

INTEGRATED ZINC MANAGEMENT WITH ZINC FERTILIZERS AND ZINC-SOLUBILIZING BACTERIA FOR IMPROVED GROWTH, PHYSIOLOGY, AND YIELD OF RICE (*ORYZA SATIVA* L.)

S.Anandha Krishnaveni¹, S. Sheeba Joyce Roseleen^{2*}, S. Nithila³, R. Parthasarathi⁴

^{1,2,4} Anbil Dharmalingam Agricultural College and Research Institute, Tiruchirappalli, Tamil Nadu, India

^{2*} Department of Agricultural Entomology, ADAC&RI, Tiruchirappalli 620027, Tamil Nadu, India. mail id: sheeba@tnau.ac.in

³ Horticultural College and Research Institute for Women Tiruchirappalli, Tamil Nadu, India 620 027

ABSTRACT

Zinc (Zn) deficiency is an important nutritional constraint affecting rice productivity and plant physiological performance. Field experiments were conducted at the Anbil Dharmalingam Agricultural College and Research Institute, Tiruchirappalli, Tamil Nadu, India, during 2024 and 2025 to evaluate the effect of integrated Zn nutrition involving zinc sulfate (ZnSO₄), zinc-solubilizing bacteria (ZSB) and foliar Zn application on rice. Rice variety TRY 5 was evaluated under eight Zn nutrition treatments in a randomized block design with three replications. The treatments consisted of farmers' practice, ZnSO₄ at 25 and 37.5 kg ha⁻¹, ZSB at 2 kg ha⁻¹, combinations of ZnSO₄ and ZSB, and combinations of ZnSO₄, ZSB and 0.5% foliar ZnSO₄. The experimental soil was clay loam with pH 8.26, electrical conductivity 2.029 dS m⁻¹, organic carbon 0.32% and available Zn 0.48 mg kg⁻¹. Biometric observations were recorded at active tillering, panicle initiation and harvest stages, whereas physiological observations were recorded at the vegetative stage. Integrated Zn nutrition substantially improved rice growth, physiological characteristics and yield. The highest plant height (137.6 cm), tiller number (412 m⁻²), dry matter production (11841 kg ha⁻¹), SPAD value (49), chlorophyll content (4.12 mg g⁻¹), panicle number (344 m⁻²), grain yield (5434 kg ha⁻¹) and straw yield (6943 kg ha⁻¹) were recorded with ZnSO₄ @ 37.5 kg ha⁻¹ + ZSB @ 2 kg ha⁻¹ + foliar ZnSO₄ @ 0.5%. The same treatment recorded the lowest Na⁺/K⁺ ratio (1.8). Grain yield under T₈ was 27.2% higher than farmers' practice. The findings indicated that integration of soil-applied ZnSO₄ with ZSB and foliar ZnSO₄ was an effective strategy for improving growth, physiological performance and productivity of rice under the experimental conditions.

KEYWORDS: Rice, Zinc nutrition, Zinc-solubilizing bacteria, ZnSO₄, SPAD; Chlorophyll, Na⁺/K⁺ ratio

INTRODUCTION

Rice (*Oryza sativa* L.) is one of the major cereal crops and provides food and energy to a large proportion of the world's population. Sustaining rice productivity under intensive cultivation and declining soil fertility is a major challenge in modern rice production. Among the essential micronutrients, zinc (Zn) plays an important role in plant growth and development through its involvement in enzyme activation, protein synthesis, membrane stability, carbohydrate metabolism, gene expression and regulation of several physiological processes. Zinc deficiency can adversely affect rice growth, tillering, photosynthetic activity and grain production (Wissuwa *et al.*, 2006; Rehman *et al.*, 2012).

The availability of Zn to rice plants is influenced by soil properties, chemical forms of Zn and soil-water interactions. In rice-growing soils, particularly under flooded conditions, Zn availability may be reduced because of changes in soil chemical reactions following submergence. Consequently, Zn fertilization is an important management practice for improving Zn availability and crop productivity. Several studies have demonstrated that Zn application can improve rice growth, yield attributes, grain yield and Zn accumulation in grain (Roy *et al.*, 2014; Singson *et al.*, 2021). Agronomic Zn biofortification through fertilizer application also offers an opportunity to improve the nutritional quality of rice grain (Phattarakul *et al.*, 2012; Saha *et al.*, 2017).

Zinc sulfate (ZnSO₄) is widely used as a Zn fertilizer because of its availability and effectiveness in correcting Zn deficiency. However, the efficiency of soil-applied Zn may be affected by soil characteristics and fixation processes. The response of rice to Zn application also depends on the rate, source and method of application. Integrated approaches involving soil and foliar Zn application have been reported to improve rice yield and Zn accumulation more effectively than individual application methods (Das *et al.*, 2019; Tyagi *et al.*, 2017).

Microbial approaches provide an additional means of improving Zn availability. Zinc-solubilizing bacteria (ZSB) can mobilize relatively unavailable forms of Zn through microbial processes, including production of organic acids and other metabolites, thereby increasing the availability of Zn for plant uptake. Root-associated bacterial strains may additionally promote plant growth through nutrient mobilization and other plant-growth-promoting mechanisms. Shakeel *et al.* (2015) reported that root-associated *Bacillus* strains improved rice growth, yield and Zn translocation. More recently, the combined application of Zn-solubilizing bacteria and ZnSO₄ was reported to enhance rice growth, chlorophyll content, yield and grain Zn concentration (Shakeel *et al.*, 2024).

Physiological characteristics such as SPAD value and chlorophyll content provide useful indicators of crop response to nutrient management. Zinc contributes to the maintenance of several metabolic and physiological processes associated with photosynthetic activity. Improved Zn nutrition can therefore contribute to better leaf chlorophyll status, dry matter accumulation and crop productivity. The beneficial effect of Zn-solubilizing bacteria and Zn fertilization on chlorophyll and growth characteristics has been reported in rice (Shakeel *et al.*, 2015; Shakeel *et al.*, 2024).

Plant mineral-ion relationships may also be influenced by Zn nutrition. The Na^+/K^+ ratio provides an indication of the relative balance between sodium and potassium within plant tissues. Differences in Na^+ and K^+ accumulation and their ratio have been associated with rice responses to Zn deficiency and sodicity (Qadar and Azam, 2007). However, changes in Na^+/K^+ ratio should be interpreted as an indicator of ionic balance in the present study rather than direct evidence of salinity tolerance because the experiment was not specifically conducted under salinity stress.

Foliar application provides an additional route for Zn delivery to plants and may complement soil-applied Zn, particularly during later stages of crop development. Soil plus foliar Zn application has been shown to improve rice yield and grain Zn enrichment under different production environments (Saha *et al.*, 2017; Tyagi *et al.*, 2017). Combining soil-applied Zn, ZSB and foliar Zn may therefore provide a more continuous and efficient supply of Zn throughout crop development. The experimental field in the present study had an initial available Zn concentration of 0.48 mg kg^{-1} . Under such conditions, evaluation of integrated Zn management is relevant for determining whether microbial Zn mobilization can complement chemical Zn fertilization. Therefore, the present investigation was undertaken to evaluate the effects of ZnSO_4 , ZSB and foliar ZnSO_4 , individually and in combination, on growth, dry matter production, SPAD value, chlorophyll content, Na^+/K^+ ratio, yield attributes, grain yield and straw yield of rice variety TRY 5.

MATERIAL AND METHODS

Experimental site

Field experiments were conducted at the Anbil Dharmalingam Agricultural College and Research Institute, Tiruchirappalli, Tamil Nadu, India, during 2024 - 2025. Rice variety TRY 5 was used as the test crop. The experiment was conducted under field conditions representative of rice production in the region.

Initial soil characteristics

Before imposing the treatments, representative soil samples were collected from 0–15 cm depth from the experimental field. The samples were air-dried, gently crushed, passed through a 2-mm sieve and analyzed for selected physicochemical properties and available nutrients following standard analytical procedures.

The experimental soil was clay loam in texture, with a pH of 8.26 and electrical conductivity of 2.029 dS m^{-1} . Organic carbon was 0.32%. The soil contained 155 kg ha^{-1} available Nitrogen, 11.3 kg ha^{-1} available Phosphorous and 146 kg ha^{-1} available Potassium. Available sulphur was 7.5 mg kg^{-1} , while exchangeable calcium and magnesium were 6.8 and $4.7 \text{ cmol (p}^+) \text{ kg}^{-1}$, respectively. The initial available Zn concentration was 0.48 mg kg^{-1} .

Experimental design and treatments

The experiments were laid out in a **randomized block design (RBD)** with eight treatments and three replications. Each plot measured $5 \text{ m} \times 4 \text{ m}$, giving a gross plot area of 20 m^2 . The treatments were randomly allocated within each replication.

The treatments were:

T₁: Farmers' practice

T₂: ZnSO_4 @ 25 kg ha^{-1}

T₃: ZnSO_4 @ 37.5 kg ha^{-1}

T₄: Soil application of ZSB @ 2 kg ha^{-1}

T₅: ZnSO_4 @ 25 kg ha^{-1} + ZSB @ 2 kg ha^{-1}

T₆: ZnSO_4 @ 37.5 kg ha^{-1} + ZSB @ 2 kg ha^{-1}

T₇: ZnSO_4 @ 25 kg ha^{-1} + ZSB @ 2 kg ha^{-1} + foliar ZnSO_4 @ 0.5%

T₈: ZnSO_4 @ 37.5 kg ha^{-1} + ZSB @ 2 kg ha^{-1} + foliar ZnSO_4 @ 0.5%

Crop establishment and nutrient management

Twenty-eight-day-old seedlings of rice variety TRY 5 were transplanted in the experimental field. Land preparation, irrigation, weed management and plant protection practices were maintained uniformly across all treatments.

A blanket recommendation of $150:50:50 \text{ kg ha}^{-1} \text{ N:P}_2\text{O}_5:\text{K}_2\text{O}$ was applied uniformly to the crop. Nitrogen and potassium were applied in three splits at the basal, tillering and flowering stages. Full dose of Phosphorus was applied as basal.

The required quantities of ZnSO_4 and ZSB were applied as soil treatments at 10 days after transplanting (DAT). ZnSO_4 was applied at 25 or 37.5 kg ha^{-1} according to the treatment schedule, while ZSB was applied at 2 kg ha^{-1} . In T₇ and T₈, ZnSO_4 was additionally applied as a 0.5% foliar spray at the tillering stage.

Biometric observations

Biometric observations were recorded at active tillering, panicle initiation and harvest stages. Plant height was measured from the ground level to the tip of the tallest portion of representative plants and expressed in cm. Total tiller number was recorded from a representative area of each plot and expressed as number of tillers m^{-2} .

Dry matter production was determined from representative plant samples collected from each treatment. The samples were dried to constant weight and dry matter production was calculated and expressed as kg ha^{-1} .

Measurement of SPAD value

Physiological observations were recorded at panicle initiation stage. Leaf greenness was measured using a SPAD meter. Measurements were taken from fully expanded, physiologically active leaves of representative plants, avoiding the midrib. Multiple readings were taken and the mean SPAD value was calculated for each treatment.

Estimation of total chlorophyll

Fresh leaf samples collected at panicle initiation stage were used for estimation of total chlorophyll. A known quantity of fresh leaf tissue was thoroughly ground and the pigments were extracted using 80% acetone. The absorbance of the extract was measured spectrophotometrically at 645 and 663 nm, using 80% acetone as the blank.

Total chlorophyll content was calculated using the equation:

$$\text{Total chlorophyll (mg g}^{-1}\text{)} = [20.2(A_{645}) + 8.02(A_{663})] \times V / 1000 \times W$$

Where, A_{645} and A_{663} represent absorbance at 645 and 663 nm, respectively, V represents the final volume of extract (ml), and W represents the weight of fresh leaf tissue used for extraction (g).

Estimation of Na^+ and K^+ and Na^+/K^+ ratio

Fresh leaf samples collected at panicle initiation stage were used for estimation of sodium and potassium concentrations. The samples were subjected to acid digestion following the standard laboratory protocol. The concentrations of Na^+ and K^+ in the resulting digest were determined using a flame photometer.

The Na^+/K^+ ratio was calculated as:

$$\text{Na}^+/\text{K}^+ \text{ ratio} = \text{Na}^+ \text{ concentration} / \text{K}^+ \text{ concentration}$$

Yield attributes and yield

At physiological maturity, the number of panicles was recorded from a representative area of each plot and expressed as panicles m^{-2} . The crop from the net plot area was harvested separately for each treatment and threshed. Grain yield was recorded after cleaning and expressed as kg ha^{-1} . Straw obtained after threshing was weighed separately and expressed as kg ha^{-1} .

Statistical analysis

The data recorded for biometric observations, physiological parameters, yield attributes and yield were subjected to analysis of variance appropriate for a randomized block design with three replications. Treatment effects were tested using the F-test. When the treatment effect was significant, treatment means were compared using the critical difference at the 5% probability level. Standard error of difference was calculated for each parameter. Treatment differences exceeding the respective critical difference were considered statistically significant at $P < 0.05$.

RESULTS AND DISCUSSION

Effect of zinc nutrition on rice growth parameters

Zinc nutrition influenced the growth characteristics of rice, with numerical improvements in plant height, tiller production and dry matter accumulation across the treatments (Table 1). Plant height under farmers' practice (T_1) was 104.3 cm, which increased to 113.5 and 119.4 cm with ZnSO_4 application at 25 and 37.5 kg ha^{-1} , respectively. Soil application of ZSB alone recorded 108.7 cm. Integration of ZnSO_4 with ZSB further improved plant height, recording 122.2 cm in T_5 and 131.5 cm in T_6 . The highest plant height of 137.6 cm was recorded in T_8 , where $\text{ZnSO}_4 @ 37.5 \text{ kg ha}^{-1}$ was combined with ZSB @ 2 kg ha^{-1} and foliar $\text{ZnSO}_4 @ 0.5\%$. However, the difference between T_8 and T_6 (6.1 cm) was less than the CD value of 15.50 cm and hence was not statistically significant.

A similar numerical trend was observed for tiller production. Farmers' practice recorded 320 tillers m^{-2} , whereas $\text{ZnSO}_4 @ 25$ and 37.5 kg ha^{-1} resulted in 349 and 361 tillers m^{-2} , respectively. ZSB alone recorded 324 tillers m^{-2} . Combining ZnSO_4 with ZSB increased tiller production to 376 tillers m^{-2} in T_5 and 401 tillers m^{-2} in T_6 . The maximum numerical value of 412 tillers m^{-2} was recorded in T_8 . The difference between T_8 and T_1 was 92 tillers m^{-2} , exceeding the CD of 39.67 tillers m^{-2} , indicating a significant treatment effect. However, the difference between T_8 and T_6 was only 11 tillers m^{-2} and was not significant.

Dry matter production increased from 8862 kg ha^{-1} in T_1 to 9345 and 9871 kg ha^{-1} in T_2 and T_3 , respectively. ZSB alone resulted in 9064 kg ha^{-1} . Combined application of ZnSO_4 and ZSB resulted in 10055 kg ha^{-1} in T_5 and 11249 kg ha^{-1} in T_6 . The highest numerical dry matter production of 11841 kg ha^{-1} was recorded in T_8 . Although T_8 exceeded T_1 by 2979 kg ha^{-1} , the difference between T_8 and T_1 exceeded the CD of 1401.69 kg ha^{-1} , whereas the difference between T_8 and T_6 was only 592 kg ha^{-1} and therefore was not significant.

Effect of zinc nutrition on physiological parameters

The different Zn nutrition treatments influenced the physiological parameters of rice (Table 2). The SPAD value under farmers' practice was 31 and increased to 35 and 37 with ZnSO_4 application at 25 and 37.5 kg ha^{-1} , respectively. ZSB alone recorded a SPAD value of 33. Integration of ZnSO_4 and ZSB increased the SPAD value to 38 in T_5 and 46 in T_6 . The highest value of 49 was recorded in T_8 , followed by 42 in T_7 . The difference between T_8 and T_1 was 18 SPAD units, which exceeded the CD of 5.08, indicating a significant improvement over farmers' practice. The difference between T_8 and T_6 was 3 SPAD units and was below the CD; therefore, T_8 was not significantly different from T_6 .

Total chlorophyll content showed a similar increasing trend. Farmers' practice recorded 2.34 mg g^{-1} , while ZnSO_4 application at 25 and 37.5 kg ha^{-1} resulted in 2.76 and 3.12 mg g^{-1} , respectively. ZSB alone recorded 2.45 mg g^{-1} . Combined application of ZnSO_4 and ZSB increased chlorophyll content to 3.41 and 4.06 mg g^{-1} in T_5 and T_6 , respectively. The highest numerical value of 4.12 mg g^{-1} was recorded in T_8 . The increase from T_1 to T_8 was 1.78 mg g^{-1} , which was greater than the CD of 0.35 mg g^{-1} and hence significant. However, the difference between T_8 and T_6 was only 0.06 mg g^{-1} and was not significant.

The Na^+/K^+ ratio showed an opposite trend, decreasing progressively with improved Zn nutrition. Farmers' practice recorded the highest value of 3.1, while ZnSO_4 application at 25 and 37.5 kg ha^{-1} reduced the ratio to 2.7 and 2.5, respectively. ZSB alone recorded 2.8. The ratio declined to 2.3 and 2.0 under T_5 and T_6 , respectively, while the lowest value of 1.8 was recorded under T_8 .

The reduction in Na^+/K^+ ratio from 3.1 in T_1 to 1.8 in T_8 was 1.3, which exceeded the CD of 0.31 and was therefore significant. The difference between T_8 and T_6 was 0.2 and was below the CD, indicating that the two treatments were not significantly different.

Effect of zinc nutrition on yield attributes and yield

The yield attributes and yield of rice were positively influenced by Zn nutrition (Table 3). The number of panicles increased from 226 m⁻² under farmers' practice to 278 and 293 m⁻² with ZnSO₄ application at 25 and 37.5 kg ha⁻¹, respectively. ZSB alone produced 240 panicles m⁻². Combined application of ZnSO₄ and ZSB resulted in 304 panicles m⁻² in T₅ and 332 panicles m⁻² in T₆. The highest numerical value of 344 panicles m⁻² was recorded in T₈. The increase in panicle number from T₁ to T₈ was 118 panicles m⁻², which was greater than the CD of 29.18 panicles m⁻², indicating a significant treatment effect. However, the difference between T₈ and T₆ was only 12 panicles m⁻² and was not statistically significant.

Grain yield increased from 4272.0 kg ha⁻¹ in T₁ to 4863.0 and 5080.0 kg ha⁻¹ under T₂ and T₃, respectively. ZSB alone recorded 4635.0 kg ha⁻¹. Combined application of ZnSO₄ and ZSB resulted in grain yields of 4863.0 and 5192.0 kg ha⁻¹ in T₅ and T₆, respectively. The highest numerical grain yield of 5434.0 kg ha⁻¹ was recorded in T₈, followed by 5086.0 kg ha⁻¹ in T₇. Grain yield under T₈ was 1162 kg ha⁻¹ higher than farmers' practice, corresponding to an increase of approximately 27.2%. This difference exceeded the CD of 436.35 kg ha⁻¹ and was therefore statistically significant. However, the difference between T₈ and T₆ was 242 kg ha⁻¹, which was below the CD; hence, the grain yield of T₈ was not significantly different from T₆.

Straw yield followed a trend similar to grain yield. Farmers' practice recorded 5315 kg ha⁻¹, compared with 6079 and 6350 kg ha⁻¹ under T₂ and T₃, respectively. ZSB alone recorded 5794 kg ha⁻¹. Integration of ZnSO₄ and ZSB resulted in 6079 kg ha⁻¹ in T₅ and 6490 kg ha⁻¹ in T₆. The highest numerical straw yield of 6943 kg ha⁻¹ was recorded in T₈, followed by 6358 kg ha⁻¹ in T₇. The increase in straw yield from T₁ to T₈ was 1628 kg ha⁻¹, exceeding the CD of 579.98 kg ha⁻¹ and indicating a significant treatment effect. In contrast, the difference between T₈ and T₆ was 453 kg ha⁻¹ and did not exceed the CD, indicating no significant difference between these treatments.

The present study demonstrated that integrated Zn nutrition improved rice growth, physiological performance and productivity compared with farmers' practice. The response was particularly pronounced when ZnSO₄ was combined with ZSB and foliar ZnSO₄. The initial soil available Zn concentration of 0.48 mg kg⁻¹ provided a relevant background for evaluating Zn fertilization and microbial Zn mobilization. The improvement in plant height, tillering and dry matter production with ZnSO₄ application may be associated with the important role of Zn in enzyme activation, protein synthesis, membrane stability and carbohydrate metabolism. Improved Zn availability can promote vegetative development and assimilate production, resulting in greater plant growth. Similar improvements in rice growth and productivity following Zn fertilization have been reported previously (Wissuwa *et al.*, 2006; Roy *et al.*, 2014; Singson *et al.*, 2021). The greater response observed with combined ZnSO₄ and ZSB application suggests that microbial Zn solubilization may have complemented the direct supply of Zn from ZnSO₄. Zinc-solubilizing microorganisms can mobilize less-available Zn fractions through microbial activity, potentially increasing Zn availability in the rhizosphere. Root-associated *Bacillus* strains have previously been shown to improve rice growth, yield and Zn translocation (Shakeel *et al.*, 2015). A recent field study further demonstrated synergistic effects between ZSB and ZnSO₄ on rice growth, chlorophyll, yield and grain Zn content (Shakeel *et al.*, 2024). The present results are consistent with these observations. The highest growth and dry matter production under T₈ indicate that combining soil-applied ZnSO₄ and ZSB with foliar Zn provided a more comprehensive Zn nutrition strategy. Soil application supplied Zn to the root environment, while ZSB may have contributed to Zn mobilization. Foliar ZnSO₄ provided an additional source of Zn during crop development. Similar benefits from combined soil and foliar Zn application have been reported in rice (Saha *et al.*, 2017; Tyagi *et al.*, 2017). The improvement in SPAD value and chlorophyll content with Zn nutrition indicates enhanced leaf physiological status. Zinc has an important role in maintaining several metabolic processes associated with photosynthetic activity. The greater chlorophyll content recorded under T₆ and T₈ may have contributed to greater dry matter production by maintaining photosynthetically active foliage. The results agree with observations of improved chlorophyll and growth in rice following combined ZnSO₄ and Zn-solubilizing bacterial application (Shakeel *et al.*, 2015; Shakeel *et al.*, 2024).

The Na⁺/K⁺ ratio declined with increasing integration of Zn nutrition. The lowest value in T₈ indicates a more favourable relative balance between Na⁺ and K⁺ compared with farmers' practice. Changes in Na⁺ and K⁺ relations have previously been associated with rice responses to Zn deficiency and sodicity (Qadar and Azam, 2007). Nevertheless, the present reduction in Na⁺/K⁺ ratio should be interpreted primarily as an improvement in relative ionic balance because the experiment was not specifically designed to evaluate salt or sodicity tolerance. Yield improvement was consistent with the increases observed in tiller production, dry matter accumulation and panicle number. The maximum grain yield of 5434 kg ha⁻¹ under T₈ represented a 27.2% increase over farmers' practice. The increased number of panicles under integrated Zn management likely contributed to the higher grain yield. Similar positive responses of rice grain yield to Zn fertilization have been reported by Roy *et al.* (2014), Singson *et al.* (2021) and other workers. The superiority of T₈ over the individual Zn treatments indicates the potential advantage of integrating soil and foliar Zn with ZSB. Soil application of ZnSO₄ provided the principal fertilizer source, ZSB potentially enhanced Zn mobilization, and foliar ZnSO₄ supplemented Zn during crop growth. This complementary supply of Zn may have supported improved physiological activity and reproductive development. The findings are in agreement with reports showing improved rice productivity from integrated Zn fertilization and microbial Zn-solubilization approaches (Saha *et al.*, 2017; Shakeel *et al.*, 2024).

Overall, the treatment comprising ZnSO₄ @ 37.5 kg ha⁻¹ + ZSB @ 2 kg ha⁻¹ + foliar ZnSO₄ @ 0.5% (T₈) recorded the highest numerical values for most growth, physiological and yield parameters. It recorded 137.6 cm plant height, 412 tillers m⁻², 11841 kg ha⁻¹ dry matter production, SPAD value of 49, chlorophyll content of 4.12 mg g⁻¹, 344 panicles m⁻², 5434 kg ha⁻¹ grain yield and 6943 kg ha⁻¹ straw yield, while recording the lowest Na⁺/K⁺ ratio of 1.8. These findings indicate that integrated Zn management can be an effective approach for improving rice productivity under the experimental conditions.

CONCLUSION

The present investigation demonstrated that integrated Zn nutrition significantly influenced rice growth, physiological characteristics and yield. Application of ZnSO₄ alone improved plant growth and productivity compared with farmers' practice, while the response was further enhanced by combining ZnSO₄ with ZSB. The addition of foliar ZnSO₄ produced the greatest overall response. Among the treatments evaluated, ZnSO₄ @ 37.5 kg ha⁻¹ + ZSB @ 2 kg ha⁻¹ + foliar ZnSO₄ @ 0.5% (T₈) recorded the highest values for plant height, tiller production, dry matter accumulation, SPAD value, chlorophyll content, panicle number, grain yield and straw yield, together with the lowest Na⁺/K⁺ ratio. Grain yield increased from 4272 kg ha⁻¹ under farmers' practice to 5434 kg ha⁻¹ under T₈. The results suggest that integration of chemical Zn fertilizer with Zn-solubilizing bacteria and foliar Zn application can improve Zn nutrition and enhance growth, physiological performance and productivity of rice variety TRY 5 under the conditions of the present study. Further multi-location and multi-season studies are warranted to validate the effectiveness and economic feasibility of this integrated Zn management strategy.

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Table 1. Effect of zinc nutrition on growth parameters of rice variety TRY 5

Treatment	Plant height (cm)	Total tillers (no. m ⁻²)	Dry matter production (kg ha ⁻¹)
T ₁ – Farmers' practice	104.3	320	8862
T ₂ – ZnSO ₄ @ 25 kg ha ⁻¹	113.5	349	9345
T ₃ – ZnSO ₄ @ 37.5 kg ha ⁻¹	119.4	361	9871
T ₄ – ZSB @ 2 kg ha ⁻¹	108.7	324	9064
T ₅ – T ₂ + ZSB @ 2 kg ha ⁻¹	122.2	376	10055
T ₆ – T ₃ + ZSB @ 2 kg ha ⁻¹	131.5	401	11249
T ₇ – T ₂ + ZSB @ 2 kg ha ⁻¹ + foliar ZnSO ₄ @ 0.5%	124.1	383	10637
T ₈ – T ₃ + ZSB @ 2 kg ha ⁻¹ + foliar ZnSO ₄ @ 0.5%	137.6	412	11841
SEd	7.22	18.49	653.54
CD (P=0.05)	15.50	39.67	1401.69

ZSB - zinc-solubilizing bacteria; SED - standard error of difference; CD - critical difference.

Table 2. Effect of zinc nutrition on SPAD value, total chlorophyll content and Na⁺/K⁺ ratio of rice

Treatment	SPAD value	Total chlorophyll (mg g ⁻¹)	Na ⁺ /K ⁺ ratio
T ₁ – Farmers' practice	31	2.34	3.1
T ₂ – ZnSO ₄ @ 25 kg ha ⁻¹	35	2.76	2.7
T ₃ – ZnSO ₄ @ 37.5 kg ha ⁻¹	37	3.12	2.5
T ₄ – ZSB @ 2 kg ha ⁻¹	33	2.45	2.8
T ₅ – T ₂ + ZSB @ 2 kg ha ⁻¹	38	3.41	2.3
T ₆ – T ₃ + ZSB @ 2 kg ha ⁻¹	46	4.06	2.0
T ₇ – T ₂ + ZSB @ 2 kg ha ⁻¹ + foliar ZnSO ₄ @ 0.5%	42	3.83	2.1
T ₈ – T ₃ + ZSB @ 2 kg ha ⁻¹ + foliar ZnSO ₄ @ 0.5%	49	4.12	1.8
SEd	2.37	0.16	0.15
CD (P=0.05)	5.08	0.35	0.31

ZSB - zinc-solubilizing bacteria; SED - standard error of difference;
CD - critical difference.

Table 3. Effect of zinc nutrition on panicle number, grain yield and straw yield of rice

Treatment	Panicles (no. m ⁻²)	Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)
T ₁ – Farmers' practice	226	4272.0	5315
T ₂ – ZnSO ₄ @ 25 kg ha ⁻¹	278	4863.0	6079
T ₃ – ZnSO ₄ @ 37.5 kg ha ⁻¹	293	5080.0	6350
T ₄ – ZSB @ 2 kg ha ⁻¹	240	4635.0	5794
T ₅ – T ₂ + ZSB @ 2 kg ha ⁻¹	304	4863.0	6079
T ₆ – T ₃ + ZSB @ 2 kg ha ⁻¹	332	5192.0	6490
T ₇ – T ₂ + ZSB @ 2 kg ha ⁻¹ + foliar ZnSO ₄ @ 0.5%	315	5086.0	6358
T ₈ – T ₃ + ZSB @ 2 kg ha ⁻¹ + foliar ZnSO ₄ @ 0.5%	344	5434.0	6943
SEd	13.61	203.45	270.41
CD (P=0.05)	29.18	436.35	579.98

ZSB - zinc-solubilizing bacteria; SED - standard error of difference;
CD - critical difference.