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OPTIMIZING IRON AND ZINC NUTRITION IN MAIZE THROUGH SEED PRIMING AND FOLIAR APPLICATION UNDER DIFFERENT FERTILIZER REGIMES

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ABSTRACT
A field experiment was conducted to evaluate the effect of fertilizer application, seed priming and foliar micronutrient supplementation on the growth, productivity and economic performance of maize (*Zea mays* L.). The study comprised two fertilizer levels, M1: 100% recommended dose of fertilizer (RDF; 250:75:75 kg $N:P_2O_5:K_2O$ ha^{-1}) and M2: 125% RDF, combined with nine seed priming and foliar nutrient management treatments. The treatments included unprimed control, seed priming with 0.5% $FeSO_4$ or $ZnSO_4$, and their integration with foliar application of 0.2% $FeSO_4$ or 0.5% $ZnSO_4$ at 45 and 60 days after sowing. The economic analysis considered cost of cultivation, gross return, net return and benefit cost (B:C) ratio. The results demonstrated clear differences among nutrient management treatments, with integrated seed priming and foliar micronutrient application generally improving economic returns over the untreated control. Under 100% RDF, COC ranged from ₹44,223 to ₹50,073 ha^{-1}, while GR increased from ₹111,716.7 to ₹138,116.7 ha^{-1} and NR from ₹66,994 to ₹88,044 ha^{-1}. Under 125% RDF, COC ranged from ₹45,736 to ₹51,586 ha^{-1}, whereas GR increased from ₹113,483.3 to ₹152,737.7 ha^{-1} and NR from ₹67,747 to ₹101,152 ha^{-1}. The highest economic performance was recorded with M2S9, involving 125% RDF combined with seed priming using 0.5% $ZnSO_4$ and foliar application of 0.5% $ZnSO_4$ at 45 and 60 days after sowing. This treatment recorded the highest gross return (₹152,737.7 ha^{-1}), net return (₹101,152 ha^{-1}) and B:C ratio (2.96), despite having a comparatively higher cost of cultivation (₹51,586 ha^{-1}). The lowest economic performance was observed under M1S1, where 100% RDF was combined with no seed priming, recording a gross return of ₹111,716.7 ha^{-1} and net return of ₹67,494 ha^{-1}. Overall, the findings indicate that balanced fertilizer management integrated with Zn-based seed priming and foliar nutrition can substantially improve the profitability of maize production. The superior economic returns under M2S9 suggest that integrating enhanced fertilizer supply with targeted micronutrient application provides a promising strategy for improving resource-use efficiency, crop productivity and farm profitability. The study highlights the importance of integrated nutrient management for achieving economically sustainable maize production while simultaneously supporting micronutrient enrichment of the crop.

KEYWORDS: Maize, Seed priming, Zinc sulphate, Iron sulphate, Foliar application, Biofortification

INTRODUCTION
Maize (*Zea mays* L.) is a high-yielding cereal crop with substantial nutrient requirements throughout its growth cycle. The productivity of maize depends on the adequate and balanced supply of macronutrients as well as micronutrients that regulate several physiological and metabolic functions. Among the micronutrients, iron and zinc are particularly important because they participate in enzyme activation, chlorophyll formation, photosynthetic activity, protein synthesis and various oxidation–reduction processes. Deficiencies of Fe and Zn can consequently impair plant development and reduce yield potential. Agronomic biofortification through appropriate fertilizer management offers an opportunity to improve crop productivity while simultaneously increasing the concentration of essential micronutrients in edible plant parts. Field investigations in maize have demonstrated that combined management of Fe and Zn through seed, soil and foliar pathways can improve growth, yield attributes and grain micronutrient concentration (Kumar and Salakinkop, 2017).
Foliar fertilization is particularly useful because it permits micronutrients to be supplied during active vegetative and reproductive development. The effectiveness of foliar Zn application in maize has been demonstrated under field conditions, where foliar Zn treatments substantially increased grain Zn concentration and improved its estimated bioavailability without necessarily producing adverse effects on agronomic characteristics (Xia et al., 2019). Other research has shown that soil and foliar Zn application can improve maize growth, yield and nutritional attributes, although the magnitude of the response depends on the application method and rate (Imran and Rehim, 2017). Therefore, combining seed priming with later foliar application may provide a sequential nutrient supply, with early nutrient availability supporting establishment and later application maintaining micronutrient availability during reproductive development. Such an approach is particularly relevant to the present experiment, where $FeSO_4$ and $ZnSO_4$ were supplied through seed priming and/or foliar sprays at 45 and 60 days after sowing.

In addition to micronutrient management, the quantity of primary nutrients supplied through the recommended fertilizer dose can strongly influence crop growth, nutrient accumulation and yield formation. Nitrogen, phosphorus and potassium contribute to canopy development, dry matter production, reproductive growth and grain formation, while adequate Fe and Zn availability supports the physiological processes associated with these responses. Thus, increasing fertilizer application from the recommended level to 125% RDF may interact with micronutrient management and alter growth indices such as crop growth rate (CGR), relative growth rate (RGR) and net assimilation rate (NAR). The interaction between fertilizer level and micronutrient application is therefore important when developing an integrated nutrient-management strategy. Previous field research involving Fe and Zn application in maize has shown improvements in growth, yield attributes, grain yield and stover yield when micronutrient management was integrated with the major nutrient supply (Kumar and Salakinkop, 2018).
An effective nutrient-management programme should ultimately be evaluated not only on biological performance but also on its economic feasibility. Additional fertilizer and application operations increase production costs; therefore, a treatment producing higher yield is not necessarily the most profitable unless the additional returns compensate for the increased expenditure. Economic indicators such as cost of cultivation, gross return, net return and benefit–cost ratio provide a practical basis for identifying nutrient combinations suitable for farm-level adoption. Earlier maize research has demonstrated that Zn fertilization can improve productivity and profitability, with soil application, seed priming and foliar strategies differing in their effectiveness (Ahmed et al., 2021). Therefore, evaluating Fe and Zn management under contrasting fertilizer regimes is essential for identifying a treatment that combines improved plant growth, yield attributes, grain and stover productivity, nutrient status and economic returns. The interaction between micronutrient application method and crop developmental stage is also important when evaluating Fe and Zn nutrition in maize. Micronutrient demand is not constant throughout the crop cycle, and nutrient uptake, translocation and partitioning can differ between vegetative and reproductive stages. Field experiments have shown that the response to foliar Fe and Zn application is strongly dependent on the presence of nutrient deficiency and the timing and rate of application. In particular, foliar Fe application produced a consistent grain-yield response under Fe-deficient conditions, whereas foliar Zn application produced comparatively variable responses across environments (Stewart et al., 2021). These findings emphasize that micronutrient fertilization should be integrated with the nutritional status of the crop rather than applied solely on the basis of increased fertilizer rates. For the present study, the use of Fe and Zn foliar sprays at 45 and 60 days after sowing provides an opportunity to supplement nutrient availability during important stages of canopy development and reproductive growth.
The present investigation was consequently undertaken to optimize Fe and Zn nutrition in maize through seed priming and foliar application under different fertilizer regimes. The study compared 100% and 125% recommended doses of N, P and K in combination with nine Fe- and Zn-based seed-priming and foliar-application treatments. The response of maize was assessed in terms of plant height, leaf area index, dry matter production and days to 50% tasseling, followed by cob characteristics, 100-grain weight, shelling percentage, grain yield and stover yield. In addition, CGR, RGR, NAR and plant N, P and K concentration were considered to understand the physiological and nutritional responses to the treatments Thus, the present study aims to evaluate the effectiveness of Fe and Zn biofortification strategies, assess the responses of biofortified and non-biofortified maize hybrids, and identify the most suitable fertilizer regime and nutrient-application combination for improving maize growth, productivity, nutritional quality, and economic returns.

MATERIALS AND METHODS

A field experiment was conducted during the kharif seasons of 2024 and 2025 at South Farm, KITS Campus, Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu, India (10°59′ N, 76°64′ E; 474 m above mean sea level). The experimental site belongs to the Western Agro Climatic Zone of Tamil Nadu and experiences a semi-arid tropical climate with warm summers and relatively mild winters. The experimental soil was sandy clay loam in texture, alkaline in reaction (pH 8.3), and non-saline, with an electrical conductivity of 0.33 dS m^{-1}. The initial soil analysis indicated low available nitrogen (212.45 kg ha^{-1}), moderate phosphorus (10.50 kg ha^{-1}) and potassium (143.24 kg ha^{-1}). The soil contained adequate Fe (5.12 mg kg^{-1}), Cu (1.11 mg kg^{-1}) and Mn (14.00 mg kg^{-1}), whereas available Zn (0.41 mg kg^{-1}) was below the critical level, indicating zinc deficiency. The experiment was laid out in a split-plot design with eighteen treatment combinations and three replications. The main-plot treatments consisted of M_1: 100% recommended dose of fertilizer (250:75:75 kg N:P:K ha^{-1}) and M_2: 125% recommended dose of fertilizer.
The sub-plot treatments included untreated control, $FeSO_4$ or $ZnSO_4$ seed priming at 0.5%, and their combinations with foliar $FeSO_4$ (0.2%) or $ZnSO_4$ (0.5%) applications. Seed priming was performed by soaking the seeds in the respective micronutrient solutions for 24 hours using a 1:5 seed-to-solution ratio, followed by shade drying to the original moisture content. Maize hybrid was used and sown at a spacing of 60 × 25 cm under the recommended crop establishment and management practices. Foliar applications of $FeSO_4$ (0.2%) and $ZnSO_4$ (0.5%) were carried out at 45 and 60 days after sowing using knapsack sprayers. The experimental data were subjected to analysis of variance appropriate for a split-plot design following Gomez and Gomez (1984), and treatment means were compared using the critical difference at the 5% significance level; non-significant differences were denoted as NS.

RESULTS AND DISCUSSION

Growth Parameters

Plant height differed markedly among the micronutrient management treatments. The main-plot treatments M_1 (100% RDF) and M_2 (125% RDF) recorded the same plant height of 215.30 cm. Among the subplot treatments, S_1 (no priming) recorded the minimum plant height (208.17 cm), whereas S_2 and S_3 recorded 212.00 and 213.83 cm, respectively, following $FeSO_4$ and $ZnSO_4$ seed priming. Combining seed priming with foliar micronutrient application resulted in a further improvement in plant height. The maximum plant height (224.00 cm) was obtained with S_9, indicating the favourable response of maize to Zn seed priming followed by foliar Zn application. The improvement in plant height under S_9 may be attributed to the continuous availability of Zn from seed establishment through the later vegetative stages. Zinc is involved in enzymatic activity, protein synthesis, membrane function and plant growth regulation. Raza et al. (2023) reported that Zn seed priming significantly improved plant growth and nutrient acquisition in maize, with $ZnSO_4$ priming producing superior growth compared with untreated plants.

The LAI values also showed a progressive improvement with micronutrient application. Both M_1 and M_2 recorded an LAI of 5.07. The minimum LAI (4.55) was observed under S_1, whereas S_2 and S_3 increased LAI to 4.85 and 5.00, respectively in fig 1. Raza et al. (2023) observed significant improvement in maize growth parameters following Zn seed priming and reported that Zn-containing treatments enhanced overall plant development and nutrient acquisition. In another study, Tondey et al. (2022) demonstrated that Zn-based seed invigoration improved vegetative growth and photosynthetic characteristics of maize, further supporting the positive response observed in the present investigation.

Dry matter production showed a response pattern comparable to plant height and LAI. The main-plot treatments M_1 and M_2 recorded 14261.9 kg ha^{-1}. Among the subplot treatments, S_1 recorded the lowest DMP (13582.0 kg ha^{-1}). Seed priming with $FeSO_4$ and $ZnSO_4$ increased DMP to 14041.7 and 14250.0 kg ha^{-1} in S_2 and S_3, respectively. The higher biomass accumulation under S_9 could be associated with the greater plant height and LAI recorded under the same treatment. Improved Zn availability may have enhanced photosynthetic efficiency and carbohydrate accumulation, resulting in greater biomass production. The findings of Raza et al. (2023) support this response, as Zn seed priming significantly improved maize growth and nutrient acquisition compared with untreated seeds. Furthermore, Grujcic et al. (2021) demonstrated that improved micronutrient nutrition can influence physiological processes and nutrient accumulation, highlighting the importance of appropriate micronutrient management for maintaining crop growth. The number of days required to reach 50% tasseling was also influenced by micronutrient management. Both M_1 and M_2 recorded 51.93 days. The earliest tasseling was observed under S_1 (49.50 days), followed by S_2 (50.67 days) and S_3 (51.33 days). The maximum duration to 50% tasseling (56.50 days) was observed in S_9.

The comparatively longer period to tasseling under S_9 may be associated with prolonged vegetative development and greater accumulation of biomass before the crop entered the reproductive phase. This interpretation is supported by the simultaneously higher plant height, LAI and dry-matter production recorded under S_9 in fig 1. Ahmad et al. (2023) reported that Zn-based seed treatments improved morphological and physiological performance of maize, particularly under conditions where nutrient availability limited plant growth.

(PH = plant height; LAI = leaf area index; DMP = dry matter production; Days to 50% tasseling; RDF = recommended dose of fertilizer; Fe = iron; ZnO = zinc oxide. S represents significance at $P \leq 0.05$, Means with the same lowercase superscript letter are considered statistically at par at the 5% level.)

Table 1. Assessment of Maize Growth Attributes under Different Fe and Zn Nutrient Treatments (Pooled Kharif Data, 2024 and 2025)

Treatments		PH (cm)	LAI	DMP ($kg ha^{-1}$)	Days to 50% tasseling
M1-100% RDF (N:P: K – 250:75:75 kg ha^{-1})		215.30	5.07	14261.9	51.93
M2-125% RDF		215.30	5.07	14261.9	51.93
SE(d)		0.10	0.03	60.84	0.07
CD at 5%		0.10	0.11	261.79	0.32
S1- No priming (control)		208.17	4.55	13582.0	49.50
S2- Seed priming with 0.5% Fe SO_4		212.00	4.85	14041.7	50.67
S3- Seed priming with 0.5% Zn SO_4		213.83	5.00	14250.0	51.33
S4-S_1 + 0.2% Fe SO_4 foliar spray at 45 and 60 DAS		216.83	5.25	14504.8	52.67
S5-S_2 + 0.2% Fe SO_4 foliar spray at 45 and 60 DAS		219.83	5.43	14713.2	53.83
S6-S_3 + 0.2% Fe SO_4 foliar spray at 45 and 60 DAS		221.83	5.53	14854.8	54.83
S7-S_1 + 0.5% Zn SO_4 foliar spray at 45 and 60 DAS		218.33	5.27	14525.0	52.33
S8-S_2 + 0.5% Zn SO_4 foliar spray at 45 and 60 DAS		223.17	5.64	14934.8	55.83
S9-S_3 + 0.5% Zn SO_4 foliar spray at 45 and 60 DAS		224.00	5.72	15001.3	56.50
SE(d)		0.21	0.11	58.76	0.15
CD at 5%		0.42	0.06	119.68	0.30
S at M	SE(d)	0.29	0.04	83.09	0.21
	CD at 5%	0.59	0.08	169.25	0.42
M at S	SE(d)	0.29	0.05	99.19	0.21
	CD at 5%	0.67	0.13	286.60	0.49

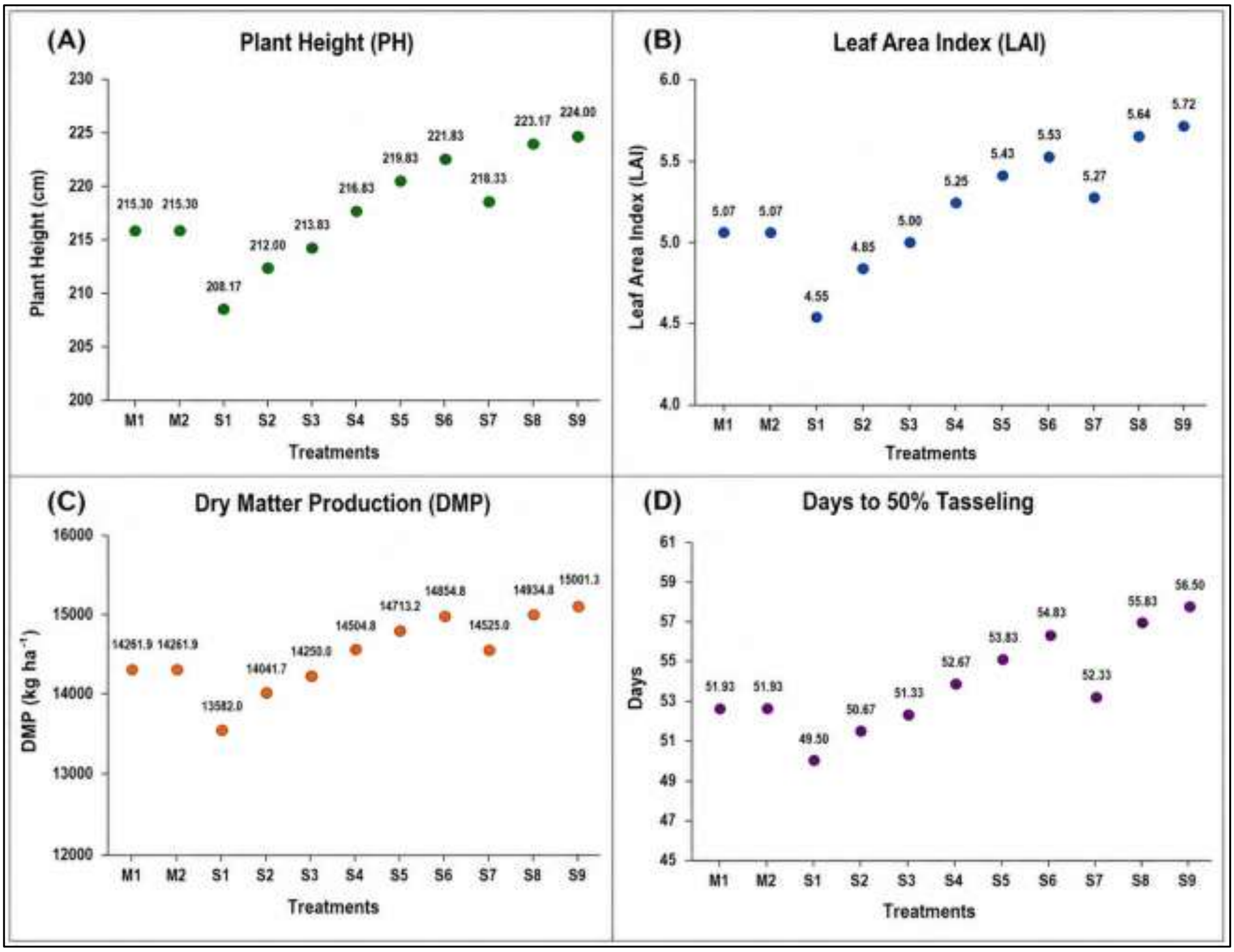

Fig 1: Growth parameters of maize

Yield attributes and Yield

Cob length was influenced by fertilizer level and micronutrient management. Under the main-plot treatments, M_1 (100% RDF) recorded a cob length of 17.34 cm, while M_2 (125% RDF) also recorded 17.34 cm. Among the subplot treatments, the shortest cob length (16.20 cm) was recorded in S_1 (no priming). Seed priming with 0.5% $FeSO_4$ and 0.5% $ZnSO_4$ increased cob length to 16.95 and 17.20 cm in S_2 and S_3, respectively. The maximum cob length (19.40 cm) was recorded under S_9. The improvement in cob length under S_9 may be associated with the better vegetative growth and greater nutrient availability achieved through Zn seed priming followed by foliar Zn application. Zinc contributes to enzyme activity, carbohydrate metabolism and reproductive development, which can favour better cob development. Ariraman et al. (2022), who reported that Zn application through seed treatment, soil application and foliar spraying improved growth and yield attributes of maize. Cob weight exhibited a progressive increase with improved micronutrient management. The main-plot treatment M_1 recorded 295.33 g, whereas M_2 produced a higher cob weight of 304.70 g. Among the subplot treatments, S_1 recorded the lowest value (285.00 g) in fig 2.The corresponding Zn treatments recorded 300.00 g in S_7, 308.33 g in S_8 and the highest cob weight of 309.83 g in S_9. The greater cob weight under S_9 may be attributed to improved assimilate production and translocation to the developing reproductive organs. The improved grain yield and Zn accumulation in maize, indicating that Zn supplied through seed treatment can enhance subsequent crop productivity. The present result therefore suggests that combining seed priming with later foliar Zn application provided a favourable nutritional environment for cob development (Choukri et al., 2022).

The 100-grain weight also responded positively to the micronutrient treatments. The main-plot treatments M_1 and M_2 recorded 24.69 and 25.16 g, respectively. Among the subplot treatments, S_1 produced the lowest 100-grain weight (24.40 g). The Zn-based treatments S_7, S_8 and S_9 recorded 24.83, 25.27 and 25.48 g, respectively, with S_9 recording the maximum value. The greater 100-grain weight under S_9 indicates more effective grain filling under integrated Zn management. Adequate Zn availability can support enzymatic processes, carbohydrate metabolism and assimilate transfer to developing grains. Recent field research by Jarecki et al. (2025) demonstrated that foliar Zn application significantly increased grain size and yield components of maize, with Zn-treated crops producing higher thousand-grain weight than the control. Although the experimental environment and application strategy differed, the positive response of grain weight to Zn nutrition is consistent with the present findings.

Seed priming increased shelling percentage to 81.81% in S_2 and 82.65% in S_3. Further improvement was observed with foliar application, with values of 84.05, 85.02 and 85.76% in S_4, S_5 and S_6, respectively. The Zn-based treatments recorded 83.68, 86.38 and 87.47% under S_7, S_8 and S_9 in fig2, respectively. The maximum shelling percentage (87.47%) was recorded in S_9. The findings also agree with Ariraman et al. (2022), who summarized the beneficial effects of Zn application on maize growth, yield components and productivity and emphasized the importance of Zn in physiological processes associated with chlorophyll formation, photosynthesis, nutrient uptake and protein synthesis.

Grain yield showed a substantial response to the fertilizer and micronutrient treatments. Under the main-plot treatments, M_1 (100% RDF) produced 5625.93 kg ha^{-1}, whereas M_2 (125% RDF) recorded a considerably higher grain yield of 6233.33 kg ha^{-1}. Among the subplot treatments, S_1 produced the lowest grain yield (5075.00 kg ha^{-1}). The Zn-based treatments produced 5916.67, 6466.67 and 6566.67 kg ha^{-1} in S_7, S_8 and S_9, respectively. The maximum grain yield (6566.67 kg ha^{-1}) was recorded in S_9. The higher grain yield under S_9 can be attributed to the cumulative improvement in cob length, cob weight, 100-grain weight and shelling percentage. Seed priming with $FeSO_4$ and $ZnSO_4$ increased stover yield to 7950.00 and 8150.00 kg ha^{-1}, respectively. Foliar $FeSO_4$ application further increased stover yield to 8450.00, 8750.00 and 8925.00 kg ha^{-1} under S_4, S_5 and S_6, respectively. The corresponding Zn treatments recorded 8500.00, 9000.00 and 9113.33 kg ha^{-1} under S_7, S_8 and S_9, respectively. The maximum stover yield (9113.33 kg ha^{-1}) was recorded under S_9. The increased grain and stover production under S_9 may be associated with the superior vegetative growth, higher LAI and greater dry matter accumulation observed under the same treatment. Improved Zn nutrition can enhance several physiological processes associated with photosynthesis and biomass formation. Tamindžić et al. (2021) observed that Zn seed priming enhanced plant growth and final field performance of maize hybrids, which was associated with improved yield formation. Furthermore, Stewart et al. (2021) emphasized that micronutrient responses in maize depend strongly on the crop's nutritional status and the timing and method of application. This supports the greater response observed in the present study, where the soil was initially deficient in available Zn.

Table 2. Influence of Fe and Zn Management Practices on Yield Components and Productivity of Maize (Pooled Data of Kharif Seasons 2024–2025)

Treatments		**Cob length (cm)**	**Cob weight (g)**	**100 grain weight (g)**	**Shelling (%)**	**Grain yield (kg ha-1)**	**Stover yield (kg ha-1)**
M1-100% RDF (N:P: K – 250:75:75 kg ha^{-1})		17.34	295.33	24.69	82.59	5625.93	8183.33
M2-125% RDF		17.34	304.70	25.16	85.47	6233.33	8780.74
SE(d)		0.01	0.51	0.02	0.43	1.85	17.64
CD at 5%		0.03	2.21	0.07	1.84	7.97	75.91
S1- No priming (control)		16.20	285.00	24.40	79.47	5075.00	7500.00
S2- Seed priming with 0.5% Fe SO_4		16.95	291.50	24.60	81.81	5441.67	7950.00
S3- Seed priming with 0.5% Zn SO_4		17.20	294.50	24.68	82.65	5575.00	8150.00
S4-S_1 + 0.2% Fe SO_4 foliar spray at 45 and 60 DAS		17.90	300.50	24.88	84.05	5866.67	8450.00
S5-S_2 + 0.2% Fe SO_4 foliar spray at 45 and 60 DAS		18.45	304.17	25.03	85.02	6141.67	8750.00
S6-S_3 + 0.2% Fe SO_4 foliar spray at 45 and 60 DAS		18.75	306.33	25.13	85.76	6316.67	8925.00
S7-S_1 + 0.5% Zn SO_4 foliar spray at 45 and 60 DAS		17.85	300.00	24.83	83.68	5916.67	8500.00
S8-S_2 + 0.5% Zn SO_4 foliar spray at 45 and 60 DAS		19.05	308.33	25.27	86.38	6466.67	9000.00
S9-S_3 + 0.5% Zn SO_4 foliar spray at 45 and 60 DAS		19.40	309.83	25.48	87.47	6566.67	9113.33
SE(d)		0.03	0.54	0.03	0.35	13.96	20.27
CD at 5%		0.01	1.11	0.06	0.71	28.43	41.30
S at M	SE(d)	0.01	0.77	0.04	0.49	19.74	28.67
	CD at 5%	0.02	1.57	0.08	1.00	40.21	58.40
M at S	SE(d)	0.02	0.89	0.04	0.63	18.70	32.28
	CD at 5%	0.03	2.49	0.10	1.94	38.51	87.60

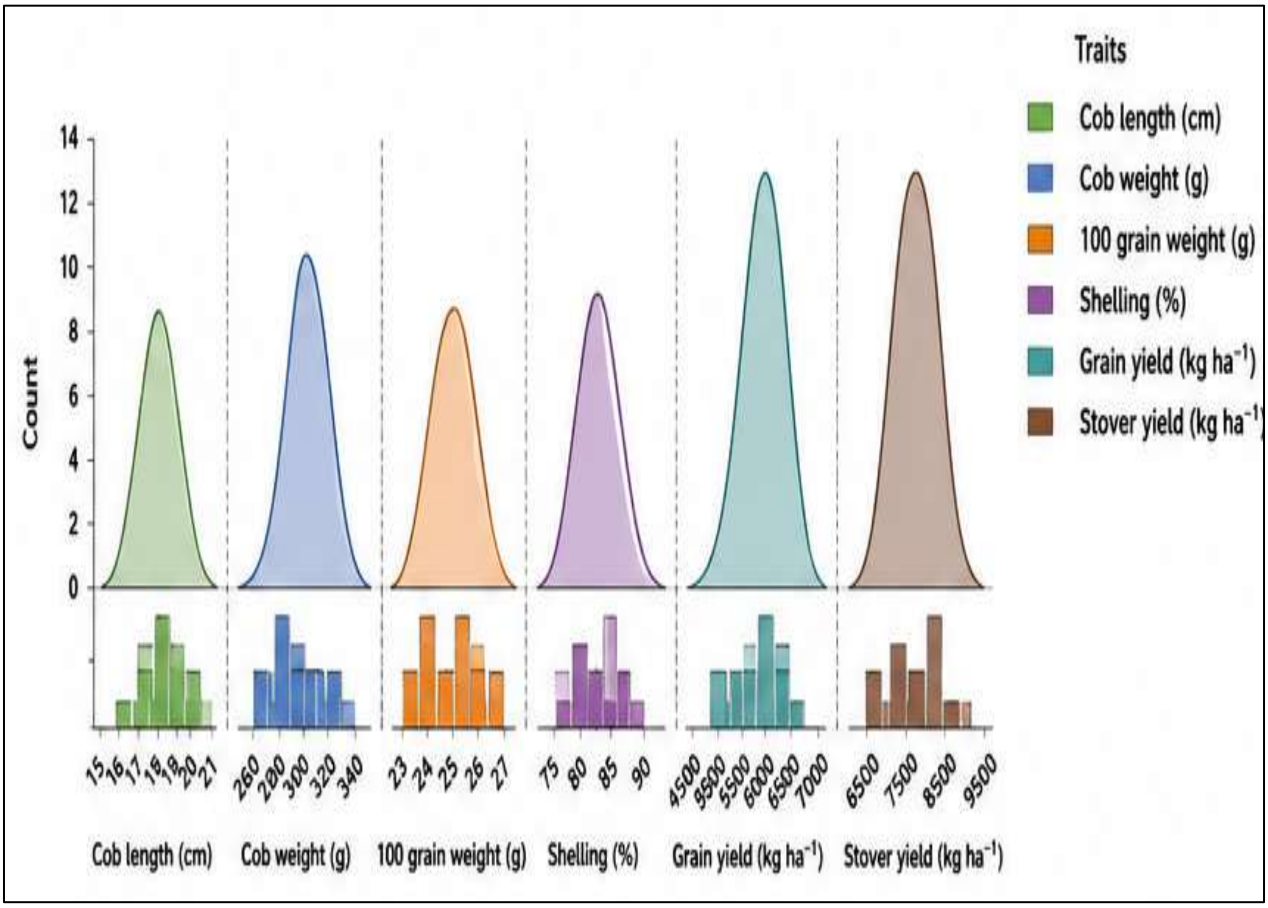

Fig2: Yield Components and Productivity of Maize

Crop Growth Rate, Relative Growth Rate, Net Assimilation Rate and Nutrient Concentration.

The crop growth rate differed between the fertilizer levels and micronutrient treatments. Application of 125% RDF (M_2)recorded a higher CGR of 75.50, compared with 71.49 under 100% RDF (M_1). Among the micronutrient treatments, the lowest CGR (66.87) was observed in S_1 (no priming). Seed priming with 0.5% $FeSO_4$ and 0.5% $ZnSO_4$ increased CGR to 69.96 and 71.15, respectively. The maximum CGR of 78.05 was recorded with S_9, in fig3 indicating that Zn seed priming followed by foliar Zn application promoted greater biomass accumulation. Earlier physiological research in maize demonstrated that improved crop growth was associated with greater photosynthetic activity and leaf development under favourable nutrient-management conditions (Bakhtavar et al., 2015).

The RGR values ranged from 0.007 to 0.008 across the treatments. The main-plot treatment M_1 recorded an RGR of 0.007, whereas M_2 recorded 0.008. Among the micronutrient treatments, S_1 recorded 0.007, while S_2, S_3, S_4, S_5 and S_7 also recorded 0.007. The treatments S_6, S_8 and S_9 recorded 0.008, indicating a relatively greater rate of biomass development under these treatments. The higher RGR under S_9 could be related to improved nutrient acquisition and physiological activity resulting from combined Zn seed priming and foliar application. Seed-applied Zn can improve the availability of Zn during early plant development, while foliar application provides an additional nutrient source during periods of active growth. The NAR values varied from 0.15 to 0.17. The 100% RDF treatment recorded 0.16, while 125% RDF also recorded 0.16. The highest NAR among the subplot treatments was observed in S_1 (0.17). Bakhtavar et al. (2015) demonstrated that improved physiological performance in maize can involve simultaneous changes in LAI, photosynthetic rate and CGR under appropriate crop-management practices. This provides a physiological basis for interpreting the present differences between CGR and NAR.

Nitrogen concentration

Nitrogen concentration increased from 1.74% in S_1 to 1.87% in S_9. Under the fertilizer treatments, M_1 recorded 1.79% N, whereas M_2 increased the value to 1.84%. Seed priming with $FeSO_4$ and $ZnSO_4$ resulted in 1.77 and 1.79% N, respectively. The combination treatments increased N concentration further, with 1.81, 1.83 and 1.84% under S_4, S_5 and S_6, respectively. The highest N concentration under S_9 may be associated with improved Zn nutrition and its interaction with nitrogen metabolism. Alloway (2009) emphasized that adequate Zn nutrition is closely associated with improved nitrogen metabolism and protein synthesis in crops. The present findings therefore suggest that Zn seed priming followed by foliar Zn application enhanced the nutritional status of maize and promoted more efficient utilization of applied nitrogen.

Phosphorus concentration

Phosphorus concentration ranged from 0.32 to 0.35%. The M_1 treatment recorded 0.33% P, whereas M_2 recorded 0.34% P. The control treatment S_1 recorded the lowest value of 0.32%. $FeSO_4$ and $ZnSO_4$ seed priming increased P concentration to 0.33% in both S_2 and S_3. Foliar Fe treatments resulted in 0.33, 0.34 and 0.34% P in S_4, S_5 and S_6, respectively. The Zn-based treatments recorded 0.34% in S_7 and S_8, while the highest P concentration (0.35%) was recorded under S_9 in fig3.

Zinc and phosphorus interactions are particularly important because an adequate supply of Zn can influence phosphorus uptake and utilization, while excessive phosphorus can induce Zn deficiency. The several physiological processes that influence root growth, nutrient acquisition and plant metabolism. Thus, the higher P concentration under S_9 indicates that combined Zn seed priming and foliar application helped maintain a more balanced nutritional status of maize Marschner (2012) .

Potassium concentration

Potassium concentration showed a clear improvement with enhanced fertilizer and micronutrient management. M_1 recorded 1.32% K, whereas M_2 increased K concentration to 1.37%. Among the subplot treatments, S_1 recorded the lowest concentration (1.26%). Seed priming with $FeSO_4$ and $ZnSO_4$ increased K concentration to 1.30 and 1.32%, respectively. Foliar Fe treatments recorded 1.35, 1.37 and 1.38% in S_4, S_5 and S_6, respectively. The corresponding Zn treatments resulted in 1.34, 1.39 and 1.41% in S_7, S_8 and S_9. The maximum K concentration (1.41%) was recorded under S_9. The improvement in K concentration under Zn supplementation may also be related to better plant water relations and assimilate transport. Potassium is particularly important for stomatal regulation, maintenance of cellular turgor and translocation of photosynthates. Cakmak and Kutman (2018) highlighted the importance of balanced micronutrient nutrition in maintaining physiological processes that support efficient nutrient utilization and plant productivity. Therefore, the higher K concentration observed with integrated Zn management indicates improved overall nutritional efficiency of maize.

Table 3. Influence of Nutrient Management on Growth Indices and N, P and K Concentration of Maize

Treatments		CGR	RGR	NAR	N (%)	P (%)	K (%)
M1-100% RDF (N:P: K – 250:75:75 kg ha^{-1})		71.49	0.007	0.16	1.79	0.33	1.32
M2-125% RDF		75.50	0.008	0.16	1.84	0.34	1.37
SE(d)		0.30	1.55	0.001	0.002	0.01	0.001
CD at 5%		1.28	6.68	0.002	0.007	0.02	0.003
S1- No priming (control)		66.87	0.007	0.17	1.74	0.32	1.26
S2- Seed priming with 0.5% Fe SO_4		69.96	0.007	0.16	1.77	0.33	1.30
S3- Seed priming with 0.5% Zn SO_4		71.15	0.007	0.16	1.79	0.33	1.32
S4-S_1 + 0.2% Fe SO_4 foliar spray at 45 and 60 DAS		73.38	0.007	0.16	1.81	0.33	1.35
S5-S_2 + 0.2% Fe SO_4 foliar spray at 45 and 60 DAS		75.00	0.007	0.16	1.83	0.34	1.37
S6-S_3 + 0.2% Fe SO_4 foliar spray at 45 and 60 DAS		76.56	0.008	0.16	1.84	0.34	1.38
S7-S_1 + 0.5% Zn SO_4 foliar spray at 45 and 60 DAS		73.13	0.007	0.16	1.82	0.34	1.34
S8-S_2 + 0.5% Zn SO_4 foliar spray at 45 and 60 DAS		77.36	0.008	0.15	1.86	0.34	1.39
S9-S_3 + 0.5% Zn SO_4 foliar spray at 45 and 60 DAS		78.05	0.008	0.15	1.87	0.35	1.41
	SE(d)	0.48	2.79	0.001	0.001	0.02	0.001
CD at 5%		0.99	5.68	0.001	0.003	0.11	0.002
S at M	SE(d)	0.68	3.94	0.001	0.002	0.01	0.001
	CD at 5%	1.39	8.03	0.002	0.004	0.02	0.003
M at S	SE(d)	0.71	4.03	0.001	0.002	0.01	0.002
	CD at 5%	1.73	9.56	0.002	0.007	0.02	0.004

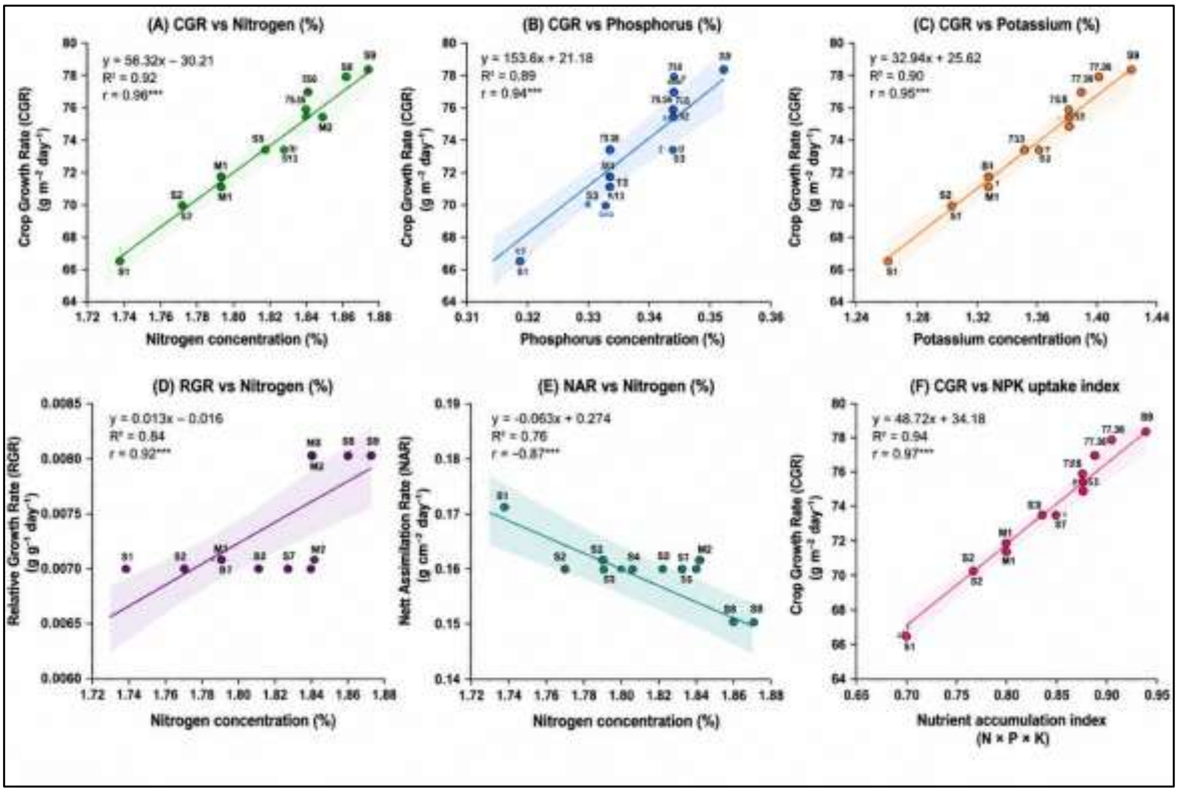

Fig3: Nutrient Management on Growth Indices and N, P and K Concentration of Maize

Economic Performance

The economic analysis showed clear differences among the treatment combinations. The cost of cultivation (COC)ranged from ₹44,223 ha⁻¹ in M_1S_1 to ₹51,586 ha⁻¹ in M_2S_9. The increase in cultivation cost under the micronutrient treatments was mainly associated with the additional expenditure involved in seed priming and foliar application. However, the higher input cost was accompanied by greater gross and net returns, indicating that the additional investment was economically beneficial. Under 100% RDF (M_1), gross returns increased from ₹111,716.7 ha⁻¹ in M_1S_1 to ₹138,116.7 ha⁻¹ in M_1S_9 in fig 4. Similarly, net returns increased from ₹67,494 ha⁻¹ to ₹88,044 ha⁻¹. The B:C ratio also improved from 2.53 in M_1S_1 to 2.76 in M_1S_9. This indicates that Zn supplementation, particularly when seed priming was combined with foliar application, generated additional returns sufficient to offset the extra cost of treatment.

The better economic performance of M_2S_9 can be linked to the improved crop growth and yield obtained through adequate NPK nutrition combined with Zn seed priming and foliar Zn application. Better nutrient availability can promote biomass production, yield formation and nutrient utilization, ultimately increasing the economic output per unit of investment. Earlier research has shown that Zn seed priming can substantially improve maize yield while requiring only a relatively small quantity of Zn fertilizer, making it an economically attractive approach, particularly in Zn-deficient soils. Harris et al. (2007) reported that Zn seed priming increased maize grain yield and produced a very high benefit-to-cost return because of the low quantity of Zn required for priming. The present findings are also consistent with Ahmed et al., (2021)who evaluated different Zn application methods in maize during 2018 and 2019 and reported improved productivity with Zn application, including seed priming and combined seed-plus-foliar approaches. Similarly, Kale and Takawale (2019) reported that $ZnSO_4$ seed priming improved fodder yield and increased net monetary returns and B:C ratio in maize. Among all treatments, M_2S_9 (125% RDF + 0.5% $ZnSO_4$ seed priming + 0.5% $ZnSO_4$ foliar spray at 45 and 60 DAS) was therefore the most economically superior treatment, recording ₹1,01,152 ha⁻¹ net return and a B:C ratio of 2.96. The result suggests that integrated Zn management along with an adequate fertilizer level can improve not only maize productivity but also the profitability of cultivation

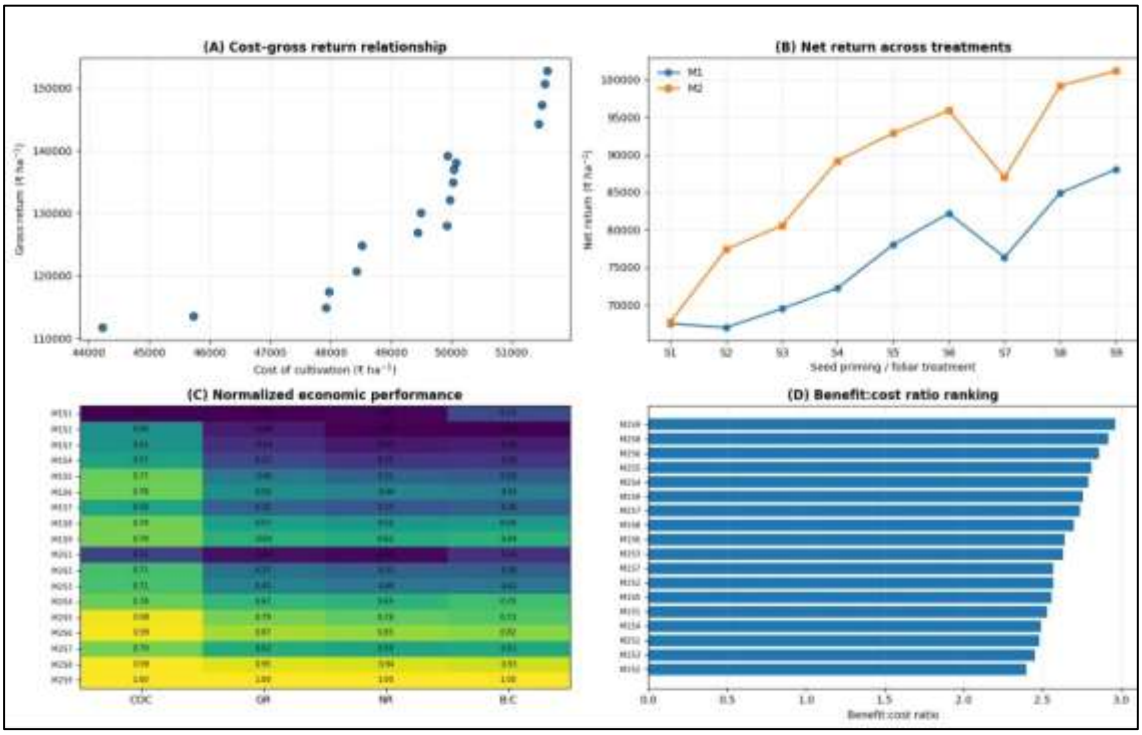

Fig4: Economic performance of nutrient management and seed priming treatments

CONCLUSIONS

The study demonstrated that integrated nutrient management enhanced maize growth, yield, nutrient uptake and economic returns. Among the micronutrient treatments, S_9 (0.5% $ZnSO_4$ seed priming + 0.5% $ZnSO_4$ foliar application at 45 and 60 DAS) performed best. Under M_2 (125% RDF), S_9 recorded the highest grain yield (6566.67 kg ha^{-1}) and stover yield (9113.33 kg ha^{-1}), along with the maximum gross returns (₹152,737.7 ha^{-1}) and net returns (₹1,01,152 ha^{-1}). The treatment also achieved the highest B:C ratio (2.96), indicating greater economic efficiency. Therefore, S_9 combined with 125% RDF (M_2) was the most effective treatment combination for improving maize productivity and profitability under the experimental conditions.

Acknowledgement

The authors sincerely express their gratitude to the management and staff of the School of Agricultural Sciences, Division of Agronomy, Karunya Institute of Technology and Sciences, Coimbatore, for providing the necessary facilities and institutional support to carry out this research work. The authors gratefully acknowledge their continuous encouragement, valuable guidance, technical assistance and cooperation throughout the experimental period. The support extended in providing field facilities, laboratory resources and other essential requirements greatly contributed to the successful completion of the study. The authors also appreciate the assistance and cooperation of all those who directly or indirectly contributed to the execution of the field experiment, collection of observations and completion of the research work.

Conflict of Interest

The authors declare that there is no conflict of interest associated with this research work.

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