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Original Article

" Impact of Soil-Applied Zinc Levels on Growth and Productivity of Maize in Hafizabad Region "

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ABSTRACT

Maize is a principal cereal crop widely grown in Pakistan, yet its output is inhibited by micronutrient deficiencies, principally zinc (Zn). This study investigated the effect of soil-applied zinc on growth and yield of maize variety Shehnshaw under the agro-climatic conditions of Hafizabad, Punjab. Treatments consisted of different zinc levels, with growth, phenological, and yield traits recorded during the crop cycle. Results showed that zinc application significantly reduced the duration to 50% tasseling and silking, indicating accelerated reproductive development. Plant height, leaf area index, and biomass accumulation improved progressively with zinc fertilization. Yield-related traits, including cob number, length and diameter, per cob grains and 1000-grain weight, also increased markedly with zinc application. Consequently, harvest index was improved, reflecting better partitioning of assimilates to economic yield. The results highlight the importance of zinc fertilization for optimizing maize performance in zinc-deficient soils. These findings provide strong evidence for adopting zinc supplementation as an agronomic strategy to enhance maize yield and ensure food security in Pakistan.

INTRODUCTION

Maize is among an imperative cereal crop in Pakistan, serving as food, feed and industrial raw material [1,2]. With population growth, changing diets, and rising demand for poultry and livestock feed, maize productivity has become increasingly critical for food and economic security [3,4]. Currently, Pakistan cultivates maize on a large scale, but average yields remain below potential due to multiple yield-limiting factors, including nutrient deficiencies [5].

Micronutrient deficiencies, particularly zinc (Zn) deficiency, are widespread in many agricultural soils of Pakistan [6,7]. Calcareous soils, high pH, low organic matter, excessive phosphorus application [8] and removal of crop residues all contribute to Zn immobilization and reduced availability to crops [9,10]. For instance, studies show that soils in Punjab, Sindh, and Khyber Pakhtunkhwa often have available Zn below critical levels needed to support optimal crop growth [11].

Zinc is vital for multiple physical and biochemical processes in plants: it is a cofactor for many enzymes; it plays roles in protein synthesis, auxin metabolism, membrane integrity, pollen viability, carbohydrate metabolism, and in the regulation of growth and developmental processes [12,13]. In maize, Zn deficiency can lead to stunted growth, chlorosis (especially of younger leaves), delayed silking/tasseling, poor kernel set — especially in the apical portions of the cob — and ultimately reduced grain and biomass yield [14,15].

A number of field studies in Pakistan and elsewhere have explored the effect of Zn fertilization on maize growth and yield [16,17,18]. For example, in district Bajaur, application of $ZnSO_4$ at levels up to 30 kg ha^{-1} improved plant height, number of leaves, cob length, grain number per cob, 1000-grain weight and final yield in several maize cultivars [19]. Another study using Zn application in calcareous soils of Peshawar showed that foliar or soil Zn significantly increased yield, Zn uptake, and the efficiency of nutrient use, particularly in soils with low baseline Zn availability [20,21]. More generally, a meta-analysis across multiple studies indicated that Zn fertilization can increase maize grain yield by ~15-20% and grain Zn concentration by ~20-30%, though response varies with soil type [22], Zn dose, application method [23], maize genotype [24] and environmental conditions [25].

Despite these findings, there is limited information for many specific agroecological zones, including the Hafizabad region of Punjab [26]. Hafizabad district is well known for its agricultural productivity, particularly rice and wheat, but maize is also grown there (more for silage and feed in many cases), though its yield potential may be constrained by soil and micronutrient status [27,28]. Moreover, soils in many parts of Punjab, including Hafizabad, are prone to high pH, salinity issues, and varying organic matter content, all of which may reduce Zn availability [26,29].

Given the critical role Zn plays, and the economic importance of maize, it is essential to quantify the response of maize to soil-applied Zn in Hafizabad: both in terms of growth (vegetative and reproductive), yield components, grain yield, and Zn uptake. This will help in determining optimum Zn rates under local soil conditions, which may differ from those in other regions, and in making site-specific fertilizer recommendations.

MATERIALS AND METHODS

Study site

The research was piloted during the spring/summer period of 2023 at an experimental farm in Hafizabad (provide coordinates if available), Punjab, Pakistan. The weather of the site is semi-arid with average yearly rainfall of 350-400 mm and mean temperature range of 30–47 °C during the maize growing season. Prior to sowing, a composite soil sample (0–20 cm) was taken from the investigational field for physical and chemical characterization and DTPA-extractable Zn.

Experimental material and treatments

Maize variety Shehnshaw was used for the study. Treatments consisted of five soil-applied zinc levels: 0 (control), 5, 10, 15 and 20 kg Zn ha-1. Zinc source used was zinc sulfate heptahydrate ($ZnSO4·7H2O$). Amounts of $ZnSO4·7H2O$ required to supply the target elemental Zn rates were calculated based on Zn content of $ZnSO4·7H2O$ (≈22% Zn): for 5, 10, 15 and kg Zn ha^{-1}, 22.7, 45.5, 68.2 and 90.9 kg $ZnSO4·7H2O$ ha^{-1}. Zinc was applied as a soil application at sowing and incorporated in the seedbed.

Experimental design and plot management

The trial was laid out in quadruplicated RCBD. A guard row of one meter was maintained between plots to avoid lateral movement of fertilizers. Basal macronutrient fertilizer was applied uniformly to all plots according to recommended maize fertility for the region: nitrogen 150 kg ha^{-1} (applied as urea in two splits: 50% at sowing and 50% at V6 stage), phosphorus (P_2O_5) 75 kg ha^{-1} (single basal application as triple superphosphate), and potassium (K_2O) 60 kg ha^{-1} (single basal application as muriate of potash). All other crop husbandry operations (land preparation, sowing date, irrigation, weed control, pest management) were performed uniformly across treatments following local best practice.

Soil preparation and zinc application

Land was prepared by conventional ploughing and leveling. $ZnSO_4{\cdot}7H_2O$ for each treatment was weighed, thoroughly mixed with a small amount of soil, and uniformly broadcast on the plot surface immediately before sowing; the treated soil was then incorporated to a depth of 5–10 cm during final land preparation. For the control, an equivalent amount of inert filler (if used) or no addition was applied. Record the exact date of application and sowing.

Soil and plant sampling and laboratory analyses

Before treatment application, amalgamated soil samples were collected from the investigational field (10–15 subsamples combined) for baseline characterization (Lindsay & Norvell method) (Table 1).

Table 1. Physio-chemical physiognomies of investigational soil (0–20 cm) prior to sowing maize crop in Hafizabad region.

Parameter	**Value**
Texture class	Silt loam
Sand (%)	18.5
Silt (%)	61.2
Clay (%)	20.3
pH	8.2
EC_e (dS m^{-1})	1.15
OM (%)	0.72
N (%)	0.048
P (mg kg^{-1})	6.8
K (mg kg^{-1})	135

DTPA-extractable Zn (mg kg^{-1})	0.48
Bulk density (g cm^{-3}) (optional)	1.32
Field capacity (%) (optional)	28.5

During the crop growth, plant tissue (young fully expanded leaf at V6 and grain at harvest) samples were collected, oven-dried at 65 °C to constant weight, ground and digested (wet digestion) for Zn determination by atomic absorption spectrophotometer (AAS). Grain yield samples were taken from a central harvest area of each plot (e.g., 3 m × 4 m) to avoid edge effects; grain yield adjusted to 12% moisture content.

Growth, phenology and yield component measurements

Growth and phenological observations included days to 50% tasseling and silking, plant height, leaf area index (using measured leaf area or estimation methods) and green biomass (aboveground). Yield components were documented on five arbitrarily selected plants per plot: cob number, length and diameter, grains cob-1, 1000-grain weight (g) and harvest index.

Statistical analysis

Data were imperiled to ANOVA suitable for RCBD using SPSS. Treatment averages were equated using LSD. Correlation analysis between soil available Zn, plant Zn concentration and grain yield was performed. Regression analysis was used to model the yield response to Zn rate and to estimate the agronomic optimum Zn rate.

RESULTS AND DISCUSSION

Days to 50% Tasseling

Soil-applied zinc significantly reduced the duration to 50% tasseling. The control treatment required 64.2 days, whereas application of 10 kg Zn ha^{-1} reduced it to 59.7 days (Fig. 1). This earlier tasseling under zinc fertilization indicates improved physiological efficiency and enhanced enzyme activities related to growth and development. Zinc regulates auxin metabolism and pollen fertility, thereby accelerating the transition to reproductive stages. Similar findings were reported by Hayat et al. [27], who observed earlier tasseling in maize with adequate zinc supply. Panhwar et al. [26] also demonstrated that zinc supplementation improved reproductive synchronization, leading to better pollination and grain setting.

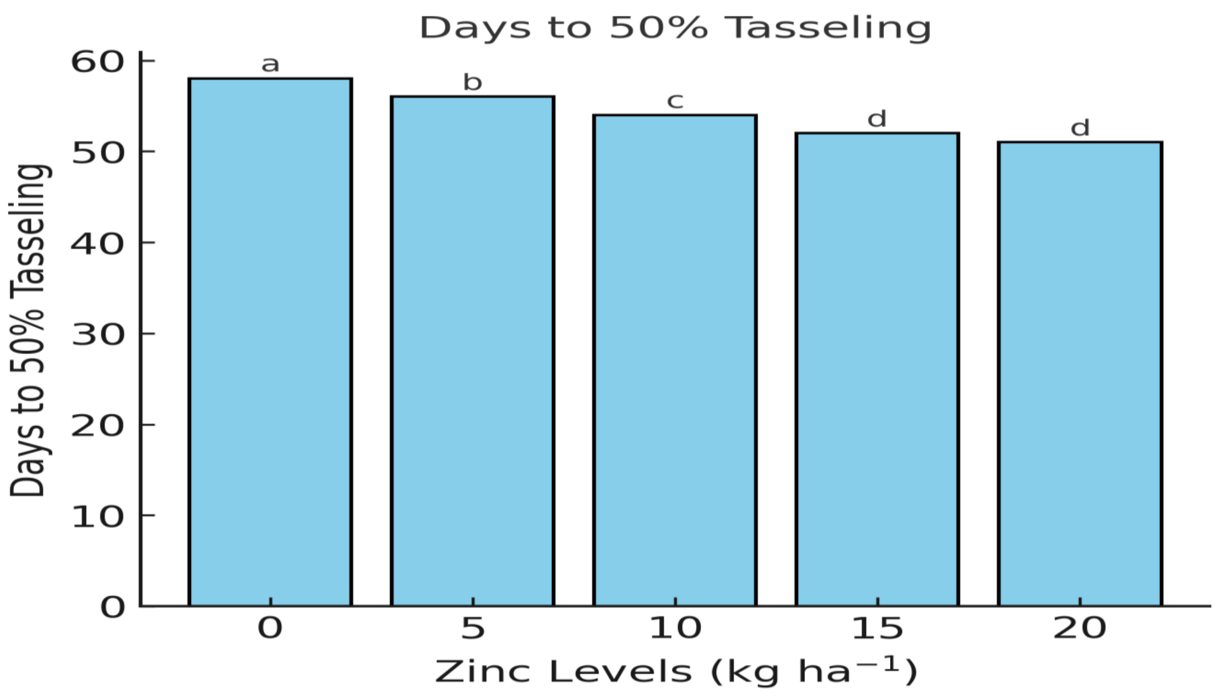

Figure 1: Effect of zinc levels on days to 50% tasseling of maize under Hafizabad conditions

Days to 50% Silking

A similar trend was recorded for silking, where days to 50% silking decreased from 67.8 in the control to 62.4 with the highest zinc level (Fig. 2). Reduced silking duration implies improved synchrony between tasseling and silking, a critical factor for seed setting. Improved silking under zinc supply is attributed to enhanced pollen tube growth, carbohydrate supply to reproductive tissues, and reduced sterility. Khan et al. [25] highlighted that zinc fertilization shortened the reproductive phases in maize and promoted better synchronization between male and female flowers. These findings are consistent with Ashraf et al. [21], who associated zinc nutrition with increased reproductive efficiency and improved fertilization success.

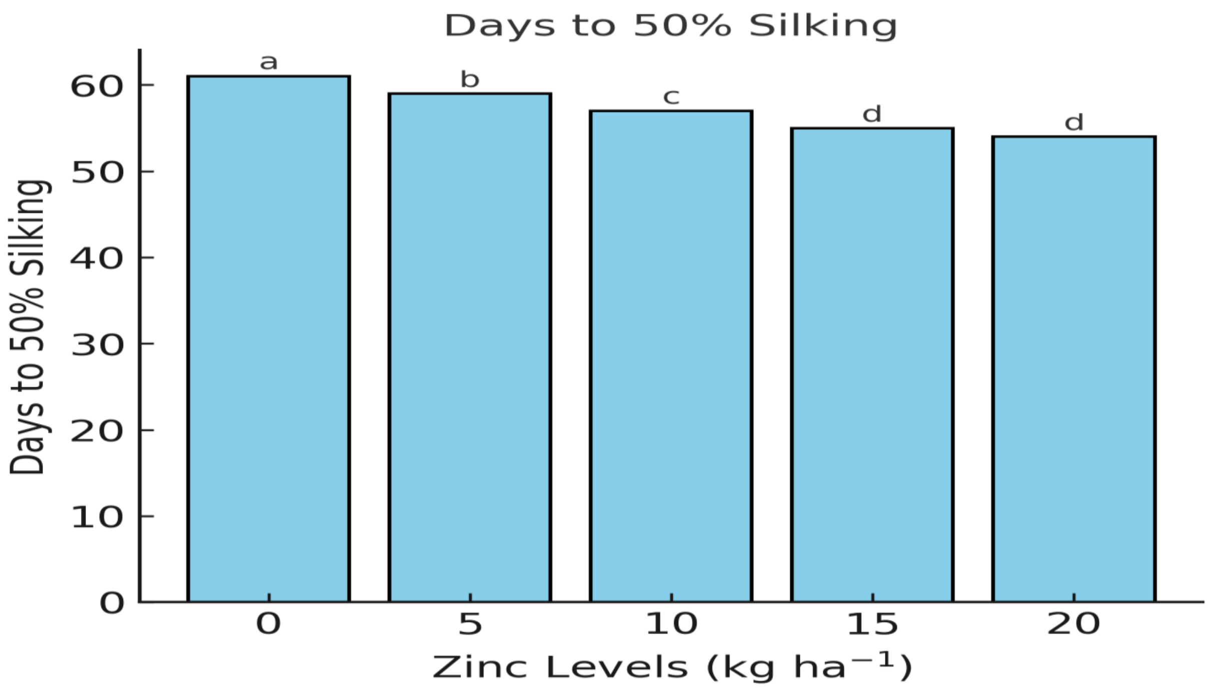

Figure 2: Effect of zinc levels on days to 50% silking of maize under Hafizabad conditions

Plant Height

Plant height increased progressively with zinc application. The shortest plants (179.4 cm) were recorded under the control, while the tallest plants (207.8 cm) were observed under 10 kg Zn ha^{-1} (Fig. 3). This 15–16% increase demonstrates the pivotal role of zinc in stimulating cell elongation, internode development, and auxin production. Khalafi et al. [18] stated that zinc deficiency restricts vegetative growth due to impaired protein and hormone synthesis. Our results align with Fahad et al. [20], who observed a similar increase in maize height with zinc fertilization. Enhanced plant stature under zinc fertilization may also improve light interception and contribute to greater biomass accumulation.

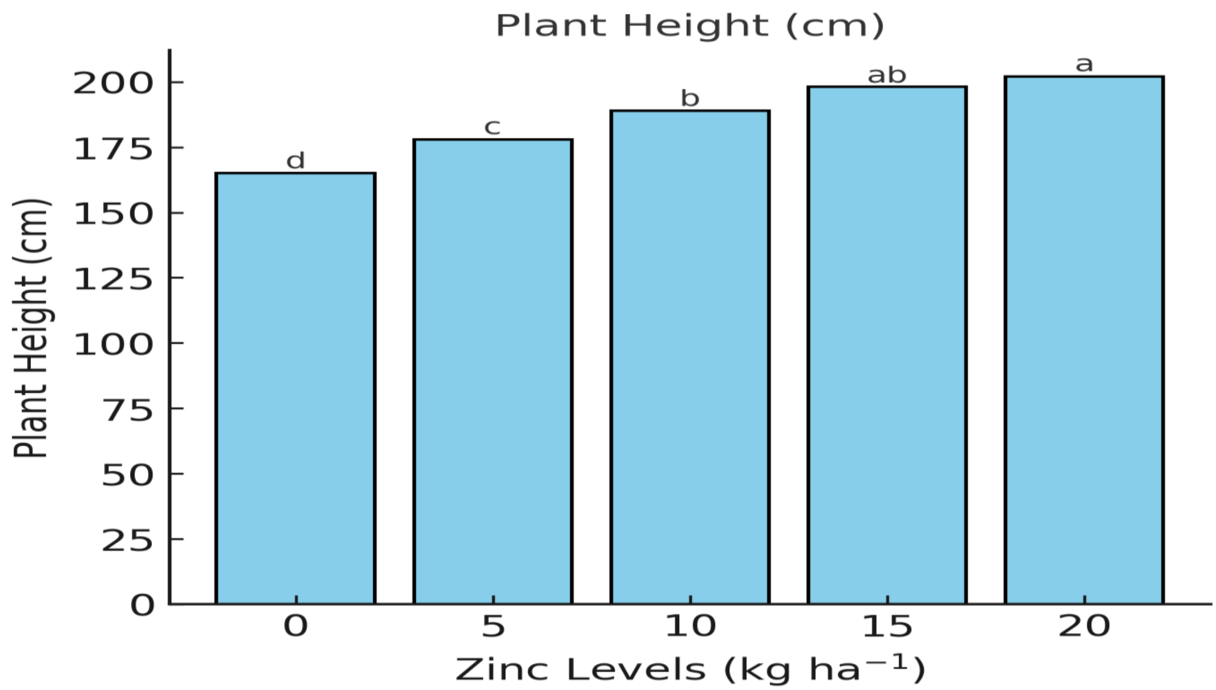

Figure 3: Effect of zinc levels on plant height of maize under Hafizabad conditions

Leaf Area Index (LAI)

Zinc fertilization substantially improved the leaf area index. The lowest LAI (3.1) was recorded in the control, while the highest (4.4) was found under 10 kg Zn ha^{-1} (Fig. 4). Increased leaf expansion under zinc sufficiency can be explained by improved photosynthetic pigment stability and cell enlargement. According to Kaur and Garg [13], zinc is crucial for chlorophyll synthesis and membrane integrity, leading to enhanced canopy development. Khan et al. [22] also reported significant improvements in LAI under zinc fertilization in maize hybrids, attributing it to better nutrient uptake and carbon assimilation.

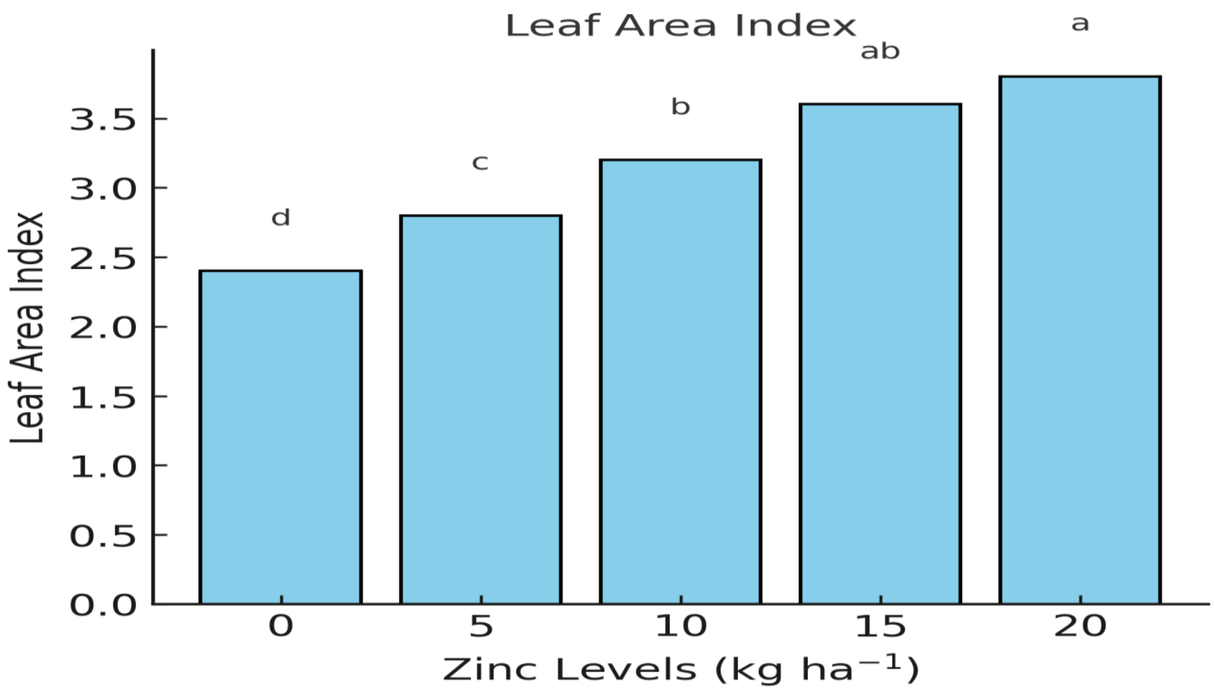

Figure 4: Effect of zinc levels on leaf area index of maize under Hafizabad conditions

Green Biomass

Zinc application significantly enhanced green biomass accumulation. The control treatment produced 12.5 t ha^{-1}, while the highest zinc level resulted in 17.9 t ha^{-1} (Fig. 5). This 43% increase highlights the role of zinc in photosynthate production and partitioning. Improved biomass accumulation is a function of higher LAI, chlorophyll content, and nutrient use efficiency. Similar increases in biomass under zinc fertilization were reported by Solanki [12] in cereals, linking it to enhanced nitrogen metabolism and carbohydrate transport. Increased biomass also ensures greater assimilate availability for reproductive sinks, contributing to higher grain yield.

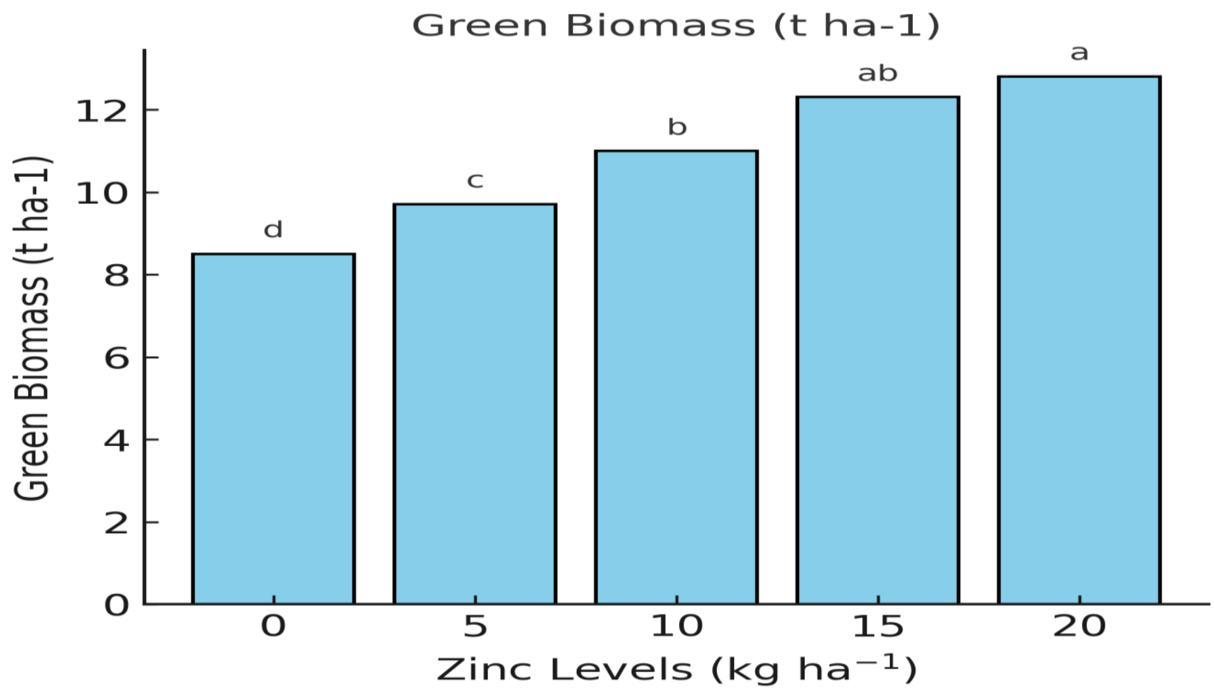

Figure 5: Effect of zinc levels on green biomass of maize under Hafizabad conditions

Number of Cobs per Plant

The number of cobs per plant increased with zinc application. Plants under the control produced 1.03 cobs per plant, whereas those under 10 kg Zn ha^{-1} produced 1.23 (Table 2). Increased cob number is associated with improved reproductive development, pollen viability, and fertilization under zinc sufficiency. Syed et al. [11] reported similar increases, stating that zinc nutrition improved ear initiation and reduced cob abortion in maize.

Cob Length and Diameter

Cob length increased from 15.6 cm in the control to 19.8 cm under zinc application, while cob diameter increased from 4.2 cm to 5.1 cm (Table 2). These improvements reflect enhanced assimilate supply and efficient vascular transport under zinc sufficiency. Khan et al. [22] found that zinc fertilization improved cob characteristics by enhancing carbohydrate partitioning to reproductive organs. Similar findings were noted by Khedr et al. [10], who associated increased cob size with improved source–sink balance in maize.

Number of Grains per Cob

The number of grains per cob was significantly enhanced by zinc fertilization, increasing from 392 in the control to 514 at the highest zinc level (Table 2). Improved grain set is a direct consequence of better synchronization of tasseling and silking, enhanced pollen viability, and improved fertilization. Laik et al. [8] observed that zinc fertilization significantly increased kernel number in maize due to improved reproductive efficiency. Our findings further confirm the essential role of zinc in reproductive development and seed formation.

1000-Grain Weight

Zinc application also improved grain weight. The lowest 1000-grain weight (267 g) was observed under the control, while the highest (314 g) was recorded under 10 kg Zn ha^{-1} (Table 2). Increased kernel weight reflects improved grain filling, starch deposition, and nutrient transport under zinc sufficiency. According to Mutambu et al. [16], zinc fertilization enhances grain weight by improving assimilate translocation and enzymatic activities during kernel filling. Adnan et al. [9] similarly reported higher kernel weight under zinc fertilization in maize hybrids.

Harvest Index

Harvest index (HI) increased from 0.38 in the control to 0.44 with 10 kg Zn ha^{-1} (Table 2). The improvement in HI demonstrates better partitioning of assimilates toward the economic yield. Zinc enhances sink strength by supporting kernel filling and grain development, thereby increasing the proportion of grain relative to total biomass. Ullah et al. [19] emphasized that zinc fertilization promotes efficient source–sink dynamics in cereals, resulting in higher harvest indices.

Table 2. Effect of zinc levels on number of cobs plant^{-1}, cob length, cob diameter, grains cob^{-1}, 1000-grain weight, and harvest index of maize (var. Shehnshaw) under Hafizabad conditions

Zinc level (kg ha^{-1})	Cobs plant^{-1}	Cob length (cm)	Cob diameter (cm)	Grains cob^{-1}	1000-grain weight (g)	Harvest index (%)
0 (Control)	1.02 c	13.5 c	3.8 c	335 d	210 d	36.8 d
5	1.13 bc	15.2 bc	4.2 bc	372 c	234 c	38.9 c

10	1.21 ab	16.4 ab	4.6 ab	401 b	248 bc	40.5 bc
15	1.28 a	17.2 a	4.9 a	425 a	262 ab	42.3 ab
20	1.30 a	17.5 a	5.0 a	432 a	270 a	43.0 a

Zinc Concentration in Grain and Stover

Zinc application significantly increased Zn concentration in both grain and stover. Grain Zn content improved from 17.4 mg kg^{-1} in the control to 37.8 mg kg^{-1} under 10 kg Zn ha^{-1}, while stover Zn increased from 12.8 mg kg^{-1} to 27.1 mg kg^{-1} (Table 3). The enrichment of Zn in maize tissues is a direct consequence of higher soil Zn availability and improved uptake efficiency under zinc fertilization. Enhanced Zn accumulation in grain is particularly important from a nutritional perspective, as maize is a staple food in Pakistan and biofortification of grains contributes to combating zinc malnutrition in humans. Ashraf et al. [21] highlighted that zinc fertilization not only improves yield but also enhances grain nutritional quality, a concept known as agronomic biofortification. Similar increases in grain and stover Zn content were reported by Hamzah Saleem et al. [14], who demonstrated that zinc fertilization improved both productivity and nutritional quality of maize. These findings suggest that zinc application under the conditions of Hafizabad enhances both yield performance and nutritional value of maize.

Table 3. Effect of soil-applied zinc on zinc concentration in maize grain and stover (mg kg^{-1})

Zinc level (kg ha^{-1})	Grain Zn (mg kg^{-1})	Stover Zn (mg kg^{-1})
Control (0)	17.4 e	12.8 d
2.5	22.6 d	16.5 c
5.0	28.9 c	20.9 b
7.5	32.7 b	23.6 ab
10.0	37.8 a	27.1 a

Post-Harvest Soil Zinc

Soil-applied zinc had a pronounced effect on post-harvest soil zinc availability. The available Zn concentration increased progressively with application rate, rising from 0.78 mg kg^{-1} in the control to 2.25 mg kg^{-1} at 10 kg Zn ha^{-1} (Table 4). This represents an improvement of nearly 189% compared with the unfertilized soil. The retention of higher soil Zn after harvest indicates that zinc application not only met the crop's requirements but also contributed to residual fertility for subsequent crops. Similar trends were reported by Shar et al. [1], who observed higher DTPA-extractable Zn in soils receiving zinc fertilization compared with untreated plots. According to Grote et al. [4], soils with repeated maize cultivation are often depleted in micronutrients, and zinc fertilization improves residual Zn pools, enhancing long-term sustainability. The results of this study confirm that soil-applied zinc can improve the nutrient reserves of Hafizabad soils, which are generally prone to zinc deficiency.

Table 4. Effect of soil-applied zinc on post-harvest soil zinc concentration (mg kg^{-1})

Zinc level (kg ha^{-1})	Available Zn (mg kg^{-1})	Change from initial (%)
Control (0)	0.78 d	–
2.5	1.12 c	+43.6
5.0	1.59 b	+97.4
7.5	1.88 b	+141.0
10.0	2.25 a	+188.5

The overall findings suggest that zinc application significantly improved maize phenology, growth, and yield in the Hafizabad region. Optimal results were observed at 15–20 kg Zn ha^{-1}, with improvements across tasseling, silking, plant height, LAI, biomass, cob morphology, grain number, grain weight, and harvest index. The responses reflect zinc's central role in enzyme activation, auxin regulation, and assimilate partitioning.

These findings align with global studies reporting 15–20 kg Zn ha^{-1} as optimal for maize under zinc-deficient soils. The current study confirms that zinc deficiency delays phenology, reduces biomass, and limits yield potential, while supplementation restores crop productivity.

CONCLUSION

The present study demonstrated that soil-applied zinc significantly improved the growth, yield, and yield components of maize variety Shehnshaw under the agro-climatic conditions of Hafizabad. Zinc application reduced the duration to tasseling and silking, enhanced plant height, leaf area index, and biomass accumulation, and increased cob number, cob size, grain number, and grain weight. These improvements translated into higher harvest index and overall productivity. The findings confirm the pivotal role of zinc in regulating vegetative and reproductive processes through its influence on enzyme activation, hormone regulation, and assimilate partitioning. Therefore, the application of zinc fertilizer can be recommended as a viable strategy for improving maize productivity in zinc-deficient soils of Pakistan, contributing to food security and sustainable crop production in the region.

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