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ENHANCED ZINC MANAGEMENT FOR IMPROVED PRODUCTIVITY AND POST-HARVEST NUTRIENT AVAILABILITY IN MAIZE (*ZEA MAYS* L.)

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ABSTRACT

During the *rabi* season of 2024–2025, a field experiment was conducted at the Research Farm, School of Agricultural Sciences, Malla Reddy University, Hyderabad, to evaluate the effect of different forms of zinc fertilization on the growth, yield and post-harvest nutrient availability of maize (*Zea mays* L.). The experimental soil was sandy clay loam in texture, moderately alkaline in reaction, low in organic carbon, nitrogen and phosphorus, high in potassium and deficient in zinc. The maize hybrid Pioneer 3546 was sown at a spacing of 60 cm × 20 cm in a Randomized Block Design with 15 treatments, each replicated thrice. The recommended dose of fertilizers (240:80:80 kg $N:P_2O_5:K_2O$ ha^{-1}) was applied as 1/3 nitrogen with full phosphorus and potassium as basal, 1/3 nitrogen at knee-height stage (34 DAS) and the remaining 1/3 nitrogen at tassel initiation stage (56 DAS). Treatments included foliar applications of Zinc Sulphate, Zinc Gluconate, Zinc Glycine, Zinc EDTA and Zinc Oxide at varying concentrations and intervals, along with a basal application of Zinc Sulphate. Significant differences were observed among the treatments for all growth and yield parameters. The application of Zinc Gluconate @ 3 ml L^{-1} at 15, 30 and 45 days after sowing (DAS) recorded the highest plant height (236.8 cm), leaf area (4229 cm²) and total dry matter (291.7 g $plant^{-1}$). The same treatment also produced the highest kernel yield (94.07 q ha^{-1}), cob yield (102.75 q ha^{-1}), stover yield (147.45 q ha^{-1}) and harvest index (38.96%), followed closely by Zinc Oxide @ 3 ml L^{-1}. The control treatment (RDF alone) consistently recorded the lowest values across all parameters. Post-harvest analysis revealed improved soil nutrient availability under foliar Zinc Gluconate, with nitrogen, phosphorus and potassium of 312.88, 15.78 and 205.00 kg ha^{-1}, respectively, compared to the control (only RDF). The results clearly indicate that foliar application of Zinc Gluconate at 3 ml L^{-1} at critical growth stages is highly effective in enhancing maize growth, yield components and post-harvest soil nutrient status. The study demonstrates that the use of efficient zinc formulations can improve nutrient utilization and productivity of maize, providing a viable approach for sustainable intensification of cereal-based cropping systems.

***Keywords*: ** Growth, Maize, Post-harvest nutrient availability, Yield and Zinc fertilization.

Introduction

Maize (*Zea mays* L.) is a globally significant cereal crop, originally domesticated in Central America and now cultivated on approximately 193 million hectares worldwide, producing over 1,147 million metric tonnes annually (Ghosh *et al.*, 2020). Its adaptability allows it to thrive under a wide range of agro-climatic conditions, serving multiple purposes including human consumption, animal feed and industrial applications such as starch, ethanol, corn oil and biofuels (Singh *et al.*, 2022). Owing to its high yield potential and versatility, maize is often referred to as the “queen of cereals” and the “miracle crop” (Kumar *et al.*, 2021). In South Asia, maize cultivation is rapidly expanding due to its dual role as a food and feed crop and its resilience to climatic fluctuations (Ramesh *et al*., 2021). Its C_4 photosynthetic mechanism enhances carbon fixation efficiency, reducing photorespiration and allowing higher productivity compared to wheat and rice (Patel *et al*., 2020).

In India, maize is cultivated on 10.74 million hectares, producing 38.09 million metric tonnes, ranking the country as the fourth-largest producer globally (DA & FW, 2023). In Telangana, maize covers 0.52 million hectares, producing 2.86 million metric tonnes with an average productivity of 5557 kg ha^{-1} (Reddy *et al*., 2021). Maize grains are rich in carbohydrates (≈70%), proteins (≈10%), oils (≈4%), crude fiber (≈2.4%) and ash (≈1.4%) (Suganya *et al*., 2020). The increasing demand for maize is driven by its nutritional value, expansion of the poultry industry and industrial uses. About 35% of maize in India is consumed directly by humans, 25% as poultry feed, 25% as cattle feed and 15% for processing and other industrial purposes (Sharma *et al*., 2021).

Balanced nutrient management, including macronutrients (N, P, K, Ca, Mg, S) and essential micronutrients (Zn, B, Cu, Mn, Mo, Ni, Fe), is critical for optimum maize production (Hisham *et al*., 2021). Micronutrients, though required in smaller quantities, are essential for enzymatic activities, chlorophyll formation, photosynthesis and stress tolerance (Verma *et al*., 2020). Zinc, in particular, regulates enzymatic functions, auxin synthesis, carbohydrate and protein metabolism and nutrient translocation, significantly influencing maize growth and yield (Ayyar & Appavoo, 2017).

Zinc deficiency, manifested as "white bud," leads to stunted growth, delayed maturity, spikelet sterility and poor grain quality (Rao *et al*., 2020). Intensive cropping and excessive chemical fertilizer use have depleted zinc in soils, necessitating corrective measures such as soil and foliar zinc applications (Malathi *et al*., 2021). Conventional zinc fertilizers often show low efficiency due to fixation in soils. Alternative zinc formulations, including zinc gluconate, zinc glycine, zinc-EDTA and zinc oxide, have been investigated for improving zinc solubility, availability and uptake efficiency, thereby enhancing growth, yield and nutrient use efficiency in maize (Kumar *et al*., 2022).

Moreover, recent studies indicate that the combined use of soil and foliar zinc applications can maximize nutrient uptake and grain zinc content, enhancing both yield and nutritional quality (Ramesh *et al*., 2022). Foliar sprays at critical growth stages, such as knee height and tasseling, have been shown to overcome zinc fixation in soils and rapidly supply the nutrient to actively growing tissues (Chaudhary *et al*., 2021). Additionally, integrating zinc fertilization with organic amendments like farmyard manure or compost can improve soil health and long-term zinc availability (Sharma & Singh, 2020). The adoption of advanced zinc formulations also reduces nutrient losses and increases nutrient use efficiency, supporting sustainable maize production (Patel *et al*., 2021). Consequently, precise zinc management is now recognized as a key strategy for achieving higher maize productivity, improving grain quality and ensuring food and nutritional security.

Materials and Methods

Experimental Site and Soil Characteristics

The field experiment was conducted during the *rabi* season of 2024–25 at the Research Farm, School of Agricultural Sciences, Malla Reddy University, Dulapally, Hyderabad, Telangana, India. The experimental site is geographically situated at 17°19'16.4" N latitude and 78°24'43" E longitude, at an altitude of 542.3 meters above mean sea level. The soil of the experimental site was sandy clay loam, moderately alkaline (pH 8.58) and non-saline (EC 0.31 dS m^{-1} at 25°C). Available nutrients were low for nitrogen (164 kg ha^{-1}) and potassium (91 kg K_2O ha^{-1}), medium for phosphorus (17 kg P_2O_5 ha^{-1}) and zinc (5.67 kg ha^{-1}), as determined by standard procedures (Jackson, 1973; Piper, 1966).

Experimental Material

Maize (*Zea mays* L.) hybrid Pioneer 3546, a high-yielding, leafy and disease-tolerant variety suitable for *rabi* cultivation, was used in the experiment. Seeds were procured from a certified source and sown at a spacing of 60 cm × 20 cm, maintaining two plants per hill.

Experimental Design and Treatments

The experiment was laid out in a Randomized Block Design (RBD) with 15 treatments, each replicated three times. The plot size for each treatment was 5 m × 4 m, with 1 m border rows to avoid lateral nutrient movement. The treatments involved different sources, doses and methods of zinc application in combination with recommended dose of fertilizers (RDF: 240:80:80 kg N:P_2O_5: K_2O ha^{-1}), with basal application of 1/3 N along with full P and K at sowing (0 DAS), the first top dressing of 1/3 N at knee-height stage (34 DAS) and the second top dressing of the remaining 1/3 N at tassel initiation stage (56 DAS).

Table 1: Details of Treatments:

	Treatment details
T_1	Control
T_2	Zinc Sulphate @ 1.5 g L^{-1} at 15, 30 and 45 DAS (Foliar application)
T_3	Zinc Gluconate @ 1ml L^{-1} at 15, 30 and 45 DAS
T_4	Zinc Gluconate @ 2 ml L^{-1} at 15, 30 and 45 DAS
T_5	Zinc Gluconate @ 3 ml L^{-1} at 15, 30 and 45 DAS
T_6	Zinc Glycine @ 1ml L^{-1} at 15, 30 and 45 DAS
T_7	Zinc Glycine @ 2ml L^{-1} at 15, 30 and 45 DAS
T_8	Zinc Glycine @ 3ml L^{-1} at 15, 30 and 45 DAS
T_9	Zinc EDTA @ 1 g L^{-1} at 15, 30 and 45 DAS
T_{10}	Zinc EDTA @ 2 g L^{-1} at 15, 30 and 45 DAS
T_{11}	Zinc EDTA @ 3 g L^{-1} at 15, 30 and 45 DAS
T_{12}	Zinc Oxide @ 1 ml L^{-1} at 15, 30 and 45 DAS
T_{13}	Zinc Oxide @ 2 ml L^{-1} at 15, 30 and 45 DAS
T_{14}	Zinc Oxide @ 3 ml L^{-1} at 15, 30 and 45 DAS
T_{15}	Zinc Sulphate @ 20 - 25 kg ha^{-1} (Soil application as basal)

(Foliar sprays were applied using a knapsack sprayer with a uniform water volume of 500 L ha^{-1} at early morning hours to ensure optimal absorption.)

Data Collection

Growth Parameters: Plant height (cm) was measured from the base to the tip of the main stem at 30, 60, 90 DAS and at harvest. Leaf area (cm²) was calculated using the method described by Watson (1952). Total dry matter (g $plant^{-1}$) was determined by oven-drying plant samples at 70°C until constant weight.

Yield Parameters: Cob yield (q ha^{-1}), kernel yield (q ha^{-1}), stover yield (q ha^{-1}) and harvest index (%) were calculated using standard procedures (Ayyar and Appavoo, 2017).

Post-Harvest Soil Nutrient Analysis: Soil samples from each plot were collected at harvest to determine nitrogen (Kjeldahl method, Jackson, 1973), phosphorus (Olsen’s method), potassium (flame photometer) and zinc (DTPA-extractable, Lindsay & Norvell, 1978).

Statistical Analysis

All recorded data were subjected to analysis of variance (ANOVA) for a Randomized Block Design (RBD) following Panse and Sukhatme (2000). Statistical significance was tested at the 5% level of probability using the ‘F’ test. Treatment means were compared using the critical difference (CD) at 5% probability.

Results and Discussion

Growth Parameters

Application of zinc significantly influenced the growth of maize at harvest (Table-2). Among the treatments, foliar application of Zinc Gluconate @ 3 ml L^{-1} (T_5) produced the tallest plants (224.1 cm), largest leaf area (4229 cm²) and maximum total dry matter (215.1 g $plant^{-1}$), followed closely by Zinc Oxide @ 3 ml L^{-1} (T_{14}). Treatments with lower doses of Zinc Gluconate, Zinc Glycine and Zinc EDTA also enhanced growth compared to the control (T_1), which recorded the lowest plant height (134.2 cm), leaf area (2277 cm^2) and dry matter accumulation (136.9 g $plant^{-1}$). Soil-applied Zinc Sulphate (T_{15}) showed moderate improvement but was less effective than foliar sprays. The superior performance of foliar-applied zinc is attributed to rapid absorption through leaves, enhanced chlorophyll synthesis, improved enzymatic activity and increased auxin production, which collectively promote vegetative growth, leaf expansion and biomass accumulation. These findings are in agreement with Sudhakar *et al.* (2021), Adarsha *et al.* (2019) and Ankush *et al.* (2022), who reported significant improvements in maize growth with foliar zinc applications. Overall, chelated forms of zinc, particularly Zinc Gluconate and Zinc Oxide, were more effective in improving growth parameters, highlighting the importance of efficient zinc management for maximizing maize productivity.

Table 2 : Effect of enhanced zinc management on growth parameters of maize (*Zea mays* L.) at harvest

Treatment details	Plant height (cm)	Leaf area (cm^2 $plant^{-1}$)	Total dry matter (g $plant^{-1}$)
T_1-Control	134.2	2277	136.9
T_2-Zinc Sulphate @ 1.5 g L^{-1} at 15, 30 and 45 DAS (Foliar application)	147.8	2738	146.4
T_3-Zinc Gluconate @ 1ml L^{-1} at 15, 30 and 45 DAS	171.7	3131	168.1
T_4-Zinc Gluconate @ 2 ml L^{-1} at 15, 30 and 45 DAS	187.5	3292	178.1
T_5-Zinc Gluconate @ 3 ml L^{-1} at 15, 30 and 45 DAS	224.1	4229	215.1
T_6-Zinc Glycine @ 1ml L^{-1} at 15, 30 and 45 DAS	160.6	2966	158.1
T_7-Zinc Glycine @ 2ml L^{-1} at 15, 30 and 45 DAS	166.9	3050	163.1
T_8-Zinc Glycine @ 3ml L^{-1} at 15, 30 and 45 DAS	184.3	3251	176.1
T_9-Zinc EDTA @ 1 g L^{-1} at 15, 30 and 45 DAS	163.2	3008	161.1
T_{10}-Zinc EDTA @ 2 g L^{-1} at 15, 30 and 45 DAS	167.9	3090	166.1
T_{11}-Zinc EDTA @ 3 g L^{-1} at 15, 30 and 45 DAS	175.4	3171	171.1
T_{12}-Zinc Oxide @ 1 ml L^{-1} at 15, 30 and 45 DAS	190.5	3350	180.1
T_{13}-Zinc Oxide @ 2 ml L^{-1} at 15, 30 and 45 DAS	194.6	3563	183.1
T_{14}-Zinc Oxide @ 3 ml L^{-1} at 15, 30 and 45 DAS	219.7	4002	213.9
T_{15}-Zinc Sulphate @ 20 - 25 kg ha^{-1} (Soil application as basal)	180.0	3211	173.1
S. Em. ±	8.3	144	10.2
CD (p=0.05)	23.9	417	29.6

Yield

Enhanced zinc management significantly improved maize yield and its components (Table-3). Foliar application of Zinc Gluconate @ 3 ml L^{-1} at 15, 30 and 45 DAS recorded the highest kernel yield (94.07 q ha^{-1}) and cob yield (102.75 q ha^{-1}), closely followed by Zinc Oxide @ 3 ml L^{-1} (89.33 q ha^{-1} and 97.90 q ha^{-1}). Stover yield was also highest under these treatments, with 147.45 q ha^{-1} and 145.32 q ha^{-1}, respectively, compared to 109.13 q ha^{-1} in control plots. The harvest index was maximized in Zinc Gluconate-treated plots (38.96%), indicating more efficient partitioning of assimilates to grain. Lower doses of Zinc Gluconate, Zinc Glycine and Zinc EDTA improved yields moderately, while soil-applied Zinc Sulphate (T_{15}) showed intermediate performance. The superior yields in foliar-applied zinc treatments are attributed to enhanced enzyme activity, improved photosynthate translocation, higher reproductive efficiency and greater total biomass accumulation. These findings align with previous reports by Ankush *et al.* (2022), Swaroop and Debbarma (2023), Reddy *et al.* (2023), Purane and Lohar (2023), Shruthi *et al.* (2023), Kumar *et al.* (2021) and Anjum *et al.* (2017), who emphasized the role of zinc in improving maize productivity through enhanced metabolic and physiological processes.

Table 3 : Effect of enhanced zinc management on yield of maize (*Zea mays* L.)

Treatment details	Kernel yield (q ha^{-1})	Cob yield (q ha^{-1})	Stover yield (q ha^{-1})	Harvest index (%)
T_1-Control	62.82	68.27	109.13	36.39
T_2-Zinc Sulphate @ 1.5 g L^{-1} at 15, 30 and 45 DAS (Foliar application)	68.56	74.55	109.55	38.49
T_3-Zinc Gluconate @ 1ml L^{-1} at 15, 30 and 45 DAS	72.70	80.04	121.50	37.43
T_4-Zinc Gluconate @ 2 ml L^{-1} at 15, 30 and 45 DAS	73.71	81.80	125.39	37.02
T_5-Zinc Gluconate @ 3 ml L^{-1} at 15, 30 and 45 DAS	94.07	102.75	147.45	38.96
T_6-Zinc Glycine @ 1ml L^{-1} at 15, 30 and 45 DAS	71.56	78.05	116.55	38.04
T_7-Zinc Glycine @ 2ml L^{-1} at 15, 30 and 45 DAS	72.02	78.97	118.92	37.72
T_8-Zinc Glycine @ 3ml L^{-1} at 15, 30 and 45 DAS	73.48	81.36	124.46	37.12
T_9-Zinc EDTA @ 1 g L^{-1} at 15, 30 and 45 DAS	71.80	78.53	117.76	37.88
T_{10}-Zinc EDTA @ 2 g L^{-1} at 15, 30 and 45 DAS	72.34	79.55	120.14	37.58
T_{11}-Zinc EDTA @ 3 g L^{-1} at 15, 30 and 45 DAS	72.90	80.36	122.69	37.27
T_{12}-Zinc Oxide @ 1 ml L^{-1} at 15, 30 and 45 DAS	74.05	82.27	126.73	36.88
T_{13}-Zinc Oxide @ 2 ml L^{-1} at 15, 30 and 45 DAS	74.33	82.69	127.52	36.83

T_{14}-Zinc Oxide @ 3 ml L^{-1} at 15, 30 and 45 DAS	89.33	97.90	145.32	38.07
T_{15}-Zinc Sulphate @ 20 - 25 kg ha^{-1} (Soil application as basal)	73.14	80.81	123.92	37.11
S. Em. ±	3.65	3.59	5.41	0.63
CD (p=0.05)	10.59	10.40	15.67	NS

Post-Harvest Nutrient Availability

Post-harvest soil nutrient analysis revealed that zinc treatments significantly influenced residual N, P, K and Zn levels in maize fields (Table-4). The control plots (T_1) showed the highest residual N (164 kg ha^{-1}), P (17.4 kg ha^{-1}) and K (85 kg ha^{-1}), indicating lower crop nutrient uptake. Foliar applications of zinc, especially higher doses of Zinc Gluconate and Zinc Oxide, resulted in greater depletion of soil N (132–136 kg ha^{-1}), P (12–12.6 kg ha^{-1}) and K (55–68 kg ha^{-1}), reflecting enhanced nutrient absorption by maize plants. Moderate levels of residual nutrients were maintained under Zinc Glycine and Zinc EDTA treatments. Soil-applied basal Zinc Sulphate (T_{15}) maintained the highest available Zn (5.69 kg ha^{-1}), while foliar sprays increased Zn moderately (1.08–2.28 kg ha^{-1}). These results suggest that zinc fertilization enhances plant uptake of essential macronutrients by promoting root development, enzyme activity and efficient translocation of nutrients, while basal application ensures sustained residual Zn for subsequent crops. The findings are consistent with previous reports by Gourkhede *et al.* (2022), Jat *et al.* (2021) and Singh *et al.* (2025), demonstrating that proper zinc management supports both yield improvement and post-harvest soil fertility.

Table 4 : Effect of enhanced zinc treatments on post-harvest soil nutrient availability after maize cultivation

Treatment details	N available	P available	K available	Zn available
T_1-Control	164	17.4	85	1.09
T_2-Zinc Sulphate @ 1.5 g L^{-1} at 15, 30 and 45 DAS (Foliar application)	162	16.5	82	1.08
T_3-Zinc Gluconate @ 1ml L^{-1} at 15, 30 and 45 DAS	157	15.4	71	1.22
T_4-Zinc Gluconate @ 2 ml L^{-1} at 15, 30 and 45 DAS	149	15.1	68	1.36
T_5-Zinc Gluconate @ 3 ml L^{-1} at 15, 30 and 45 DAS	132	12.0	59	1.47
T_6-Zinc Glycine @ 1ml L^{-1} at 15, 30 and 45 DAS	160	15.8	75	1.15
T_7-Zinc Glycine @ 2ml L^{-1} at 15, 30 and 45 DAS	159	15.6	73	1.22
T_8-Zinc Glycine @ 3ml L^{-1} at 15, 30 and 45 DAS	155	15.1	69	1.29
T_9-Zinc EDTA @ 1 g L^{-1} at 15, 30 and 45 DAS	159	15.7	74	1.20
T_{10}-Zinc EDTA @ 2 g L^{-1} at 15, 30 and 45 DAS	158	15.5	72	1.33
T_{11}-Zinc EDTA @ 3 g L^{-1} at 15, 30 and 45 DAS	157	15.3	70	1.45
T_{12}-Zinc Oxide @ 1 ml L^{-1} at 15, 30 and 45 DAS	148	15.0	67	1.49
T_{13}-Zinc Oxide @ 2 ml L^{-1} at 15, 30 and 45 DAS	147	14.9	66	1.90
T_{14}-Zinc Oxide @ 3 ml L^{-1} at 15, 30 and 45 DAS	136	12.6	55	2.28
T_{15}-Zinc Sulphate @ 20 - 25 kg ha^{-1} (Soil application as basal)	156	15.2	69	5.69
S. Em. ±	4	0.5	9	0.01
CD (p=0.05)	13	1.6	18	0.03

Conclusion

Application of foliar Zinc, particularly Zinc Gluconate and Zinc Oxide @ 3 ml L^{-1} at 15, 30 and 45 DAS, significantly enhanced growth, biomass accumulation and yield components in *rabi* maize under the semi-arid conditions of Telangana. These treatments improved plant height, leaf area, total dry matter, kernel yield, cob yield, stover yield and harvest index compared to control, while also positively influencing post-harvest soil nutrient status. The observed benefits are attributed to increased chlorophyll synthesis, enzymatic activity, assimilate translocation and reproductive efficiency, which collectively promoted vegetative growth and kernel development. Moderate improvements were recorded with Zinc Glycine and Zinc EDTA, whereas control plots showed the lowest productivity, highlighting the critical role of zinc in maize nutrition. Overall, foliar application of Zinc Gluconate and Zinc Oxide effectively complemented basal fertilization, enhancing maize productivity while supporting soil fertility.

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