

Effect of different application methods of chelated zinc on growth, yield, and grain protein content of hybrid rice (*Oryza sativa* L.)

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Abstract

A field experiment was conducted to evaluate the effects of different methods of chelated zinc (Zn) application on the growth, yield, and grain quality of hybrid rice. The hybrid rice cultivar Fengyou-293 was grown under a fertilizer regime of 150–70–70 kg ha⁻¹ N–P–K. The experiment was conducted using a randomized complete block design (RCBD) comprising six zinc (Zn) application treatments. The treatments included an untreated control with no Zn application (T₁), seedling root dipping followed by foliar Zn application (T₂), a single soil application of Zn at 3 kg ha⁻¹ applied 10 days after transplanting (DAT) (T₃), a split soil application consisting of 2 kg Zn ha⁻¹ at 10 DAT and an additional 1 kg Zn ha⁻¹ before panicle initiation (T₄), and a combined soil and foliar application involving 2 kg Zn ha⁻¹ applied to the soil at 10 DAT followed by a 1% Zn foliar spray before panicle initiation (T₅), and two foliar sprays applied at 10 DAT and before panicle initiation (T₆). The results demonstrated that zinc application significantly affected several yield and quality parameters.

The split soil application of zinc (T₄) produced the highest number of grains per panicle (242.75), biological yield (14.80 t ha⁻¹), and grain yield (4.205 t ha⁻¹). Significant treatment effects were also observed for harvest index, grain sterility, and protein content. In contrast, plant height, number of tillers per hill, panicle length, and thousand-grain weight were not significantly influenced by the different methods of chelated zinc application. The results demonstrated that the split application of chelated zinc, with 2 kg Zn ha⁻¹ applied at 10 days after transplanting followed by an additional 1 kg Zn ha⁻¹ before panicle initiation, was the most effective zinc management practice for enhancing both grain yield and quality attributes of hybrid rice. Further research should focus on evaluating split applications of chelated zinc under diverse environmental conditions and integrating this approach with nutrient management to enhance crop productivity and zinc use efficiency. © 2026 The Author(s)

Keywords: Chelated zinc, Grain yield, Micronutrients, *Oryza sativa* L., Panicle length, Tillers, Zn deficiency

Citation: Khan, S. U., Khan, M. A., Sadiq, M., & Abbas, R. (2026). Effect of different application methods of chelated zinc on growth, yield, and grain protein content of hybrid rice (*Oryza sativa* L.). *Journal of Plant Production and Sustainability*, 2(1), 27–36. <https://doi.org/10.63072/jpps.26003>

Introduction

Rice (*Oryza sativa* L.) ranks among the most widely cultivated cereal crops worldwide and constitutes the principal dietary staple for approximately half of the global population (Hassan et al., 2022; Roheen et al., 2023; Omar et al., 2025). It belongs to the family Gramineae (Poaceae). In Pakistan, rice is cultivated across a wide range of agro-climatic regions. Basmati rice is predominantly grown in the rice-producing areas of Punjab, whereas coarse IRRI varieties are mainly cultivated in the southern regions of Khyber Pakhtunkhwa (Hassan et al., 2024). Rice production in Pakistan is forecast to reach 9.8 million tons in 2026-27, driven primarily by an anticipated increase in the area under rice cultivation. Assuming normal harvesting conditions, rice exports are also projected to recover to approximately 5.0 million tons in 2026-27, compared with an estimated 4.7 million tons in 2025-26 due to the currently slower pace of exports (United States Department of Agriculture, Foreign Agricultural Service,

2026). To satisfy the increasing demand for food, strengthen export potential, and ensure sustainable and stable rice production, the adoption of hybrid rice technology has become increasingly important (Ibrahim, 2020). In recent decades, hybrid rice cultivation has demonstrated yield advantages of up to 50% per hectare in China (Gong et al., 2026). Hybrid rice refers to the commercial cultivation of F₁ plants developed by crossing two genetically distinct parental lines (Wang & Deng, 2018). These parental lines are highly homozygous, genetically stable inbred varieties. The superior performance of hybrid rice is attributed to heterosis, also known as hybrid vigor, whereby the F₁ progeny exhibit enhanced growth, productivity, and overall performance compared with their parents (Singh et al., 2013; Lee et al., 2026). However, this heterotic advantage is confined to the first filial (F₁) generation and is lost in subsequent generations. Consequently, farmers cannot retain seeds from hybrid crops for replanting and must purchase fresh hybrid seeds for each growing season (Curry, 2023; Samuel & Dines, 2023). Currently, numerous aspects of hybrid rice production are being investigated worldwide to further

improve its productivity and sustainability (Shankar et al., 2021). Among these research areas, the nutritional requirements of hybrid rice, particularly the role of micronutrients such as zinc (Zn), have received considerable attention because of their importance in promoting plant growth, development, and grain yield (Zafar & Jianlong, 2023; Ashraf et al., 2024; Sokra et al., 2026).

Zinc (Zn) is a vital microelement needed for normal growth, development and productivity of crop plants. It plays an important role in different physiochemical processes, including enzyme functioning, protein and photosynthesis, carbohydrate metabolism, chlorophyll formation and hormone regulation (Suganya et al., 2020; Nandal & Solanki, 2021; Saleem et al., 2022). Adequate zinc nutrition enhances plant vigor, improves grain formation, and increases crop yield and quality. However, zinc deficiency has become one of the most widespread micronutrient disorders affecting agricultural soils worldwide, particularly in rice-growing regions where alkaline soils, high pH, and intensive cropping systems reduce zinc availability to plants (Alloway et al., 2008; Lakshmi et al., 2021; Saleem et al., 2022; Mandal et al., 2026). Zinc (Zn) is an essential micronutrient that plays a fundamental role in the growth, physiological processes, and overall development of rice plants. Traditionally, zinc has been applied to rice fields in the form of zinc sulphate. However, only about 40–60% of the applied zinc is readily available for plant uptake, with the remaining portion becoming unavailable due to fixation in the soil (Recena et al., 2021). This problem is particularly pronounced in saline and alkaline soils, where zinc availability is further reduced, often leading to zinc deficiency in rice plants (Taşpınar et al., 2025). To improve zinc use efficiency, recent research has focused on the application of chelated zinc fertilizers (Thiyagarajan, 2022). In chelated formulations, zinc ions are chemically bound to organic chelating agents, which maintain the nutrient in a soluble and plant-available form for an extended period (Xu et al., 2022). These negatively charged organic complexes protect positively charged zinc ions from reacting with soil constituents that would otherwise immobilize them. As a result, chelated zinc remains available for plant uptake over a longer duration, enhancing nutrient absorption and improving fertilizer efficiency (Mir et al., 2019). Zinc fertilizers can be supplied to rice crops through various application methods, depending on soil conditions, crop requirements, and management practices (Neocleous et al., 2020).

Rice plants are particularly vulnerable to zinc deficiency during the early stages of growth and establishment. In many rice-producing areas, inadequate zinc availability limits plant establishment, nutrient uptake, and grain production. Previous studies have shown that imbalanced fertilizer management, with greater emphasis on nitrogen and phosphorus while neglecting micronutrients such as zinc is a major factor responsible for lower rice productivity despite the high yield potential

of modern cultivars (Shireen et al., 2018). Furthermore, the low availability of zinc in the rhizosphere, where several nutrients become insoluble under unfavorable soil conditions, restricts zinc uptake and ultimately affects plant growth and yield (Kobayashi & Nishizawa, 2008). Several researchers have demonstrated the beneficial effects of zinc fertilization on rice growth, nutrient uptake, and grain yield. Application of different zinc sources pointedly enhanced plant biological yield, nutrient accumulation, and grain yield compared with untreated soils (Kwaslema et al., 2025). Likewise, zinc application @ 5 kg ha⁻¹ enhanced zinc uptake by rice, while residual benefits were also observed in subsequent wheat crops grown after rice (Parkash et al., 2007). Studies have further indicated that zinc application rates exceeding 9 kg Zn ha⁻¹ substantially improved grain yield, and an application rate of approximately 11 kg Zn ha⁻¹ as granular zinc fertilizer was recommended for alkaline, zinc-deficient soils because of its superior effectiveness under such conditions (Slaton et al., 2005).

The effectiveness of zinc fertilization depends not only on the application rate but also on the source, formulation, and method of application. Surface application of zinc fertilizers before crop emergence has been found to provide satisfactory crop responses without requiring soil incorporation under suitable field conditions (Slaton et al., 2005). Similarly, zinc sulphate has been reported to be a more effective fertilizer source than zinc oxide, producing higher agronomic and physiological efficiency in rice (Shivay et al., 2008). However, increasing zinc coating levels beyond the optimum may reduce fertilizer use efficiency, indicating the importance of selecting appropriate fertilizer sources and application rates (Shivay et al., 2008).

The availability and mobility of zinc in soils are strongly influenced by soil properties and environmental conditions. Long-term saturated conditions following precipitation can enhance the release of zinc from sandy soils, thereby affecting its availability to plants and movement within the soil profile (He et al., 2005). On the other hand, the concentration of potentially available and water-soluble zinc generally declines over successive cropping seasons, reducing zinc availability for plant uptake (Alvarez et al., 2008). Soil zinc concentration has also been positively correlated with zinc accumulation in rice grains, suggesting that maintaining adequate soil zinc levels is essential for improving grain nutritional quality (Zhu et al., 2008). Research has also highlighted the importance of rhizosphere processes in improving zinc acquisition by rice plants. Rhizosphere interactions have been found to play a greater role in zinc efficiency than internal physiological mechanisms in lowland rice (Wissuwa et al., 2006). Moreover, increased malate exudation from rice roots enhances zinc mobilization in the rhizosphere, contributing to improved zinc uptake among rice genotypes differing in zinc efficiency (Gao et al., 2009). Environmental conditions also influence zinc uptake, as rice grown under aerobic conditions has shown lower shoot zinc concentration and total zinc uptake than rice cultivated under anaerobic conditions (Gao et al., 2010).

Despite the established importance of zinc nutrition in rice production, an important research gap remains regarding the

comparative effectiveness of different application methods of chelated zinc in hybrid rice. Most previous studies have focused on conventional zinc sources, particularly zinc sulphate, or have evaluated zinc application rates without adequately comparing different delivery methods of chelated zinc under hybrid rice production systems. Moreover, limited information is available on how different chelated zinc application methods influence not only growth and yield components but also grain protein content, an important indicator of rice nutritional quality. Therefore, the optimum method for delivering chelated zinc to hybrid rice to improve zinc use efficiency, productivity, and grain quality remains insufficiently established. Addressing this gap is essential for developing an efficient zinc management strategy that can enhance the yield potential and nutritional quality of hybrid rice under field conditions. The present research study was executed to evaluate different application methods of chelated zinc (Zn) on the growth, productivity and yield of hybrid rice. The specific objectives were to identify the most effective zinc application method for improving crop performance, enhancing zinc use efficiency, and maximizing rice productivity through appropriate zinc management practices.

Materials and Methods

A field trial was carried out at the Agronomic Research Area, Faculty of Agriculture, Gomal University, D.I. Khan, Khyber Pakhtunkhwa, Pakistan (KPK), to evaluate the efficacy of different means of application of chelated zinc (Zn) on the growth and yield of hybrid rice. The research study was arranged in a randomized complete block design

(RCBD) comprising six treatments with four replications. The net experimental area measured 20 m × 15 m, while each experimental unit measured 5 m × 2.5 m. The F₁ hybrid rice cultivar Fengyou-293 was used as the experimental material. Forty-day-old seedlings were transplanted into a well-prepared field. Fertilizers at the rate of 150–70–70 kg ha⁻¹ N–P–K were applied. The full dose of potassium and phosphorus were incorporated at the time of transplanting, whereas three split doses of nitrogen were applied during the crop growth period. The crop was irrigated at seven-day intervals throughout the growing season. Urea, DAP (diammonium phosphate) and SOP (sulphate of potash) were the sources of nitrogen, phosphorus and potassium, respectively. Zinc was supplied as a commercial zinc poly-phenolate formulation, which was used as the Zn source for all soil, seedling root-dip, and foliar applications. Zinc poly-phenolate is an organic Zn complex in which Zn is associated with polyphenolic ligands. The formulation was selected because the organic polyphenolic ligand can complex Zn and help maintain it in a soluble and potentially plant-available form, thereby reducing Zn immobilization in the soil. The soil application treatments supplied Zn at a total rate of 3 kg elemental Zn ha⁻¹, whereas the root-dip and foliar treatments received a 1% Zn fertilizer solution according to the treatment schedule presented in Table 1. The 1% solution was prepared by dissolving 1 g of the Zn formulation in 100 mL of water and thoroughly mixing before application. In this study, the term “chelated Zn” specifically refers to the zinc poly-phenolate formulation used as the Zn fertilizer source. Six zinc application strategies were investigated, encompassing untreated, soil-applied, foliar-applied, and integrated soil–foliar Zn management practices (Table 1).

Table 1 Zinc application strategies employed under different treatment combinations.

Treatments	Zinc application strategy
T1	Untreated control without Zn supplementation
T2	Seedlings were root-dipped in a 1% Zn solution before transplanting, followed by a 1% foliar Zn spray prior to panicle initiation
T3	A single soil application of Zn at 3 kg ha ⁻¹ was applied 10 days after transplanting (DAT)
T4	Zinc was supplied through split soil applications, with 2 kg ha ⁻¹ at 10 DAT and the remaining 1 kg ha ⁻¹ before panicle initiation
T5	Soil-applied Zn (2 kg ha ⁻¹) at 10 DAT was supplemented with a 1% foliar Zn spray before panicle initiation
T6	Two foliar Zn sprays (1%) were applied, the first at 10 DAT and the second before panicle initiation

Parameters studied

The following agronomic and yield-related parameters were recorded during the study.

Plant height (cm)

At physiological maturity, ten representative plants were randomly selected from the inner rows of each experimental unit, excluding border plants. Plant height was measured from the ground level to the tip of the

panicle using a meter rod, and the mean value of the ten plants was calculated for each experimental unit.

Number of tillers

The number of tillers was counted from the same representative plants/hills selected from the inner rows of each experimental unit, excluding border plants. The mean number of tillers was calculated and expressed as tillers per plant/hill, as appropriate.

Panicle length (cm)

Ten representative panicles were randomly selected from the inner-row plants of each experimental unit. Panicle length was measured from the panicle base to its tip using a graduated scale, and the mean of the ten panicles was calculated for each experimental unit.

Number of grains per panicle

The grains present on the same ten selected panicles were counted manually, and the average number of grains panicle⁻¹ was calculated for each experimental unit.

1000-grain weight (g)

After harvest, three independent samples of 1,000 grains were randomly taken from each experimental unit. Each 1,000-grain sample was weighed separately using an analytical balance, and the mean of the three measurements was recorded as the 1000-grain weight (g) for each experimental unit.

Biological yield (t ha⁻¹)

The biological yield was calculated by using the following formula:

$$\text{Biological yield} = \frac{\text{Biological yield per plot (kg)} \times 10,000}{\text{Plot size (m}^2\text{)} \times 1000}$$

Grain yield (t ha⁻¹)

After harvesting and threshing, the produce from each experimental unit was sun-dried. The obtained grains from each experimental unit were weighed and recorded on a plot basis. The recorded values were subsequently converted into tonnes per hectare (t ha⁻¹) using the following formula:

$$\text{Grain yield} = \frac{\text{Plot grain yield (kg)} \times 10,000}{\text{Plot size (m}^2\text{)} \times 1000}$$

Harvest index (%)

Harvest index (HI) was calculated by using the following formula:

$$\text{Harvest index} = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100$$

Sterility percentage

Sterility percentage was determined to assess the proportion of unfilled and non-viable grains. For this purpose, 30 panicles were randomly selected from each

treatment. After harvesting, the panicles were carefully examined to distinguish sterile, aborted, opaque, and normal kernels. Grain classification was carried out using a seed examination board equipped with a flexible electric lamp to facilitate accurate identification of the different grain categories. Sterility percentage was calculated as:

$$\text{Sterility} = \frac{\text{Number of sterile grains}}{\text{Total number of grains}} \times 100$$

Grain protein content (%)

Grain protein content was determined using the Kjeldahl method. Ground brown rice samples (1.00 g) were digested with concentrated sulfuric acid in the presence of potassium sulfate and copper sulfate as catalysts at 420 °C for 1 h. After digestion, the released ammonia was distilled and absorbed in a boric acid solution (40 g L⁻¹) containing mixed indicators, and nitrogen content was determined using an automatic Kjeldahl nitrogen analyzer (Kjeltec 2300, FOSS, Hillerød, Denmark). Protein content was calculated by multiplying the nitrogen content by a conversion factor of 5.95 (Hu et al., 2022):

$$\text{Protein (\%)} = \text{Nitrogen (\%)} \times 5.95$$

The analysis was conducted using three analytical replicates per experimental unit, and the replicate values were averaged for statistical analysis. All analytical procedures were performed under standard laboratory conditions using calibrated laboratory equipment and appropriate quality-control procedures.

Statistical analysis

The data obtained from all studied parameters were subjected to statistical analysis using analysis of variance (ANOVA) appropriate for a randomized complete block design (RCBD). Treatment means were compared by applying the Least Significant Difference (LSD) test at 5% level of significance.

Results**Plant height (cm)**

Plant tallness is one of the most important growth parameters that reflect the combined influence of the plant's genetic potential and prevailing environmental conditions. The data offered in Table 2 indicate that the application of different techniques of chelated zinc (Zn) did not produce statistically significant values for plant height of hybrid rice. Although the differences were non-significant, numerical variation was observed among different studied treatments. The highest plant height with the value of 109.75 cm was recorded within T₄. This treatment was closely followed by T₅. In contrast, the

shortest plants (105.25 cm) were obtained under T₆.

Number of tillers hill⁻¹

Tillers per hill are a key yield-contributing trait because grain yield largely depends on the number of productive panicle-bearing tillers (Huang et al., 2020). The results presented in Table 2 showed that different modes of chelated zinc application did not significantly influence the counted tillers hill⁻¹. Nevertheless, slight numerical differences were observed among the treatments. The maximum count of tillers hill⁻¹ (22.25) was recorded in T₂, while the minimum count of tillers hill⁻¹ (16.75) was observed in T₅.

Table 2 Morphological traits of hybrid rice as influenced by different application techniques of chelated zinc

Treatments	Plant height (cm)	Number of tillers per hill
T ₁	108.75 ns	19.50 ns
T ₂	105.75	22.25
T ₃	106.75	20.50
T ₄	109.75	20.25
T ₅	109.50	16.75
T ₆	105.25	18.00

ns = Non-significant

Panicle length (cm)

The data presented in Table 3 exhibited that different methods of chelated zinc (Zn) application did not significantly influence panicle length in hybrid rice. Although numerical differences were observed among the different treatments, these differences were non-significant statistically at 5% level of probability. Longest panicles (28.40 cm) were recorded in the control treatment (T₁, without Zn application), whereas the shortest panicles (26.85 cm) were observed in T₄.

Number of grains per panicle

Table 3 Yield traits of hybrid rice as influenced by different application techniques of chelated zinc

Treatments	Panicle length (cm)	Number of grains per panicle	1000-grains weight (g)	Sterility (%)
T ₁	28.400 ns	199.75 b	25.923 ns	11.003 ab
T ₂	27.275	215.50 ab	27.973	11.318 ab
T ₃	28.225	200.00 b	27.940	10.050 ab
T ₄	26.850	242.75 a	27.840	7.663 b
T ₅	28.275	212.50 b	28.827	11.540 ab
T ₆	26.225	204.75 b	26.940	11.910 a

ns = Non-significant; Means followed by different letters are significantly different @ 5% level of probability.

Biological yield (t ha⁻¹)

The data presented in Table 4 showed that biological yield was significantly influenced by the different methods of chelated zinc (Zn) application in hybrid rice. The highest biological yield (14.80 t ha⁻¹) was recorded in T₄ followed

The grains counted per panicle are an important yield contributing character that directly contributes to grain productivity. As shown in Table 3, this trait was positively influenced by the various application techniques of chelated zinc. The maximum count of grains panicle⁻¹ (242.75) was recorded in T₄. This was followed by T₂ with the value of 215.50. The lowest number of grains per panicle (199.75) was observed in the control treatment (T₁) without zinc application. Although numerical differences existed among T₂, T₃, T₅, and T₆, these treatments were statistically at par. The superior performance of T₄ suggests that split application of chelated zinc may have ensured an adequate nutrient supply during the critical reproductive stage, thereby enhancing grain formation.

1000-grain weight (g)

The results presented in Table 3 showed that different zinc application methods did not significantly affect thousand-grain weight. Nevertheless, slight numerical differences were recorded among the treatments. The data indicated that the greatest 1000-grain weight (28.827 g) was achieved under T₅. Conversely, the control treatment (T₁), which received no zinc, produced the lowest 1000-grain weight (25.923 g). Despite these numerical differences among the treatments, statistical analysis revealed that the effects of the various zinc application methods on 1000-grain weight were not significant.

Sterility percentage

Grain sterility is a major factor influencing the final yield of rice. The data presented in Table 3 demonstrate that sterility percentage varied among the different zinc application methods. The highest sterility (11.91%) was recorded in T₆ followed by T₅ (11.54%). The lowest sterility percentage (7.66%) was observed in T₄. Treatments T₁, T₂, T₃, and T₅ were statistically similar, whereas significant differences were observed between these treatments and the remaining treatments. The lower sterility observed in T₄ may be attributed to the sustained availability of zinc during the reproductive stage, which likely improved pollen viability, fertilization, and grain development.

by T₅ (12.00 t ha⁻¹). Whereas the lowest biological yield (10.40 t ha⁻¹) was observed in T₂. Statistical analysis indicated that T₄ produced higher biological yield than the remaining treatments, whereas the other zinc application methods were statistically comparable. The superior performance of T₄ may be attributed to the continuous availability of zinc during

critical growth stages, which enhanced nutrient uptake, vegetative growth, and biomass accumulation.

Grain yield (t ha⁻¹)

Grain yield was also significantly affected by the different modes of chelated zinc application (Table 4). The highest grain yield (4.205 t ha⁻¹) was obtained in T₄. The second-highest yield (3.832 t ha⁻¹) was recorded in T₃. In contrast, the lowest grain yield (2.84 t ha⁻¹) was observed in the control treatment (T₁) without zinc application. Treatments T₃, T₄, and T₆ were statistically at par with one another but differed significantly from the remaining treatments. The increased grain yield observed under these treatments was likely associated with improved zinc availability throughout the crop growth cycle, which promoted better grain filling and enhanced overall productivity. The results demonstrated that the mode of chelated zinc application played an important role in improving grain yield of hybrid rice. The application methods that ensured greater zinc

availability resulted in better yield performance.

Harvest index (%)

Harvest index (HI) is an important indicator of the efficiency with which plants allocate total biomass to grain production. The highest HI (34.10%) was achieved with the soil application of 3 kg Zn ha⁻¹ at 10 days after transplanting (T₃), followed by the two foliar applications of 1% Zn (T₆), which recorded an HI of 32.78% (Table 4). In contrast, the untreated control (T₁) produced the lowest harvest index (25.46%), indicating reduced biomass partitioning to grain under zinc-deficient conditions. Statistical analysis indicated that T₂, T₄, T₅, and T₆ were statistically similar, whereas significant differences existed between these treatments and the remaining treatment groups. The higher harvest index observed in T₃ may be associated with improved zinc availability during the critical stages of crop development, resulting in more efficient partitioning of assimilates toward grain production.

Table 4 Yield and harvest attributes of hybrid rice as affected by different modes of application of chelated zinc

Treatments	Biological yield (t ha ⁻¹)	Grain yield (t ha ⁻¹)	Harvest index (%)
T ₁	11.40 b	2.845 b	25.46 b
T ₂	10.40 b	3.342 ab	32.08 ab
T ₃	11.40 b	3.832 a	34.10 a
T ₄	14.80 a	4.205 a	28.46 ab
T ₅	12.00 b	3.730 ab	32.26 ab
T ₆	11.80 b	3.855 a	32.78 ab

Means followed by different letters are significantly different @ 5% level of probability.

Grain protein content (%)

The results presented in Table 5 indicate that the highest grain protein content (9.785%) was recorded in T₂ followed by protein content (8.692%) obtained in T₅. In contrast, the lowest protein content (8.470%) was observed in the control treatment (T₁) without zinc application. Statistical analysis showed that treatments T₃, T₄, T₅, and T₆ were statistically at par with one another but differed significantly from the remaining treatments. The superior protein content recorded in T₂ may be attributed to improved zinc availability during both the early vegetative and reproductive stages, which could have enhanced nitrogen metabolism and protein synthesis in the developing grains. In addition, environmental conditions prevailing during the growing season may also have contributed to the observed differences among treatments.

Table 5 Grain quality of hybrid rice as affected by different methods of application of chelated zinc

Treatments	Protein content (%)
T ₁	8.470 b
T ₂	9.785 a
T ₃	9.410 ab
T ₄	9.312 ab
T ₅	8.692 ab
T ₆	9.325 ab

Means followed by different letters are significantly different at

5% level of probability

Discussion

The appropriate application of zinc to rice crop is very important for getting vigorous plant growth, better ripening and high yield (Kunlanit et al., 2025). Recent studies have demonstrated that poor yield of rice, in spite of heavy application of nitrogen and phosphorus fertilizers, may be attributed to the deficiency of zinc in soil (Rehim et al., 2014). Although zinc is essential for plant growth, excessive zinc accumulation may become toxic and adversely affect plant metabolism (Ali et al., 2014). Zinc toxicity has been shown to induce structural changes in root cells, including alterations in the nucleus, disruption of cytoplasmic organization, and disintegration of cellular organelles, ultimately impairing plant growth and development (Rout & Das, 2003). Furthermore, studies on zinc speciation have indicated that changes in soil zinc forms do not necessarily reduce zinc accumulation in plant shoots and roots, emphasizing the complexity of zinc dynamics in contaminated soils (Isabel et al., 2006). The formation of zinc-cadmium sulphide solid solutions has also been reported to have limited influence on reducing zinc and cadmium toxicity to plants and soil organisms (Barrett & McBride, 2007).

Residual and cumulative effects of zinc fertilization have also been documented in cereal-based cropping systems. Zinc

application not only improves rice productivity but also enhances the yield and yield components of succeeding wheat crops, including plant height, spike length, grain weight, and number of spikes, demonstrating the long-term benefits of balanced zinc fertilization (Khan et al., 2009). In addition, zinc fertilizers containing approximately 19.8% zinc have been reported to promote greater accumulation of phosphorus, zinc, copper, and manganese in rice grains, thereby improving both crop productivity and grain nutritional quality (Mollah et al., 2009). Genotypic variation in response to zinc fertilization has also been widely reported. Significant differences among rice varieties have been observed in grain yield response to zinc application, with some cultivars responding more positively than others (Farooq et al., 2018). Similarly, variation among rice genotypes in zinc uptake efficiency has been associated with differences in root characteristics and rhizosphere processes, indicating opportunities for developing zinc-efficient cultivars through breeding programs (Wissuwa et al., 2006; Gao et al., 2009).

Our findings are in line with those of Obrador et al. (2003), who reported that the availability and mobility of zinc in calcareous soils depend largely on the source of zinc fertilizer applied. Their incubation study demonstrated that the water-soluble and exchangeable fractions of zinc, which represent the most readily available forms for plant uptake, were significantly higher when Zn-CH fertilizer was used. This suggests that selecting an appropriate zinc source is essential for improving zinc availability and enhancing crop performance under calcareous soil conditions (Obrador et al., 2003). Our findings are also consistent with those of Stuczynski et al. (2003), who observed that zinc amendments significantly influenced soil pH and consequently affected soil biological activity and zinc toxicity. Similarly, Jim and Dustin (2004) reported that zinc sorption in calcareous soils is strongly influenced by phosphate-iron oxide interactions, while the lability of sorbed zinc varies according to soil type and the presence of background ions. These observations emphasize that soil chemical properties play a crucial role in regulating zinc availability and should be considered when developing efficient zinc fertilization strategies (Stuczynski et al., 2003; Jim & Dustin, 2004).

The present results further agree with the findings of Khoshgoftar et al. (2004), who demonstrated that zinc application substantially increased shoot zinc concentration and improved plant tolerance to salinity stress. Their study showed that zinc fertilization enhanced shoot zinc concentration by 75–103% while significantly increasing shoot dry matter production. These findings support the beneficial role of adequate zinc nutrition in improving nutrient uptake, plant growth, and stress tolerance under adverse environmental conditions (Khoshgoftar et al., 2004). Our observations are further supported by Zuo and Zhang (2009), who suggested that effective zinc biofortification strategies, including intercropping nutrient-efficient plant species, can alleviate zinc and iron deficiencies in crops. Their findings indicate that improved

nutrient management practices can enhance micronutrient acquisition and contribute to better crop productivity and nutritional quality, which is consistent with the positive response observed in the present study (Zuo & Zhang, 2009).

The results are also in agreement with Ayten et al. (2010), who reported that excessive accumulation of heavy metals, including zinc, adversely affects soil quality by reducing soil enzyme activities. Although zinc is an essential micronutrient for plant growth, maintaining its concentration within the optimum range is important because excessive levels may impair soil biological processes and reduce overall soil health (Ayten et al., 2010). Our findings are further corroborated by Okpala and Moneke (2010), who found that the growth of *Pseudomonas fluorescens* was enhanced in the presence of zinc under glyphosate-treated conditions. This indicates that appropriate zinc availability may stimulate beneficial microbial activity in the soil, thereby improving nutrient cycling and supporting healthier crop growth (Okpala & Moneke, 2010). The present study is also consistent with the findings of Mousavi et al. (2010), who reported that vermicompost-amended soils, particularly those enriched with micronutrients, resulted in the highest zinc uptake by rice plants. Their results highlight the importance of integrated nutrient management practices combining organic amendments with micronutrient fertilization to improve zinc availability, nutrient uptake, and overall crop productivity (Mousavi et al., 2010).

Conclusion

The present study demonstrated that different modes of chelated zinc (Zn) application significantly influenced the yield and yield-related traits of hybrid rice (*Oryza sativa* L.). Among the tested application methods, the split application of chelated Zn (2 kg ha⁻¹ applied at 10 days after transplanting followed by another application before panicle initiation) proved to be the most effective, producing the highest number of grains per panicle (242.75), maximum biological yield (14.80 t ha⁻¹), highest grain yield (4.205 t ha⁻¹), and the lowest spikelet sterility (7.66%). These results indicate that split application of chelated Zn ensures a more efficient supply of zinc during the critical growth stages of rice, thereby improving reproductive development and grain production. Application of a single dose of chelated Zn at 10 days after transplanting resulted in the highest harvest index (34.10%), whereas dipping rice seedlings in a 1% Zn solution followed by a foliar spray before panicle initiation produced the highest grain protein content (9.79%). In contrast, plant height, number of tillers per hill, panicle length, and 1000-grain weight were not significantly affected by the different modes of zinc application.

Declarations

i. Ethics approval and consent to participate

Ethical approval and informed consent were not required for this study as it did not involve human participants, human data, or animals.

ii. Consent for publication

Consent for publication is not applicable.

iii. Data availability

All data generated or analyzed during this study are included in this article.

iv. Competing interests

Authors have declared that no competing interests exist.

v. Authors' contributions

S.U.K performed the experiments and collected the data; M.A.K. designed the study and supervised the research; M.S. performed the statistical analysis and interpreted the results; R.A. wrote the first draft of the manuscript and participated in its critical revision. All authors read and approved the final manuscript.

vi. Funding

No funding was received for the design, data collection, analysis, interpretation, or writing of this research manuscript.

vii. Acknowledgement

Not applicable.

viii. SDGs addressed

Zero Hunger (SDG 2)

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