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Research Article

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Enhancing rice yield and grain zinc concentration through strategic zinc application

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ABSTRACT

Rice is a staple food globally, yet its grain zinc concentration is inherently low, contributing to widespread zinc deficiency. This study evaluated the effects of zinc application methods control, seed coating (2 g Zn kg^{-1} seed), soil application (10 kg Zn ha^{-1}) and foliar spray (0.5% $ZnSO_4$) under two rice production systems: direct-seeded and transplanted. The experiment was conducted at the University of Agriculture, Faisalabad, during summer 2023 in a randomized complete block design with three replications. Foliar zinc application in transplanted rice produced the tallest plants (97.04 cm), highest productive tillers (367.67 m^{-2}), longest panicles (27.18 cm) and maximum grain yield (4.75 t ha^{-1}). Grain zinc concentration increased from 14.87 mg kg^{-1} in control to 30.24 mg kg^{-1} under foliar zinc, showing a 103% rise. Overall, foliar zinc application was most effective for enhancing both yield and nutritional quality of rice.

Keywords: Rice, zinc application, foliar spray, seed coating, soil application and grain zinc.

INTRODUCTION

Rice (*Oryza sativa* L.) is the staple food for more than half of the world's population and plays a pivotal role in global food security. As a primary energy source for billions, rice contributes significantly to daily caloric intake especially in Asia, Africa and Latin America. However, while rice provides calories, it remains inherently low in micronutrients especially zinc (Zn) which is crucial for human health (Junaid et al., 2022). Zinc deficiency in rice-consuming populations is a major nutritional challenge, particularly in developing countries, where rice often forms the bulk of the diet. From an agronomic standpoint, improving the yield and nutritional quality of rice especially grain zinc concentration has become an important goal in sustainable agriculture and public health policy (Baghaie et al., 2025).

Zinc is not only vital for human nutrition but also plays an essential role in plant physiological and biochemical processes. It is involved in key functions such as enzyme activation, protein synthesis, auxin metabolism, membrane integrity and stress resistance (Amin et al., 2023). In rice, adequate zinc availability enhances root development, chlorophyll synthesis, photosynthetic activity and grain filling all of which contribute to improved biomass accumulation and grain yield (Khongchiu et al., 2025). Zinc deficiency in soil, however, is widespread in rice-growing areas especially in submerged, high pH, calcareous and saline soils where its availability to plants is significantly reduced due to adsorption and precipitation reactions (Shen et al., 2023). Irrigation water quality can further influence soil zinc dynamics and its uptake in rice, thereby affecting yield and grain nutritional quality (Sajjad et al., 2025a; Shakeel et al., 2021). This results in stunted growth, chlorosis, reduced tillering and ultimately poor yield and nutritional quality. To address these limitations, researchers have increasingly advocated for zinc fertilization as a practical agronomic approach aimed at enhancing both the nutritional quality and yield of rice crops (Akter et al., 2024). To increase zinc availability and absorption, agronomic techniques

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including seed coating, foliar spraying and soil treatment have been investigated.

Zinc foliar treatment increases grain zinc concentration directly, especially during the booting or grain-filling stage (Ijaz et al., 2023a; Chattha et al., 2023). This method enables a quick and effective solution to zinc deficiency when it is important for plant growth. Zinc application to soil will adjust the zinc availability in the rhizosphere to aid in early root and vegetative growth. It is effective in terms of supplying Zn in the long-term, however soil moisture and pH can influence effectiveness (Patel et al., 2022). Zinc seed coating is an easy and effective method to supplying Zn and provides early development of rice and nutrient absorption. Once again, applying zinc seed coating enables the seedling vigor needed for stand establishment by improving zinc availability when needed during germination. This treatment is economical and therefore appropriate for both transplanted and direct-seeded systems. Further research is needed to understand the effectiveness of applying treatments compared to other zinc applications (Donia and Carbone, 2023). An agronomically optimal zinc application methodology enhances zinc density in the edible portion of the grain while enhancing crop performance within the bounds of soil and environment. A new study indicates that there are various interactions between rice, zinc and production systems, methods of application and genotype. Soil application enhances development, foliar application improves grain zinc and seed coating is associated with enhanced early vigour. Ultimately, an integrated assessment is needed to optimise yield and nutritional quality (Rehman et al., 2025; Kandil et al., 2022).

Soil physical characteristics, root systems and nutrient availability are influenced by rice crop management methods such as transplanting and sowing (Negi et al., 2024). Transplanted rice is typically rated more positively than direct-seeded rice because when grown under controlled puddled and anaerobic conditions, the rice crop can typically establish better and be able to penetrate deeper into the soil, thereby improving nutrient uptake (Panda et al., 2021). This will then impact rice production and grain zinc concentration where transplanting is implemented with used strategic zinc application with good soil conditions and nutrient uptake (Ahmed et al., 2023 and Sajjad et al., 2025b). On the other hand, direct-seeded rice requires less water and inputs and has a shallower rooting depth and irregular germination with highly variable zinc distribution in aerobic soils that can limit zinc uptake (Chaudhary et al., 2023). Many times, these practices do not maximize production and grain quality for achieving zinc fertilization target (Zahra et al., 2022).

Direct-seeded and transplanted rice systems differ markedly in soil-water conditions, root development and nutrient dynamics which can influence zinc availability and uptake. Transplanted rice, grown under puddled and anaerobic conditions, generally favors zinc solubility and uptake, whereas direct-seeded rice faces greater zinc deficiency due to aerobic soil environments and reduced root–soil contact. Therefore, comparing zinc application methods across these systems is essential to identify the most effective strategy for improving both yield and grain zinc concentration under diverse production environments. Although zinc improves rice output and nutritional quality, it is yet unknown how best to apply it in different production methods. The development of tailored nutrition strategies is hampered by the lack of comprehensive data on grain Zn concentration and yield. It is hypothesized that zinc application methods significantly affect rice yield and grain Zn levels, with foliar sprays enhancing Zn content and soil applications improving overall growth. These effects may vary across production systems due to differences in soil-water dynamics and nutrient availability. This study aims to identify the most effective zinc application method across rice production systems to enhance both yield and grain zinc content.

MATERIALS AND METHODS

Experimental Site and Details

The field trial was conducted during the summer season of 2023 at the Agronomic Research Area, University of Agriculture, Faisalabad (UAF), Pakistan, located at 31.260°N latitude, 73.090°E longitude and an elevation of 135 meters above sea level. The region experiences a semi-arid climate favorable for rice cultivation. Prior to sowing, composite soil samples were collected from depths of 15 cm and 30 cm using a soil auger. These samples were analyzed in the Environmental Science Laboratory, Institute of Soil and Environmental Sciences, UAF, to determine key physico-chemical properties. Soil analysis mentioned in Table 1. The meteorological data for the crop growing period was collected from the Agro-meteorology Cell, Department of Agronomy, University of Agriculture, Faisalabad and is presented in Figure 1.

Table 1. Soil attributes of experimental site

Parameters	Depths		Status
	0-15 (cm)	15-30 (cm)	
pH	7.9	8	Alkaline
EC (dSm^{-1})	1.09	1.1	Saline
Saturation (%)	36	34	
P_2O_5 (ppm)	22.9	17.5	High
K_2O	186	174	Medium
Organic Matter	1.75	1.61	Medium
Sand (%)	20	19	
Silt (%)	17	16	
Clay (%)	63	65	

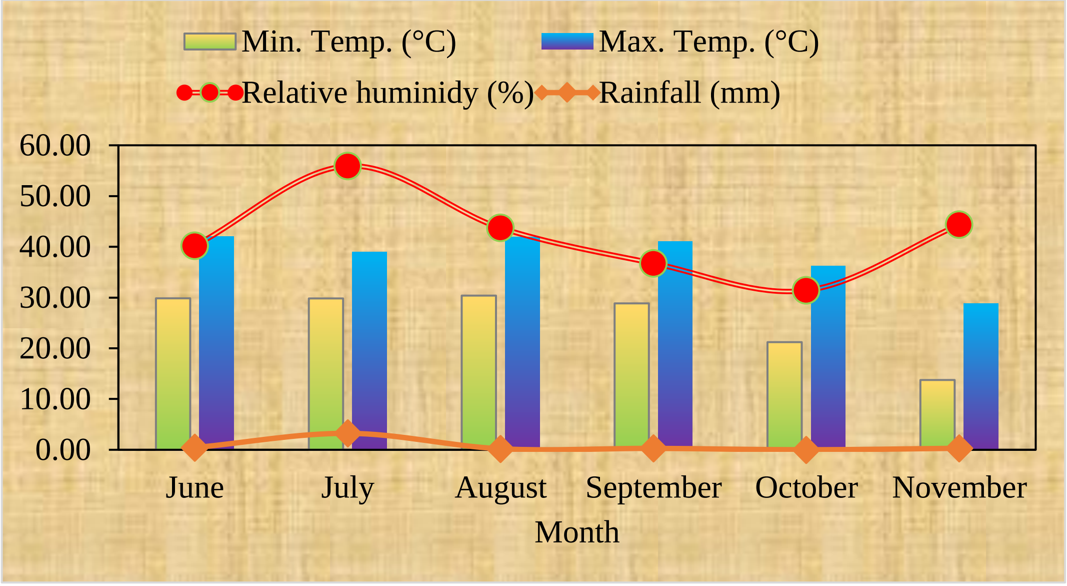

Figure 1. Weather prevailed during crop season.

Crop Husbandry and Treatments

The field, previously under wheat, was prepared with 2-3 cultivations and planking, followed by irrigation and puddling to ensure suitable tilth. For the transplanted system, a wet-bed nursery of the rice variety Chenab Basmati was raised by broadcasting pre-germinated seeds at 1 kg per marla. Regular watering and weed control ensured healthy seedling establishment. One-month-old seedlings were transplanted at 9-inch spacing with two seedlings per hill. Direct seeded plots were sown simultaneously. Water was managed through continuous flooding with 7 cm standing water, discontinued a week before harvest. A basal dose of P and K was applied at transplanting, while nitrogen was split into three applications: before transplanting, at tillering and panicle initiation. Zinc sulphate was used as a source of Zn. The zinc source was zinc sulphate heptahydrate ($ZnSO_4 \cdot 7H_2O$), equivalent to 0.5% (≈18.4 mM) $ZnSO_4$ solution for foliar application. Zinc was applied according to treatments. The crop was manually harvested on November 5, 2023 and each plot was threshed separately. Uniform agronomic practices were adopted across all treatments to ensure consistent management and valid comparisons. The same nitrogen, phosphorus and potassium fertilizer rates were applied in both production systems to maintain uniform nutrient supply and ensure that yield differences were solely due to zinc treatments and production methods. The gross size of plot was 5 m×1.8 m. The direct seeded rice and transplanted rice methods were used for sowing. Direct seeded rice was sown by hand drill. While, in transplanted rice 30 days old seedlings was transplanted. Direct seeded crop was sown on 10 June, 2023. While, puddled rice nursery was transplanted on 20 July, 2023. Chenab basmati 2016 was the test crop with seed rate 25 kg ha^{-1} for direct seeded rice and 12kg ha^{-1} for puddled transplanted rice. The experiment was arranged in a randomized complete block design (RCBD) following factorial arrangement with three replications with two factors: production systems and zinc application methods. Factor A included two rice production systems P1: direct-seeded rice and P2: transplanted rice. Factor B consisted of four zinc application methods. These included Zn1: Control (no zinc), Zn2: Seed coating (2 g Zn kg^{-1} seed), Zn3: Soil application (10 kg Zn ha^{-1}), Zn4: Foliar application (0.5% $ZnSO_4$ as a foliar spray solution). Foliar zinc was applied twice at tillering and panicle initiation to ensure adequate zinc during critical growth stages. Zinc concentrations were measured at regular intervals throughout the growth period. For each treatment, samples were collected from three randomly selected plants per plot, and measurements were replicated three times to ensure accuracy and reliability of the data.

Biochemical Analysis

For determination of zinc, wet digestion technique by means of HNO_3-$HCLO_4$ was used as termed by Miller in 2007. Grains were separated, washed with distilled water and dried in oven at temperature of 70^0C till persistent weight and converted to fine powder by means of grinding mill. One gram (1 g) of oven desiccated grain powder was conveyed to digestion flask of volume 100 mL for digestion and 10 mL of bi-acid fusion (HNO_3-$HCLO_4$) with 2:1 proportion was mixed and permitted to stay one night. This digest was permitted to slow warming at 150^0C and after that temperature in block digester is increased to 235^0C to sustain digestion for 30 min subsequently after visibility of dense silvery hazes of acid. After cooling the digestion ducts for some minutes and purified water was added to make preferred volume. Every sample collection was digested deprived of any plant material. Samples were scrutinized for Zn contents after digestion on Atomic Absorption Spectrophotometer (Model Thermo S- Series). The digested samples were filtered and diluted to a final volume of 50 mL with deionized water before analysis. Zinc concentration was determined at a wavelength of 213.9 nm using an Atomic Absorption Spectrophotometer (Thermo S-Series), following standard calibration with certified Zn standards.

$$\text{Zinc (mg/kg)} = \frac{\text{Zinc(from calibration curve)} \times A}{\text{weight}}$$

A= Entire volume of extract (mL)

W= Weight of dehydrated plant (g)

Statistical Analysis

Data was examined using Fisher's Analysis of Variance (ANOVA) technique and the treatment's means was analyzed using Tukey's HSD test at 5% significance level by software statistix 8.1 (Steel *et al.*, 1997).

RESULTS

The data related to plant height is presented in (Figure 2a). To enhance clarity and reduce lengthy descriptions, key results for major agronomic and zinc-related traits have been summarized in tables, highlighting significant differences among treatments. The tallest plants (97.040 cm) were obtained in transplanted rice with foliar application of zinc (P2Zn4), followed by direct-seeded rice with foliar application (P1Zn4) at 94.250 cm and transplanted rice with soil-applied zinc (P2Zn3) at 92.340 cm. Direct-seeded rice with soil application (P1Zn3) produced 88.757 cm, while transplanted rice with seed coating (P2Zn2) and direct-seeded rice with seed coating (P1Zn2) recorded 89.450 cm and 85.443 cm, respectively. Under control conditions, transplanted rice (P2Zn1) reached 85.667 cm, whereas direct-seeded rice without zinc (P1Zn1) had the shortest plants at 82.667 cm. The highest number of productive tillers (367.67) was recorded in transplanted rice with foliar zinc application (P2Zn4) followed by direct-seeded rice with foliar zinc (P1Zn4) at 354.32 and transplanted rice with soil-applied zinc (P2Zn3) at 351.12. Transplanted rice with seed coating (P2Zn2) produced 346.23 tillers, while direct-seeded rice with soil application (P1Zn3) and seed coating (P1Zn2) recorded 340.32 and 337.43 tillers, respectively. Under control conditions, transplanted rice (P2Zn1) reached 332.13 tillers, whereas direct-seeded rice without zinc (P1Zn1) had the lowest number of productive tillers at 320.34. Relevant data are illustrated in (Figure 2b). All eight treatment combinations were significantly different from one another. The information concerning non-productive tillers can be found in (Figure 2c). The highest number of non-productive tillers (28.760) was observed in direct-seeded rice without zinc application (P1Zn1), followed by transplanted rice without zinc (P2Zn1) at 24.320. Direct-seeded rice with seed coating (P1Zn2) recorded 21.230 tillers, while direct-seeded rice with soil-applied zinc (P1Zn3) had 18.760 tillers. In transplanted rice, seed coating (P2Zn2) resulted in 17.430 tillers, whereas soil application (P2Zn3) produced 13.447 tillers. The lowest values were found under foliar application, with direct-seeded rice (P1Zn4) at 11.210 tillers and transplanted rice (P2Zn4) at only 8.720 tillers. Data supporting total no. of tillers are shown in (Figure 2d). The highest total tiller number (376.39) was recorded in transplanted rice with foliar zinc application (P2Zn4), followed by direct-seeded rice with foliar zinc (P1Zn4) at 365.53. Transplanted rice with soil-applied zinc (P2Zn3) produced 364.57 tillers, which was statistically similar to transplanted rice with seed coating (P2Zn2) at 363.66. In direct-seeded rice, soil application (P1Zn3) and seed coating (P1Zn2) resulted in 359.08 and 358.66 tillers, respectively, with no significant difference between them. Transplanted rice without zinc (P2Zn1) recorded 356.45 tillers, while the lowest total tiller number (349.10) was observed in direct-seeded rice without zinc application (P1Zn1). The longest panicle length (27.18 cm) was obtained from transplanted rice with foliar zinc application (P2Zn4), followed by direct-seeded rice with foliar zinc (P1Zn4) at 25.45 cm. Transplanted rice with soil-applied zinc (P2Zn3) recorded 24.77 cm, while both transplanted rice with seed coating (P2Zn2) and direct-seeded rice with soil application (P1Zn3) produced similar panicle lengths of 22.34 cm and 22.31 cm, respectively. Direct-seeded rice with seed coating (P1Zn2) had 21.13 cm, and transplanted rice without zinc (P2Zn1) recorded 19.87 cm. The shortest panicle length (18.54 cm) was observed in direct-seeded rice without zinc application (P1Zn1). This is demonstrated by the data presented in (Figure 2e). The interaction of production system and zinc method consistently affected branches per panicle. Across all zinc treatments, transplanted rice (P2) generally outperformed direct seeded rice (P1). The highest NBPP was recorded in P2 with foliar zinc application (Zn4), achieving 11.097, followed closely by P1 with Zn4 at 10.500. Soil-applied zinc (Zn3) also yielded strong results, with P2 Zn3 at 10.200 and P1 Zn3 at 9.600. Seed coating (Zn2) produced intermediate NBPP values, ranging from 9.800 in P2 to 9.100 in P1. The lowest values were observed under the control treatment (Zn1), where P2 recorded 8.900 and P1 recorded only 8.200. The corresponding data are depicted in (Figure 2f). Rice system and zinc method significantly affected no. grains per panicle. Transplanted rice (P2) consistently produced more grains than direct-seeded rice (P1) across all zinc treatments. The maximum NGPP was observed in P2 with foliar zinc application (Zn4), reaching 129.32, followed by P1Zn4 at 123.51. Soil-applied zinc (Zn3) also resulted in high grain numbers, with P2Zn3 at 121.34 and P1Zn3 at 111.54. Seed coating (Zn2) produced moderate NGPP values, recording 116.83 in P2 and 106.48 in P1. The lowest grain counts occurred in the control treatment (Zn1), where P2 recorded 101.36 and P1 just 93.38. This pattern demonstrates that the advantage of P2 over P1 was maintained under all zinc regimes, with the foliar method providing the most pronounced improvement. The associated data are provided in (Figure 3g). Rice system–zinc method interaction significantly affected thousand-grain weight. Transplanted rice (P2) consistently produced heavier grains than direct seeded rice (P1) under every zinc treatment. The highest 1000 grain weight was recorded in P2 with foliar zinc application (Zn4) at 26.49 g, followed by P1Zn4 at 24.75 g. Soil-applied zinc (Zn3) resulted in 22.34 g for P2 and 21.01 g for P1, while seed coating (Zn2) produced 21.12 g in P2 and 19.23 g in P1. The lowest values were observed in the control (Zn1), with P2 at 16.56 g and P1 at 14.32 g. For details, refer to the data shown in (Figure 3h). The graphical representation of grain yield is given in (Figure 3i). Grain yield (GY) was markedly influenced by the combined effects of production system and zinc application, with every treatment combination showing significant differences. The highest yield was obtained in transplanted rice (P2) with foliar zinc application (Zn4) at 4.75 t ha^{-1}, followed by direct seeded rice (P1) with Zn4 at 4.61 t ha^{-1}. For soil-applied zinc (Zn3), P2 yielded 4.51 t ha^{-1} and P1 4.40 t ha^{-1}, while seed coating (Zn2) resulted in 4.45 t ha^{-1} for P2 and 4.34 t ha^{-1} for P1. The lowest yields were in the control (Zn1), with P2 at 4.11 t ha^{-1} and P1 at 4.01 t ha^{-1}. These results clearly demonstrate that foliar zinc application, especially in the direct-seeded system, produced the most substantial improvement in grain yield. Straw yield (SY) showed a highly significant response to the combined effects of production system and zinc application, with all treatment combinations differing from one another. The greatest yield was recorded for direct-seeded rice (P2) with foliar zinc application (Zn4) at 9.30 t ha^{-1}, followed closely by transplanted rice (P1) with Zn4 at 9.21 t ha^{-1}. In the case of soil-applied zinc (Zn3), P2 produced 9.02 t ha^{-1} and P1 yielded 8.71 t ha^{-1}. For seed coating (Zn2), yields were 8.87 t ha^{-1} in P2 and 8.64 t ha^{-1} in P1. The lowest values occurred in the control (Zn1), with P2 yielding 8.24 t ha^{-1} and P1 yielding 8.00 t ha^{-1}. These results indicate that foliar zinc application consistently maximized straw yield, with direct-seeded rice showing a slight advantage over transplanted rice. Data illustrating this point are included in (Figure 3j). Biological yield (BY) was significantly influenced by the interaction between production system and zinc application, with all combinations differing from each other. The highest yield was achieved in transplanted rice (P2) with foliar zinc application (Zn4) at 14.05 t ha^{-1}, followed by direct seeded rice (P1) with Zn4 at 13.82 t ha^{-1}. For soil-applied zinc (Zn3), P2 yielded 13.53 t ha^{-1} while P1 produced 13.11 t ha^{-1}. In the seed coating treatment (Zn2), yields were 13.32 t ha^{-1} for P2 and 12.98 t ha^{-1} for P1. The lowest values occurred under the control treatment (Zn1), where P2 produced 12.35 t ha^{-1} and P1 yielded 12.01 t ha^{-1}. Overall, foliar zinc application consistently maximized biological yield, and direct-seeded rice showed a slight but consistent advantage over transplanted rice across all zinc treatments. This is supported by the data illustrated in (Figure 4k). The interaction between rice production systems and zinc application methods showed notable variations in harvest index (HI). The highest HI (33.808) was recorded in transplanted rice with foliar zinc application (P2Zn4), closely followed by direct-seeded rice with soil-applied zinc (P1Zn3) at 33.571. Slightly lower values were observed for direct-seeded rice with seed coating (P1Zn2, 33.436) and transplanted rice with seed coating (P2Zn2, 33.408). The lowest HI was found in transplanted rice without zinc application (P2Zn1, 33.297) and direct-seeded rice without zinc (P1Zn1, 33.389). (Figure 4l) summarizes the data relevant to this. The interaction between production systems and zinc application strategies significantly influenced grain zinc content in rice, with all treatment combinations showing statistically significant differences. The highest grain zinc concentration was observed in P2Zn4 recording 30.24 mg kg^{-1}, followed closely by P1Zn4 at 29.09 mg kg^{-1}. These were followed by P2Zn3 (27.31 mg kg^{-1}) and P2Zn2 (26.68 mg kg^{-1}). In direct seeded rice, intermediate zinc applications resulted in 26.03 mg kg^{-1} for P1Zn3 and 23.70 mg kg^{-1} for P1Zn2. The lowest grain zinc contents were found in control treatments without zinc application, with P2Zn1 at 18.11 mg kg^{-1} and P1Zn1 at 14.87 mg kg^{-1}. Overall, higher zinc application levels, especially Zn4, substantially enhanced grain zinc concentration and transplanted rice tended to produce higher grain zinc content than direct seeded rice under equivalent zinc levels. The data underlying this statement are presented in (Figure 4m). The information concerning this showed in (Figure 4n). The highest straw zinc concentration was recorded in P2Zn4 which reached 32.14 mg kg^{-1}, followed by P1Zn4 at 30.46 mg kg^{-1}. These were closely followed by P2Zn3 (29.32 mg kg^{-1}) and P2Zn2 (28.10 mg kg^{-1}). Intermediate zinc levels resulted in straw zinc contents of 27.43 mg kg^{-1} for P1Zn3 and 25.17 mg kg^{-1} for P1Zn2. The lowest straw zinc concentrations were observed in the control treatments without zinc application, with P2Zn1 at 17.54 mg kg^{-1} and P1Zn1 at 15.28 mg kg^{-1}.

CORRELATION

The correlation matrix depicts the relationships among various recorded parameters including plant height (PH), productive tillers (PT), non-productive tillers (NPT), total tillers (TT), panicle length (PL), no. of branches per panicle (NBPP), no. of grains per panicle (NGPP), 1000-grain weight (1000 GW), grain yield (GY), straw yield (SY), harvest index (HI), biological yield (BY), grain zinc (Grain Zn) and straw zinc (Straw Zn). Strong positive correlations are evident among most yield attributes with parameters like tillers, panicle length, grains per panicle and 1000-grain weight showing close associations with grain and biological yield. Grain Zn concentration also exhibits significant positive relationships with yield parameters and straw Zn concentration, suggesting that improved plant growth and yield traits are linked with enhanced zinc accumulation in both grain and straw. The green shading intensity and elliptical patterns indicate the strength of these associations, while the statistical significance markers confirm that many correlations are highly reliable (Figure 5).

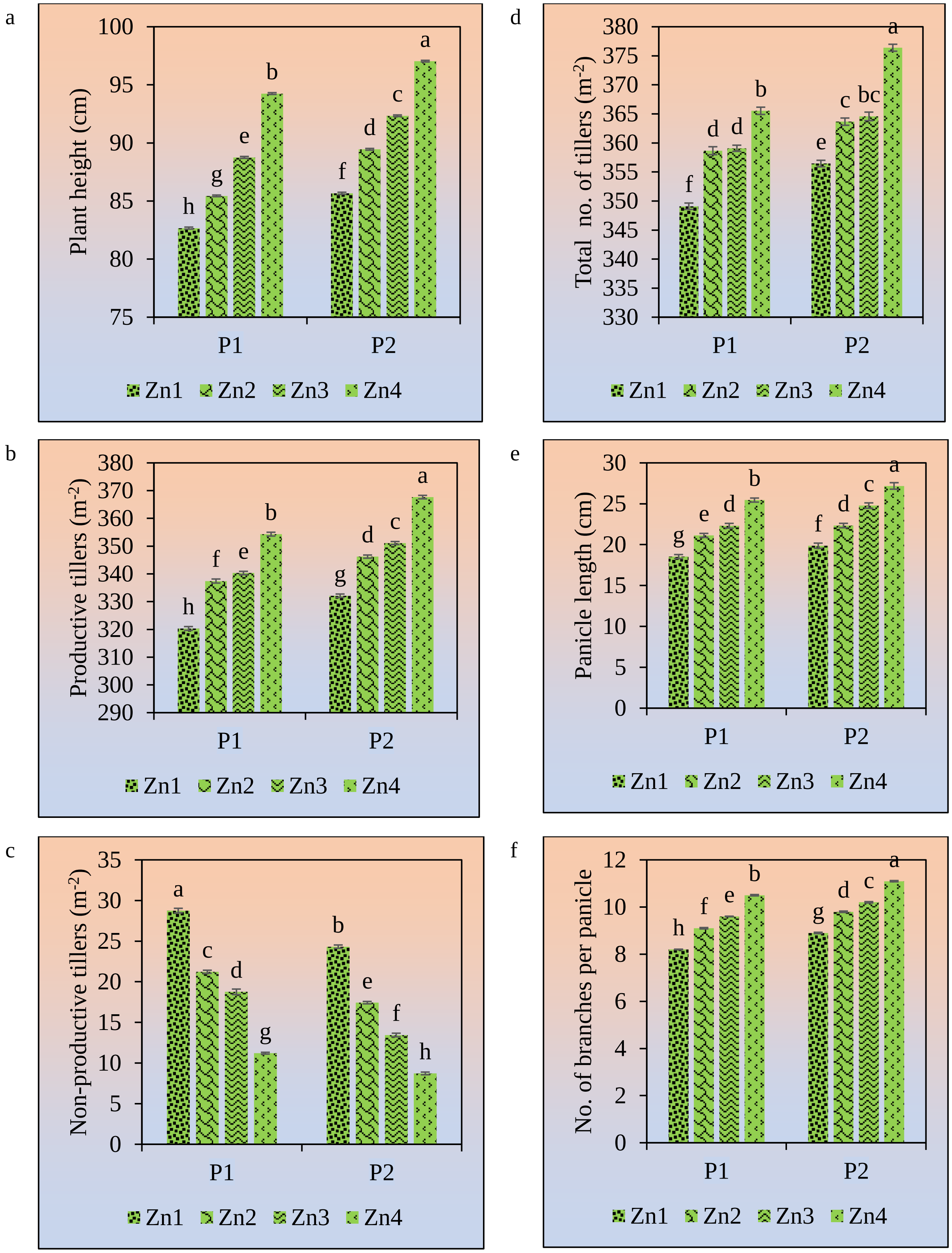

Figure 2. Impact of zinc application on (a) plant height, (b) productive tillers, (c) non-productive tillers, (d) total no. of tillers, (e) panicle length, (f) no. of branches per panicle under production systems of rice

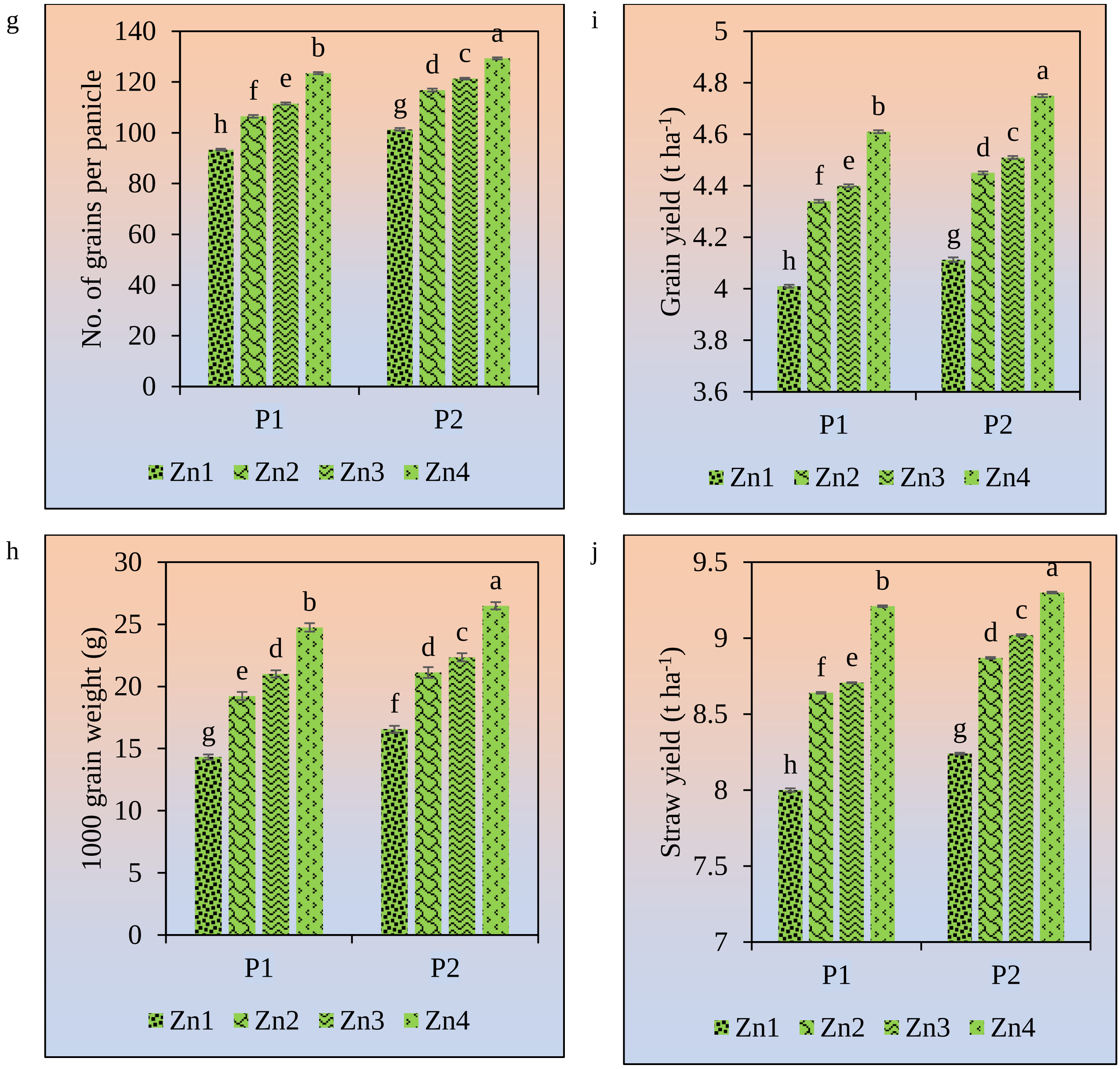

Figure 3. Impact of zinc application on (a) no. of grains per panicle, (b) 1000 grain weight, (c) grain yield, (d) straw yield under production systems of rice

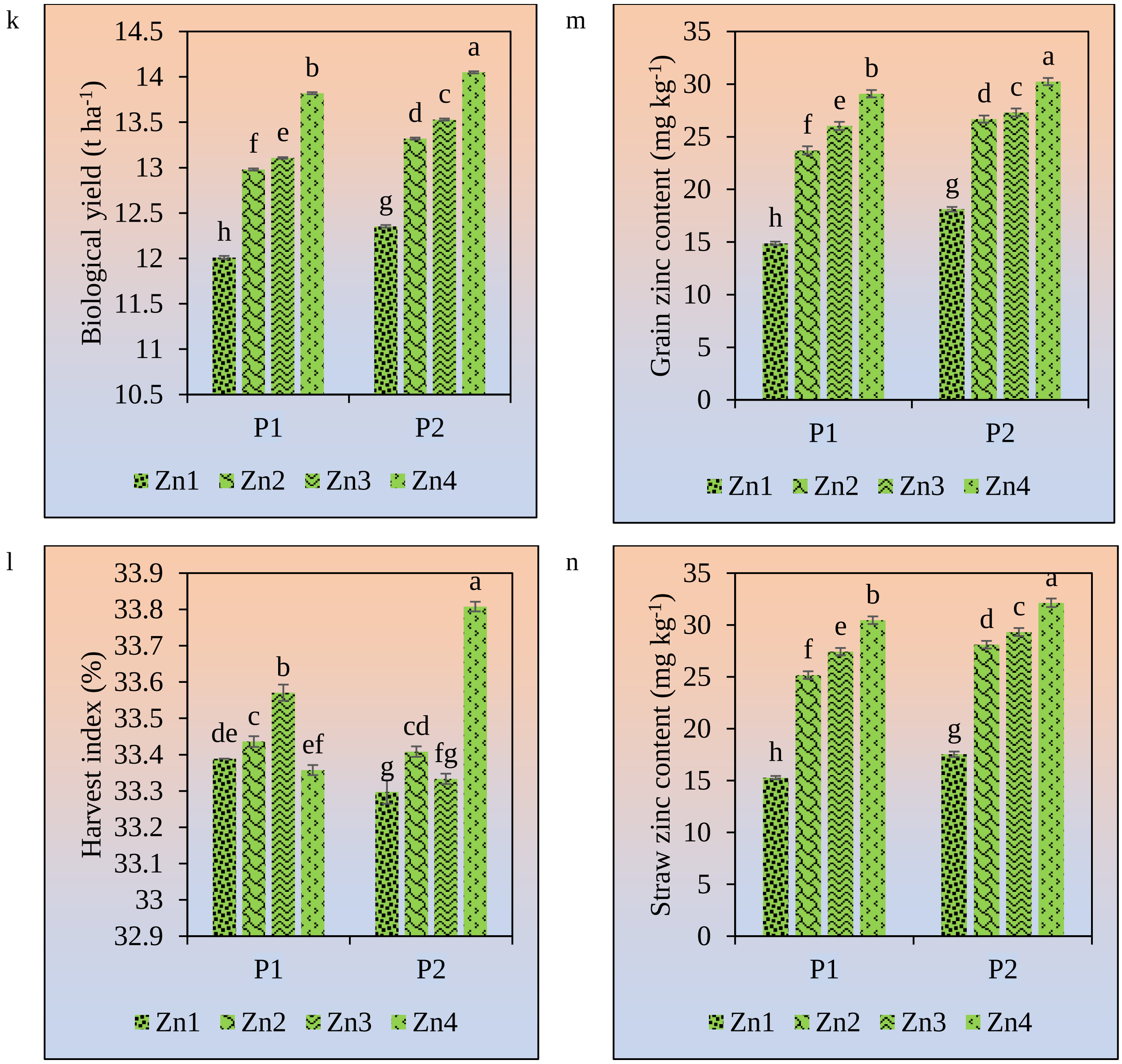

Figure 4. Impact of zinc application on (a) biological yield, (b) harvest index, (c) grain zinc content, (d) straw zinc content under production systems of rice

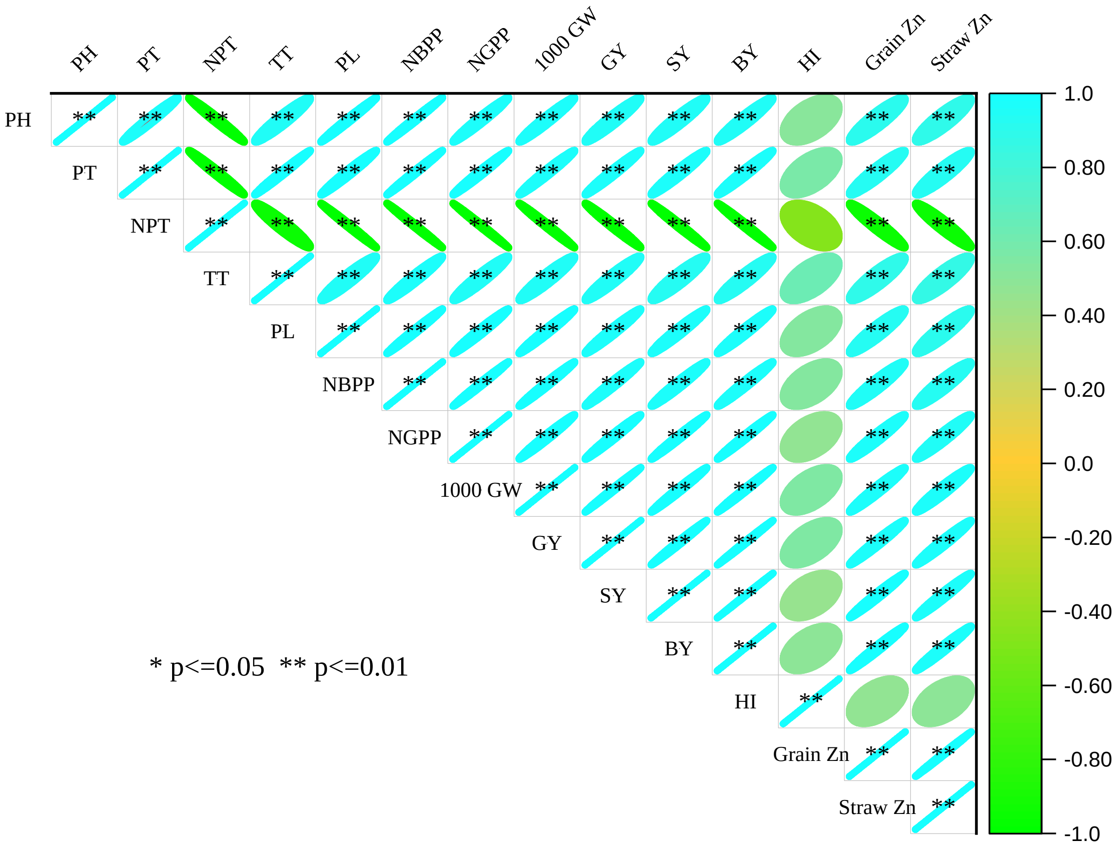

Figure 5. Correlation matrix showing the relationships between yield and zinc concentration parameters in rice including plant height (PH), productive tillers (PT), non-productive tillers (NPT), total tillers (TT), panicle length (PL), no. of branches per panicle (NBPP), no. of grains per panicle (NGPP), 1000-grain weight (1000 GW), grain yield (GY), straw yield (SY), harvest index (HI), biological yield (BY), grain zinc (Grain Zn) and straw zinc (Straw Zn). Color intensity and ellipse shape indicate the strength and direction of correlations with significance levels

DISCUSSION

Zinc is an essential nutrient that supports plant growth, development, and yield. Foliar zinc application bypasses soil limitations such as fixation or unavailability in flooded or alkaline soils, allowing rapid absorption and translocation to growing shoots. Increased plant height and improved root development enhance photosynthesis and yield (Khan et al., 2022). Zinc acts as a cofactor in carbohydrate metabolism and stimulates cytokinin production, promoting tiller initiation, survival, and overall productivity. Adequate zinc reduces unproductive tillers by mitigating stress, maintaining hormone and carbohydrate balance, and protecting membranes, ensuring early vigor and optimal tiller growth (Tuiwong et al., 2024).

Zinc plays a crucial role in rice reproductive development by enhancing panicle growth, spikelet formation, and grain set. Foliar zinc promotes panicle elongation by stimulating growth hormones such as auxins and gibberellins, stabilizing enzymes and membranes, and improving pollen viability (Saikh et al., 2022). Adequate zinc supply during panicle initiation allows proper tissue development and branching by supporting nucleic acid metabolism and energy supply to meristems (Mazhar et al., 2023). At flowering, zinc is essential for fertilization, pollen germination, and pollen tube growth, acting as a cofactor for enzymes involved in energy production and hormone synthesis, which ensures successful grain set (Sohaib et al., 2023; Nazeer et al., 2020). Transplanted rice benefits further from improved access to water and nutrients, enhancing grain set per panicle compared to direct-seeded rice (Veena et al., 2025). During grain filling, foliar zinc supports starch synthesis and carbohydrate transport by activating enzymes such as amylase and starch synthase, improving grain density and weight (Sanchez et al., 2023; Xiao et al., 2022). Timely foliar application ensures zinc availability during critical reproductive and grain-filling stages, ultimately contributing to higher yield and improved grain quality.

Grain weight, number, and tiller fertility directly affect yield, and zinc enhances all three by regulating hormones essential for development and reproduction and improving photosynthesis (Zhang et al., 2025). Zinc also promotes nitrogen metabolism, protein synthesis, and chlorophyll formation, supporting vegetative growth and straw yield (Sajjad et al., 2024). Foliar zinc ensures timely availability at critical growth stages, optimizing metabolic processes and biomass accumulation (Ahmad et al., 2025; Khaliq et al., 2023). Transplanted rice benefits from better root-soil contact and nutrient uptake, allowing more efficient zinc use and improved biological yield (Elshayb et al., 2021). Zinc influences assimilate partitioning and source-sink dynamics, slightly enhancing harvest index by promoting translocation to grains (Wang et al., 2021; Yang and Zhang, 2023). Foliar zinc also bypasses soil immobilization, delivering zinc directly to leaves for translocation to developing grains and straw, increasing grain zinc concentration and addressing human zinc deficiency (Ijaz et al., 2023b; Tuiwong et al., 2021). Residual zinc in straw contributes to nutrient cycling in the soil. Overall, improved root and shoot growth in transplanted rice supports greater zinc uptake and accumulation. Foliar zinc application at critical growth stages offers a practical and cost-effective strategy for farmers to enhance rice yield, grain quality and zinc content. This approach is particularly beneficial in soils with zinc limitations and can guide field-level nutrient management decisions, improving both productivity and nutritional value of the crop.

CONCLUSION

The research suggested that zinc has important roles in the metabolism of the plant. When a crop is treated with foliar zinc applications verses soil and seed coatings, productive and nutritional quality is enhanced, namely in transplanted rice. Foliar sprays supplied zinc right when it was needed, helping key growth stages. Human nutritional inadequacies are addressed by increasing the zinc content of grains, which makes agronomic biofortification a useful strategy for enhancing food quality. Using foliar zinc spray provides farmers and other stakeholders with a productive and economical means of increasing grain quality and yields, promoting improved livelihoods and advancing public health objectives. In order to optimize recommendations for a variety of growth circumstances, future work should concentrate on combining zinc management with other nutrients, evaluating the financial advantages, and investigating varietal responses. This study was conducted over a single season at a specific site, which may limit the generalizability of the results. Responses to foliar zinc could vary with different soils, cultivars, and environmental conditions, so multi-season and multi-location trials are recommended to validate these findings.

REFERENCES

Ahmad, S., Ouyang, X., Duan, S., Khan, Z., & Shen, H. (2025). Co-application of zinc and oligosaccharides enhances zinc bioavailability, yield and nutritional quality of rice. *Plant Physiology and Biochemistry*, *224,* 109964.

Ahmed, F., Waris, F., ibni Zamir, S., Sajjad, M., Nazeer, S., Khan, A., & Mustafa, F. (2023). Response of Different Organic and Inorganic Fertilizers on Alfalfa Yield Under Different Types of Irrigation Water. *Haya Saudi J Life Sci*, *8*(1), 1-8.

Akter, M., Islam, S. M., Islam, M. N., Rahman, M. S., Islam, A., Khanam, M., ... & Islam, M. R. (2024). Optimizing Rice Yield and Nutrient Uptake: Investigating the Interaction Between Nitrogen and Potassium in Wet Season Rice Cultivation. *Advances in Agriculture*, *2024*(1), 4984165.

Amin, H., Habib, A., Asif, M., Hameed, M. U., Wassi, M., Manzoor, M., ... & Sajjad, M. (2023). Effect of Foliar Application of Boron, Zinc and Manganese on Growth, Yield and Oil Contents of Sunflower (*Helianthus annuus* L.). *Asian J. Soil Sci. Plant Nutri*, *9*(4), 86-94.

Baghaie, A. H., & Khosravi-Dehkordi, A. (2025). The Critical Role of Zinc in Improving Public Health and Crop Quality: Examining Challenges and Strategies for Soil Enrichment in Developing Countries. *International Journal of Environmental Health Engineering*, *14*(4), 25.

Chattha, M. B., Qurban, A. L. I., Subhani, M. N., Ashfaq, M., Ahmad, S., Iqbal, Z., ... & HASSAN, M. U. (2023). Foliar applied zinc on different growth stages to improves the growth, yield, quality and kernel bio-fortification of fine rice. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, *51*(2), 13221-13221.

Chaudhary, A., Venkatramanan, V., Kumar Mishra, A., & Sharma, S. (2023). Agronomic and environmental determinants of direct seeded rice in South Asia. *Circular Economy and Sustainability*, *3*(1), 253-290.

Donia, D.T. and Carbone, M., 2023. Seed priming with zinc oxide nanoparticles to enhance crop tolerance to environmental stresses. *International Journal of Molecular Sciences*, *24*(24), p.17612.

Elshayb, O.M., Farroh, K.Y., Amin, H.E. and Atta, A.M., 2021. Green synthesis of zinc oxide nanoparticles: fortification for rice grain yield and nutrients uptake enhancement. *Molecules*, *26*(3), p.584.

Ijaz, B., Nazeer, S., Sajjad, M., Nadeem, M., Anwar, H., Idrees, M., ... & Khan, R. H. U. (2023a). Effect of various foliar applied micronutrients (Zn+ Fe+ Cu+ B) on growth and yield of wheat under Faisalabad condition. *Journal of Global Innovations in Agricultural Sciences*, *11*(2), 184-189.

Ijaz, B., Waraich, E. A., Shah, A., & Nazeer, S. (2023b). Morpho-physiological responses of wheat (*Triticum aestivum* L.) to foliar applied potassium under different planting geometry.

Junaid-ur-Rahman, S., Chughtai, M. F. J., Khaliq, A., Liaqat, A., Pasha, I., Ahsan, S., ... & Sameed, N. (2022). Rice: A potential vehicle for micronutrient fortification. *Clinical Phytoscience*, *8*(1), 14.

Kandil, E. E., El-Banna, A. A., Tabl, D. M., Mackled, M. I., Ghareeb, R. Y., Al-Huqail, A. A., ... & Abdelsalam, N. R. (2022). Zinc nutrition responses to agronomic and yield traits, kernel quality, and pollen viability in rice (*Oryza sativa* L.). *Frontiers in Plant Science*, *13*, 791066.

Khaliq, A., Zafar, M., Sajjad, M., Hassan, M. U., Mudassar, M. A., Shakoor, M. A., ... & Niaz, S. (2023). Nitrogen use efficiency in sunflower (*Helianthus annuus* l.) influenced by various fertigation and bed planting techniques. *Pakistan Journal of Biotechnology*, *20*(02), 385-392.

Khan, S. T., Malik, A., Alwarthan, A., & Shaik, M. R. (2022). The enormity of the zinc deficiency problem and available solutions; an overview. *Arabian Journal of Chemistry*, *15*(3), 103668.

Khongchiu, P., Wongkaew, A., Murase, J., Sajjaphan, K., Rakpenthai, A., Kumdee, O., & Nakasathien, S. (2025). Zinc Application Enhances Biomass Production, Grain Yield, and Zinc Uptake in Hybrid Maize Cultivated in Paddy Soil. *Agronomy*, *15*(7), 1501.

Mazhar, M. W., Ishtiaq, M., Maqbool, M., & Hussain, S. A. (2023). Foliar application of zinc oxide nanoparticles improves rice yield under biotic stress posed by Magnaporthe oryzae. *Archives of Phytopathology and Plant Protection*, *56*(14), 1093-1111.

Nazeer, S., Tahir, M., Sajjad, M., Idrees, M., Hameed, M. U., Saleem, M. A., & Shehzad, A. (2020). Response of Different Micronutrients (Zn, Cu and Mn) Soil Application on Yield and Quality of Late Sown Wheat (Triticum aestivum L.) in Agro-Climatic Conditions of Faisalabad, Pakistan. *Pakistan Journal of Life & Social Sciences*, *18*(2).

Negi, P., Rane, J., Wagh, R. S., Bhor, T. J., Godse, D. D., Jadhav, P., ... & Basavaraj, P. S. (2024). Direct-seeded rice: genetic improvement of game-changing traits for better adaption. *Rice Science*, *31*(4), 417-433.

Panda, S., Majhi, P. K., Anandan, A., Mahender, A., Veludandi, S., Bastia, D., ... & Ali, J. (2021). Proofing direct-seeded rice with better root plasticity and architecture. *International Journal of Molecular Sciences*, *22*(11), 6058.

Patel, P. S., Singh, S. K., Patra, A., & Jatav, S. S. (2022). Root dipping, foliar and soil application of zinc increase growth, yields, and grain zinc in rice (*Oryza sativa* L.) grown in moderate zinc soil of inceptisol order. *Communications in Soil Science and Plant Analysis*, *53*(15), 1917-1929.

Rehman, A., Imran, M., Sajjad, M., Umair, R., Nawaz, S., & Ijaz, B. (2025). Evaluation of herbicide efficiency and their impact with reduced rates along with adjuvants at varying application time in maize (*Zea Mays* L.). *Journal of Agricultural Research (JAR).*, *63*(1), 49-57.

Saikh, R., Murmu, K., Sarkar, A., Mondal, R., & Jana, K. (2022). Effect of foliar zinc application on growth and yield of rice (*Oryza sativa* L.) in the Indo-Gangetic Plains of India. *Nusantara bioscience*, *14*(2).

Sajjad, M., Hussain, K., Hakki, E. E., Ilyas, A., Gezgin, S., & Shakil, Q. (2025a). Impact of Irrigation Techniques on Water-Use Efficiency, Economic Returns, and Productivity of Rice. *Sustainability*, *17*(17), 7712.

Sajjad, M., Hussain, K., Wajid, S. A., & Saqib, Z. A. (2024). The impact of split nitrogen fertilizer applications on the productivity and nitrogen use efficiency of rice. *Nitrogen*, *6*(1), 1.

Sajjad, M., Ijaz, B., Khil, A., Ibtahaj, I., Hur, M., Azizi, N., ... & ur Rehman, H. (2025b). Influence of different organic mulches on growth, yield and oil content of maize (*Zea *mays* L.) hybrids and soil physical properties. *Journal of Ecological Engineering*, *26*(11), 410-427.

Sanchez-Palacios, J. T., Henry, D., Penrose, B., & Bell, R. (2023). Formulation of zinc foliar sprays for wheat grain biofortification: a review of current applications and future perspectives. *Frontiers in plant science*, *14*, 1247600.

Shakeel, A., Anjum, L., Ibni Zamir, S., Rizwan, M., Arshad, M., Mehmood, Q., ... & Waqas, A. (2021). Irrigation water quality effects on CO_2 emissions along with crop and soil responses. *Pakistan Journal of Agricultural Sciences*, *58*(2), 637-642.

Shen, Y., Wiita, E., Nghiem, A. A., Liu, J., Haque, E., Austin, R. N., ... & Bostick, B. C. (2023). Zinc localization and speciation in rice grain under variable soil zinc deficiency. *Plant and soil*, *491*(1), 605-626.

Sohaib, N., Arif, M., Shah, M. N., Mahmood, S., Ali, H., Amjid, M., ... & Anwar, H. (2023). Exploring the Role of Anti-Oxidant on Growth and Yield of Cotton to Mitigate the Heat Stress.

Steel, R. G. D., Torrie, J., H. & Dickey, D. A. (1997). Principles and Procedures of Statistics, A Biometrical Approach, 3rd ed.; McGraw-Hill Book Company, Inc.: New York, NY, USA; Toronto, ON, Canada; London, UK, 352–358.

Tuiwong, P., Cho, H. K., Rouached, H., & Prom-U-Thai, C. (2024). Synergistic Effects of Nitrogen and Zinc Foliar Application on Yield and Nutrient Accumulation in Rice at Various Growth Stages. *Plants*, *13*(23), 3274.

Veena, M., Sen, A., Faseela, P., & Puthur, J. T. (2025). Priming and foliar application as potent methods for agronomic biofortification, enhancing zinc bioavailability, photosynthetic traits and yield in rice. *Journal of Plant Nutrition*, *48*(14), 2513-2531.

Wang, L., Xia, H., Li, X., Qiao, Y., Xue, Y., Jiang, X., ... & Kong, L. (2021). Source–sink manipulation affects accumulation of zinc and other nutrient elements in wheat grains. *Plants*, *10*(5), 1032.

Xiao, Y. S., Zhou, B., Han, Z., Liu, S., Ding, C., Jia, F., & Zeng, W. (2022). Microbial mechanism of zinc fertilizer input on rice grain yield and zinc content of polished rice. *Frontiers in plant science*, *13*, 962246.

Yang, J., & Zhang, J. (2023). Simultaneously improving grain yield and water and nutrient use efficiencies by enhancing the harvest index in rice. *Crop and Environment*, *2*(3), 157-164.

Zahra, N., Hafeez, M. B., Nawaz, A., & Farooq, M. (2022). Rice production systems and grain quality. *Journal of Cereal Science*, *105*, 103463.

Zhang, N., Liu, Y., Gui, S., & Wang, Y. (2025). Regulation of tillering and panicle branching in rice and wheat. *Journal of Genetics and Genomics*, *52*(7), 869-886.