practices resulted in significant improvement in growth parameters across both seasons of cultivation. This positive response may be attributed to enhanced nutrient availability and better uptake by the plants, which improved crop growth under integrated nutrient approaches and correct soil nutrient deficiencies. Similar observations were also reported by Auwal and Amit (2017).

Leaf area index serves as a vital indicator of the photosynthetically active surface of a plant and plays a significant role in determining overall crop growth and productivity. Similarly, the leaf area ratio reflects the proportion of assimilatory surface area relative to the total dry matter produced by the plant. A detailed examination of the data presented in Table 1 on LAI of S_9 revealed among various nutrient levels application of S_3 + Foliar application – $ZnSO_4$ @ 0.5% as (5.28) recorded significantly higher leaf area index at 45th and 60th DAS. The lowest value of leaf area index (Figure 4) was obtained with S_1 constitutes of no seed priming of (3.59). The beneficial response observed with zinc and iron application may be attributed to enhanced vegetative growth and improved overall plant development, which subsequently led to greater accumulation of dry matter in maize. The higher dry matter production is observed in S_9 (2002.95 kg ha^{-1}) followed by S_8-S_2 + Foliar application – $ZnSO_4$ @ 0.5% at 45^{th} and 60^{th} DAS with (1799.29 kg ha^{-1}) in (Figure 5) . Elnaz *et al*. (2016) reported that foliar application of zinc in maize improved nitrogen uptake, which has a significant increase in leaf area index and dry matter production. The enhanced availability and absorption of zinc through integrated nutrient management practices facilitated better metabolic activity and improved photosynthetic efficiency in plants. This improvement in physiological processes promoted greater biomass accumulation and overall crop productivity.

In addition, proper dietary zinc intake is vital for enzyme activity and protein production, which, in turn, facilitates steady vegetative growth and increases grain yield potential. The results showed that the growth of the crop had an impact on the length of the cobs from the different treatments at the different times of growth (Table 1). The growth treatment S_9-S_3 + Foliar application – $ZnSO_4$ at 0.5% at 45 and 60 days after sowing had the longest length of cobs (23.55 cm) while the shortest cob was found in S_1, the control from seed priming (8.99 cm) as seen in Figure 6. Thus, the application of zinc fertilizer enhances cob development, which may result in greater overall maize productivity. The increase in the growth of the cob can be attributed to zinc role in enzymatic activity, hormone regulation, and the translocation of nutrients during the reproductive growth stage of maize. Augustine and Imayavaramban (2022) also found a positive effect of zinc application on yield-related characteristics of maize.

Table 1. Effect of Ferrous and zinc fertilization on growth attributes of maize (Pooled data of *rabi* seasons, 2024 and 2025)

Treatments	PH (cm)	LAI	DMP (kg ha^{-1})	Cob length (cm)
M_1-100% Recommended dose of fertilizer (RDF) (NPK: 250:75:75)	192.58	4.28	1245.68	14.82
M_2-125% RDF	196.42	4.58	1328.62	17.08
SE(d)	0.461	0.003	8.383	0.042
CD at 5%	2.135	0.014	38.832	0.194
S_1- Control (No seed priming)	183.73	3.59	747.86	8.99
S_2- Seed priming - $FeSO_4$ @ 0.5%	186.19	3.80	813.44	10.44
S_3- Seed priming - $ZnSO_4$ @ 0.5%	188.12	3.99	900.20	12.54
S4-S_1 + Foliar application – $FeSO_4$ @ 0.2% at 45^{th} and 60^{th} DAS	190.28	4.22	1102.46	14.43
S5 S2 + Foliar application – Fe_{sO4} @ 0.2% at 45^{th} and 60^{th} DAS	196.69	4.59	1364.32	18.08
S6-S3 + Foliar applicatio$_n$ – FesO4 @ $0.^{2\%}$ at 45th and 60^{th} DAS	199.60	4.90	1613.07	18.99
S7-S1 + Foliar applicatio$_n$ – ZnSO4 @ $0.^{5\%}$ at 45th and 60th DAS	193.88	4.39	1240.81	15.48
S8 S2 + Foliar application – Zn_SO4 @ 0.5% at ^{45}th and ^{60}th DAS	204.49	5.10	1799.29	21.07
S9 S3 + Foliar application – Zn_SO4 @ 0.5% at ^{45}th and ^{60}th DAS	207.50	5.28	2002.95	23.55
SE(d)	0.322	0.015	13.481	0.133
CD at 5%	0.660	0.030	27.584	0.272
M at S SE(d)	0.630	0.020	0.272	19.833
M at S CD at 5%	2.161	0.041	0.182	49.745
S at M SE(d)	0.456	0.021	0.398	19.064
S at M CD at 5%	1.564	0.043	0.188	47.818

PH – Plant height; LAI – Leaf area index; DMP – Dry matter Production; RDF – Recommended dose of fertilizer; Fe – iron; $FeSO_4$ – Ferrous sulphate; $ZnSO_4$ – Zinc sulphate; S: significant at P≤ 0.05; NS: Non-significant at P> 0.05; Means sharing the same case letter do not differ significantly at p ≤ 0.05

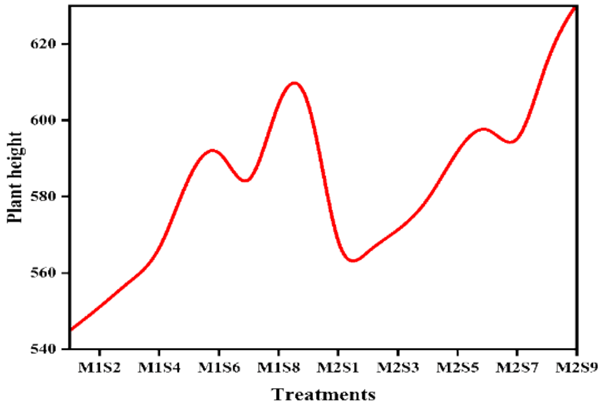

Fig. 3. Plant height of maize at different growth stages

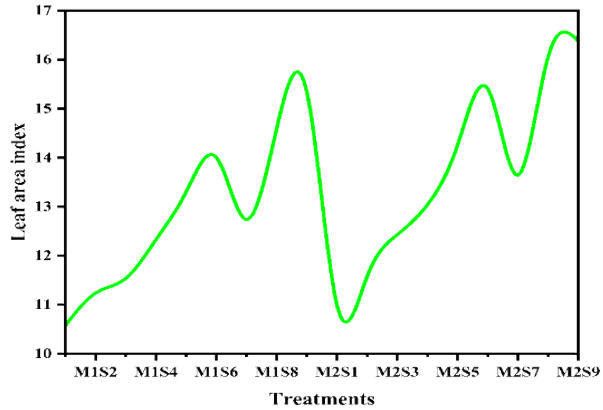

Fig. 4. LAI of maize at different growth stages

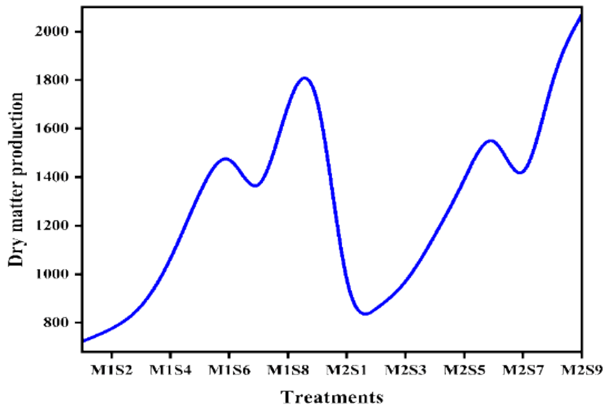

Fig. 5. DMP of maize at different growth stages

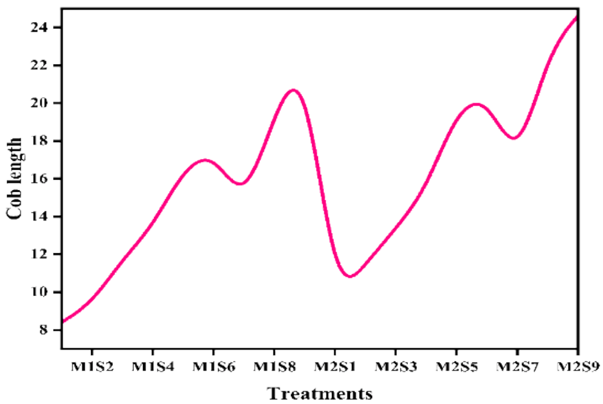

Fig. 6. Cob length of maize at different growth stages

Yield attributes and yield

The yield attributes are summarized in the Table 2 for the two cropping seasons provide significant differences for stover and grain yields due to the amount of nutrients applied as seen in Figure 7. The higher cob weight (108.868 g), test weight (277.683 g), and shelling percentages (76.92%) occurred on S_9-S_3, as well as in addition to zinc sulfate at a rate of 0.5% on the 45th and 60th days after sowing. The lower support to the cobs occurred with the control treatment (S_1). The uptake of zinc and iron is essential for photosynthesis, net assimilation, and the ability to efficiently distribute the assimilates from leaves to developing sinks; therefore both of these nutrients contributed to longer lengths of cob and higher test weight. The combined application of basal application of micronutrients with foliar applications of micronutrients will provide sufficient nutrition during critical stages of the growth process to improve kernel development and increase cob weight. Similar observations by Jayant *et al*. (2018) and Uma *et al*. (2019) indicate that the integrated use of basal and foliar nutrients significantly improves cob weight, test weight, and shelling percentage in maize.

The application of zinc and iron significantly improved overall crop performance, as evidenced by increases in plant height, leaf area, dry matter production, and yield components. These enhancements were clearly superior to those observed in treatments without micronutrient application, indicating the beneficial role of Zn and Fe in promoting plant growth and productivity in S_9-S_3 + Foliar application – $ZnSO_4$ @ 0.5% at 45th and 60th DAS increased the grain yield by (9048.65 kg ha^{-1}) followed by and S_8-S_2 + Foliar application – $ZnSO_4$ @ 0.5% at 45th and 60th DAS (8798.15 kg ha^{-1}) as presented in table 2. Similarly the stover yield was increased with the increased level of application of Zn and Fe. Application enriched with S_9-S_3 + Foliar application – $ZnSO_4$ @ 0.5% at 45th and 60th DAS has the higher stover yield with (13359.24 kg ha^{-1}). In Figure 8 the enhancement in grain yield for iron zinc application may be attributed to increased chlorophyll synthesis and elevated antioxidant enzyme activity during the crop growth period. The integrated supply of zinc along with nitrogen, phosphorus, and potassium promoted vigorous root development, which in turn supported improved nutrient uptake, enhanced photosynthetic efficiency, and superior yield components, ultimately resulting in higher grain production (Chen *et al*., 2023). The increase in both grain and straw yield can also be associated with efficient translocation of photosynthates and the development of a greater sink capacity within the plant. Similar yield improvements from the independent application of zinc in maize have previously been documented by Kathula *et al*. (2023).

Table 2. Effect of Ferrous and zinc fertilization on yield and yield attributes of maize (Pooled data of *rabi* seasons, 2024 and 2025)

Treatments	Cob weight (g)	Test weight (g)	Shelling (%)	Grain yield (kg ha^{-1})	Stover yield (kg ha^{-1})
M_1-100% Recommended dose of fertilizer (RDF) (NPK: 250:75:75)	95.232	270.760	71.50	7863.260	11812.13
M_2-125% RDF	98.63	274.47	72.89	8301.407	12961.27
SE(d)	0.10	0.370	0.04	8.47	69.968
CD at 5%	0.50	1.716	0.19	39.23	324.119
S_1- Control (No seed priming)	83.07	268.38	67.98	7189.09	11441.41
S_2- Seed priming - $FeSO_4$ @ 0.5%	87.40	269.36	69.02	7364.92	11683.92
S_3- Seed priming - $ZnSO_4$ @ 0.5%	90.99	270.37	69.86	7561.30	11940.24
S_4-S_1 + Foliar application – $FeSO_4$ @ 0.2% at 45^{th} and 60^{th} DAS	94.44	271.41	71.16	7753.42	12142.25
S_5-S_2 + Foliar application – $FeSO_4$ @ 0.2% at 45^{th} and 60^{th} DAS	100.55	273.42	72.85	8352.46	12498.19
S_6-S_3 + Foliar application – $FeSO_4$ @ 0.2% at 45^{th} and 60^{th} DAS	103.44	274.58	74.09	8598.73	12733.22
S_7-S_1 + Foliar application – $ZnSO_4$ @ 0.5% at 45^{th} and 60^{th} DAS	97.13	272.30	71.90	8074.26	12651.77
S_8-S_2 + Foliar application – $ZnSO_4$ @ 0.5% at 45^{th} and 60^{th} DAS	106.47	276.02	76.24	8798.15	13030.31
S_9-S_3 + Foliar application – $ZnSO_4$ @ 0.5% at 45^{th} and 60^{th} DAS	108.86	277.68	76.92	9048.65	13359.24
SE(d)	0.141	0.12	0.14	12.495	9.402
CD at 5%	0.289	0.26	0.28	25.568	19.238
M at S SE(d)	0.217	0.40	0.19	18.690	71.082
M at S CD at 5%	0.583	1.70	0.41	48.169	323.563
S at M SE(d)	0.199	0.18	0.19	17.671	13.296
S at M CD at 5%	0.536	0.76	0.43	45.544	60.522

RDF - Recommended dose of fertilizer; FYM - Farm yard manure; $FeSO_4$ – Ferrous sulphate; $ZnSO_4$ – Zinc sulphate; Significant at P 0.05; NS- Non-significant at P>0.05

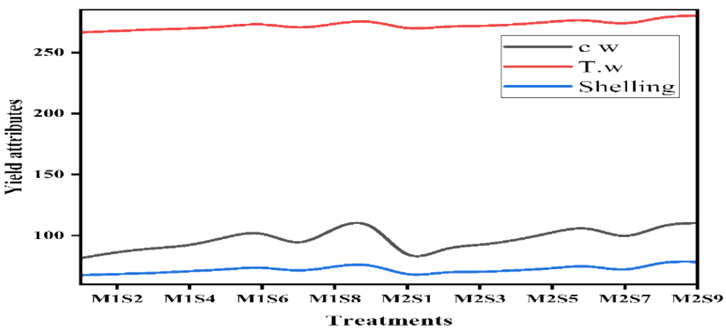

Fig. 7. Micronutrient application on cob weight, test weight, and shelling percentage.

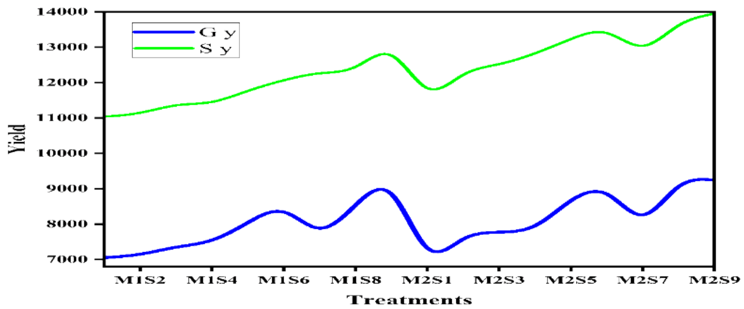

Fig. 8. Grain yield and Stover yield of maize to zinc and iron fertilization under INM practices

Quality parameters

Protein

The results evaluated for the quality parameters was illustrated in Table 3. Overall, the highest percentage of crude protein occurred with treatment S_9 (14.88% crude protein) S_9-S_3 + zinc foliar application ($ZnSO_4$ @ 0.5%) produced significantly greater amounts of crude protein at both periods measured than any of the other treatments, followed by treatment S_8-S_2 + zinc foliar application ($ZnSO_4$ @ 0.5%) in Figure 9. Zinc is an important enzyme cofactor and has direct influence upon protein metabolism and production of amino acids and other key metabolites. The higher amount of protein produced in response to the combined nutrient treatments utilized may be due to increased efficiency of physiological processes leading to enhanced biochemical processes. These physiological processes include photosynthesis, respiratory rate, and chlorophyll production (Krishnasree *et al*., 2022). Additionally, sufficient levels of zinc in the crop will promote the uptake, assimilation and conversion of nitrogen into amino acids and/or proteins. Through the combined application of zinc fertilizer, maize can achieve greater metabolic efficiency and produce maize biomass that has improved nutritional characteristics.

Starch

Starch content showed significant differences among the various nutrient treatments, ranging from 52.83 to 66.41 mg g^{-1}. The higher starch concentration (66.41 mg g^{-1}) was recorded in treatment S_9–S_3 with foliar application of $ZnSO_4$ at 0.5% applied at 45 and 60 DAS, which was statistically on par with treatment S_8 (64.54 mg g^{-1}). The increased starch accumulation under these treatments may be attributed to enhanced photosynthetic activity and efficient carbohydrate synthesis resulting from improved zinc nutrition. Increasing levels of zinc sulphate ($ZnSO_4$) application led to a progressive rise in starch concentration in maize grain. The factors responsible for improved grain yield, such as enhanced photosynthetic efficiency and assimilate translocation, also contributed to greater starch accumulation. Adequate zinc nutrition promotes carbohydrate metabolism and enzyme activity involved in starch biosynthesis, thereby improving grain quality. Stephen Mason *et al*. (2010) also reported that zinc fertilization significantly increased starch accumulation in maize grains, indicating a strong positive association between zinc application and grain starch content.

Iron

Iron content in maize hybrid grain was significantly varied by the use of agronomic biofortification through INM. It was shown that the Fe content ranged from 21.26 to 36.32 mg kg^{-1}. The highest Fe content in grain (36.32 mg kg^{-1}) was found in the S_9–S_3 with foliar application of $ZnSO_4$ at 0.5% applied at 45 and 60 DAS. The lowest result (21.26 mg kg^{-1}) was recorded in S_1 treatment which was statistically significant as shown in Figure 9. The raised levels of iron were primarily the result of increasing the amount of nitrogen applied, which in turn increased the availability of iron and its uptake would also be influenced and the amount of nitrogen supplied, the extent of root development, and the efficiency of iron translocation from the root system to the developing grains. The greater effectiveness with regard to the application of foliar iron and zinc to increasing the micronutrient content of the grains compared to soil, as the absorption rate was higher and there were less losses due to soil fixation (Saleem *et al*., 2016).

Zinc

In this study, minerals in maize grain were tested and S_9 has the higher amount of zinc compared to other treatments (32.15 mg·kg^{-1}) as well as all other treatments (Figure 9). The most similar treatment to S_9 consisted of S_8 - S_2 + Foliar application – $ZnSO_4$ @ 0.5% (30.18 mg·kg^{-1}) at 45 and 60 DAS. The greater zinc concentration from different treatments occurred due to the use of organic and inorganic fertilizers. Thus, more soil zinc can be made available for uptake by plants. Further improvements in soil quality and mobility of nutrients may have contributed to the greater zinc accumulation. These results support the results of Manzeke *et al*. (2014), demonstrating the positive effect of integrated nutrient management on zinc accumulation in maize grains.

Table 3. Effect of fertilization on quality parameters of maize (Pooled data of *rabi* seasons, 2024 and 2025)

Treatments		Protein (%)	Starch (mg g^{-1})	Iron (mg kg^{-1})	Zinc (mg kg^{-1})
M_1-100% Recommended dose of fertilizer (RDF) (NPK: 250:75:75)		9.61	57.67	26.61	22.56
M_2-125% RDF		11.39	61.22	30.13	25.62
SE(d)		0.31	0.04	0.08	0.01
CD at 5%		1.44	0.21	0.39	0.08
S_1- Control (No seed priming)		6.50	52.83	21.26	16.19
S_2- Seed priming - $FeSO_4$ @ 0.5%		7.20	54.58	22.36	18.11
S_3- Seed priming - $ZnSO_4$ @ 0.5%		8.26	55.98	24.54	20.07
S_4-S_1 + Foliar application – $FeSO_4$ @ 0.2% at 45th and 60th DAS		9.32	57.50	26.39	22.08
S_5-S_2 + Foliar application – $FeSO_4$ @ 0.2% at 45th and 60th DAS		11.26	60.81	30.06	25.89
S_6-S_3 + Foliar application – $FeSO_4$ @ 0.2% at 45th and 60th DAS		12.15	62.54	31.98	28.17
S_7-S_1 + Foliar application – $ZnSO_4$ @ 0.5% at 45th and 60th DAS		11.07	59.36	28.59	23.94
S_8-S_2 + Foliar application – $ZnSO_4$ @ 0.5% at 45th and 60th DAS		13.87	64.54	34.09	30.18
S_9-S_3 + Foliar application – $ZnSO_4$ @ 0.5% at 45th and 60th DAS		14.88	66.41	36.32	32.15
SE(d)		0.23	0.15	0.17	0.12
CD at 5%		0.47	0.30	0.35	0.25
M at S	SE(d)	0.43	0.20	0.24	0.17
	CD at 5%	1.47	0.44	0.58	0.35
S at M	SE(d)	0.32	0.21	0.24	0.17
	CD at 5%	1.09	0.46	0.57	0.37

RDF - Recommended dose of fertilizer; FYM - Farm yard manure; $FeSO_4$ – Ferrous sulphate; $ZnSO_4$ – Zinc sulphate; Significant at P 0.05; NS- Non-Significant at P>0.05.

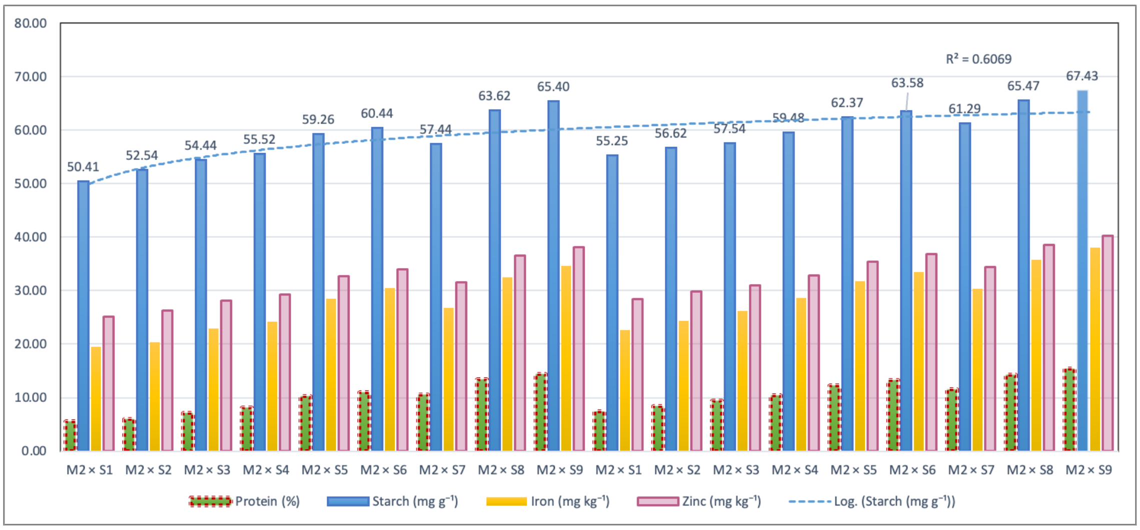

Fig. 9. Interaction effect of INM and Zinc levels on quality parameter

Interaction effects of nutrient levels

The interaction between fertilizer levels and seed priming and foliar treatments significantly influenced the all quality parameters of maize grain. The combined application of 125% RDF with zinc seed priming and foliar spray (M2 × S9) recorded the higher protein, starch, iron, and zinc contents, indicating a strong synergistic effect. In contrast, the control combination (M1 × S1) showed the lower nutritional values. Increasing fertilizer dose from 100% to 125% RDF further enhanced micronutrient accumulation when integrated with zinc treatments. Foliar application of $ZnSO_4$ at 45 and 60 DAS played a crucial role in improving grain mineral concentration. Iron and zinc concentrations were considerably higher under integrated nutrient management practices than with single nutrient applications. Overall, the interaction results indicate that combining zinc fertilization with an elevated RDF level significantly enhances the nutritional quality of maize grain.

There was a significant interaction between maize grain quality, fertiliser levels, and seed priming for foliar treatments. The combination of M_2 (125% RDF) with S_9 (Zinc seed priming and foliar spray) gave the highest values of protein, starch, iron and zinc concentrations. Thus the results demonstrated an interaction which favoured both stakes. In contrast, the control combination (M_1 + S_1) exhibited the lowest nutrition of maize grain. Increasing 100% to 125% RDF provided greater availability of micronutrients when used in conjunction with zinc applied during both seed and foliar applications. The foliar $ZnSO_4$ applied at 45 DAS and 60 DAS provided a significant improvement to the zinc concentration of grain. Iron and zinc concentrations of maize grain produced under integrated nutrient management systems were significantly greater than those produced under conventional nutrient management systems. Overall, overall the interaction of the M × S significantly increased the nutritional quality of maize grain through the use of zinc fertilisation with an increased RDF level.

CONCLUSION

The investigation results demonstrate that applying zinc fertilizer has greatly benefited maize growth, yield, and the nutrient quality of its grains. In all measured parameters, S_3 + foliar spray of $ZnSO_4$ @ 0.5% at 45 and 60 DAS(S_9) outperformed with the highest plant height, increased cob length and superior grain and stover yield. The improved quality of maize grain expressed by improved protein and starch levels, and higher levels of zinc and iron concentration in the grain, illustrates the importance of zinc in enhancing the complete nutritional composition of the crop. Compared to the control treatment without seed priming (S_1), the growth and yield attributes observed were lower, indicating the importance of selecting appropriate sources of zinc for the successful biofortification of maize. Overall, the findings support the inclusion of ferrous and zinc fertilization strategies in maize production systems to improve crop performance as well as enhance the nutritional quality of the grain.

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ETHICAL STATEMENT

Not applicable.

CONFLICT OF INTEREST

The authors also declare that there is no conflict of interest associated with this study.

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