Vol. 15, No. 2 (2026): 779 - 791
http://dx.doi.org/10.23960/jtepl.v15i2.779-791

JURNAL TEKNIK PERTANIAN LAMPUNG

ISSN 2302-559X (print) / 2549-0818 (online)
Journal homepage : https://jurnal.fp.unila.ac.id/index.php/JTP

The Influence of Zinc Biofortification on the Growth, Yield, and Zinc Content in Several Rice Varieties (*Oryza sativa* L.)

Kholfira Masoyogie[1,✉], Muhammad M. Kamal[2], Eko Pramono[2], RA. Diana Widyastuti[2], Muhammad Syamsoel Hadi[2]

[1] Master's Program in Agronomy, Faculty of Agriculture, University of Lampung, INDONESIA.
[2] Department of Agronomy and Horticulture, Faculty of Agriculture, University of Lampung, INDONESIA.

Article History:

Received : 05 August 2025
Revised : 09 November 2025
Accepted : 11 November 2025

Keywords:

Potassium uptake,
Rice prowth,
Rice productivity,
Zinc content in rice,
Zinc fertilization.

Corresponding Author:
✉ kholfiramasoyogie@gmail.com
(Kholfira Masoyogie)

ABSTRACT

Rice productivity faces challenges due to soil degradation and nutrient deficiencies. This study aims to evaluate the effects of zinc (Zn) biofortification through foliar spray on growth, yield, potassium (K) uptake, and zinc (Zn) content in rice grains. The study also assesses the response of different rice varieties to zinc application and analyzes the interaction between zinc and varieties in enhancing productivity and zinc content, which could potentially support stunting prevention efforts. The research was conducted in the rice fields of Maja Village, Pesawaran Regency, Lampung, from July to October 2024, using a split plot design. Zinc treatments included seed priming and foliar spray at the vegetative and generative stages. The results showed that zinc application significantly increased plant height, productive tillers, flowering time, number of grains per panicle, percentage of filled and empty grains, 1,000-grain weight, as well as harvest dry grain (HDG) and dry unhusked rice (DUR). Treatment P4 (priming and zinc application at both vegetative and generative stages) showed the best response, with an average increase in zinc content in rice grains of 56% compared to the control. Nutri Zinc variety showed the highest potassium uptake and zinc content. The interaction between zinc and variety had a significant impact on 1,000-grain weight and HDG. This study highlights that zinc biofortification can improve rice production and increase zinc content in rice, supporting stunting prevention.

1. INTRODUCTION

Rice (*Oryza sativa* L.) is a strategic crop for national food security in Indonesia, serving as a primary source of food for the majority of the population. However, national rice productivity has declined in recent years, with rice production in 2023 reaching 53.636 million tons, a decrease of 2.05% compared to the previous year (Badan Pangan Nasional, 2023). This decline is influenced by various factors, including soil degradation, nutrient deficiencies, improper farming practices, and disruptions during pre-harvest and post-harvest stages. The El Niño phenomenon, with moderate to strong intensity in 2023, led to delayed rainy seasons and an increase in dry days in rice-growing areas, resulting in reduced productivity and harvested area due to significant rainfall deficits (BMKG, 2023).

As the population grows, rice demand continues to rise, leading to an 833% increase in rice imports in 2023. National rice consumption is recorded at 116.77 kg per capita per year (Badan Pangan Nasional, 2023), indicating an imbalance between rice availability and demand, which threatens food security. To support food security, the government, through the biofortification program, has developed high-yielding rice varieties such as Ciherang, Inpari 32, and Nutrizink. The Nutrizink variety aims to increase zinc (Zn) content in rice to address nutritional deficiencies, such as stunting and wasting, which remain high in Indonesia (UNICEF, 2022).

Zinc (Zn) is an essential micronutrient that plays an important role in the process of photosynthesis. Zinc deficiency can reduce photosynthetic activity by approximately 50–70%, depending on the plant species. In addition, various enzymes in plants require Zn to function properly. Within these enzymatic systems, Zn serves three main roles: as a catalytic, co-catalytic, and structural component (Barman *et al.,* 2018). Additionally, zinc plays a role in regulating plant hormones such as auxin, gibberellin, and cytokinin, which are essential for cell division and elongation (Broadley *et al*., 2007). Rice productivity is also highly dependent on the availability of both macro and micronutrients. Potassium (K), as an essential macronutrient, plays a key role in photosynthesis and the translocation of photosynthesis products to storage organs. Potassium deficiency can significantly reduce rice yield (Linquist, 2020). The interaction between zinc and potassium synergistically enhance the physiological efficiency of plants (Khan *et al*., 2018; Salem *et al*., 2022).

Increasing zinc (Zn) concentration in cereal crops through biofortification is a major research priority, as it has the potential to help reduce Zn deficiency in humans. The developed varieties are expected to reach rural communities sustainably at a relatively low cost (Das *et al.,* 2018). Efforts to address Zn deficiency can be carried out through the use of Zn-rich varieties (biofortification) as well as through agronomic fertilization practices. Therefore, zinc fertilization contributes not only to agronomic aspects but also to improving the nutritional quality of staple foods, which is vital for food security and addressing nutritional problems in Indonesia.

This study aims to investigate the impact of zinc biofortification (Zn) through foliar spray on the growth, yield, potassium (K) absorption, and zinc (Zn) content in rice grains (*Oryza sativa* L.). The study also aims to assess the response of different rice varieties to zinc application and analyze the interaction between zinc application and rice varieties in improving productivity and zinc nutritional content, which can support efforts to prevent stunting. The results of this study are expected to contribute to enhancing rice productivity through more effective nutrient management, particularly in zinc biofortification. The increase in zinc content in rice is also expected to help meet daily zinc nutritional requirements for consumers, especially vulnerable groups such as children under five and pregnant women, as part of efforts to prevent stunting.

2. MATERIALS AND METHODS

This study was conducted in the rice fields of Desa Maja, Marga Punduh District, Pesawaran Regency, Lampung Province, from July to October 2024. Rice seedlings were planted in rainfed rice fields with a planting distance of 25 cm × 25 cm per plot, each measuring 12 m^2, with 3 rice seedlings per plot. A total population of 663 rice plants per plot was obtained, with an overall plant population of 29,835 rice plants.

The materials used in this study included zinc sulfate heptahydrate ($ZnSO_4 \cdot 7H_2O$), rice seeds of the varieties Ciherang, Inpari 32, and Inpari IR Nutri Zinc, fertilizers including Urea, SP-36, and KCL, as well as insecticides and fungicides. The tools used included trays, hoes, buckets, measuring cups, meters, and stationery. The experiment employed a split plot design consisting of two factors. The first factor was zinc application, which included priming with aquades for 12 hours (P0/control), priming with 0.25% Zn for 12 h (P1), priming with 0.25% Zn for 12 h followed by foliar spray with 0.5% Zn at the early vegetative phase (20 DAP) and late vegetative phase (40 DAP) (P2), priming with 0.25% Zn for 12 h followed by foliar spray with 0.5% Zn at the generative phase of grain filling (60 DAP) and milk stage (75 DAP) (P3), and priming with 0.25% Zn for 12 h followed by foliar spray with 0.5% Zn at the early vegetative phase (20 DAP), late vegetative phase (40 DAP), and generative phase of grain filling (60 DAP) and milk stage (75 DAP) (P4). The second factor was rice variety, which consisted of Ciherang (V1), Inpari-32 (V2), and Inpari IR Nutri Zinc (V3). Each treatment was repeated three times, resulting in a total of 45 experimental units. The field experiment was performed using layout presented in Figure 1.

Observed variables include plant height, number of tillers (stems), number of productive tillers, flowering time, number of grains per panicle, 1,000-grain weight, percentage of filled and unfilled grains, harvest dry grain (HDG), dry unhusked rice (DUR), and zinc content in rice. Zinc content in rice was tested through analysis at the Soil, Plant, Fertilizer, and Water Laboratory, Agricultural Standard Instrument Agency, Cimanggu, West Java. The data obtained from the observations were then analyzed using RStudio software and further tested with the Least Significant Difference (LSD) test at a 5% significance level.

I

V1P1	V1P3	V1P4	V1P2	V1P0
V2P1	V2P3	V2P4	V2P2	V2P0
V3P1	V3P3	V3P4	V3P2	V3P0

II

V2P2	V2P0	V2P3	V2P1	V2P0
V3P2	V3P0	V3P3	V3P1	V3P0
V1P2	V1P0	V1P3	V1P1	V1P0

III

V3P0	V3P2	V3P4	V3P1	V3P3
V1P0	V1P2	V1P4	V1P1	V1P3
V2P0	V2P2	V2P4	V2P1	V2P3

Figure 1. Experimental layout (description of variety (V) and zinc priming (P) is in the text)

3. RESULTS AND DISCUSSION

The analysis of variance (Table 1) shows that zinc application has a significant effect on all growth and yield parameters of rice, including plant height, number of tillers (stems), number of productive tillers, flowering time, number of grains per panicle, 1,000-grain weight, and rice quality (filled grains, unfilled grains, HDG, and DUR). The variety treatment also significantly affects several parameters, indicating that genetic differences between varieties influence the response to the treatment and the resulting yield. The interaction between zinc and varieties was highly significant for 1,000-grain weight, HDG, and DUR, suggesting variations in the varieties' responses to zinc application. The choice of the right variety is an important factor in achieving optimal results from zinc application, particularly in improving both the quality and quantity of grains. However, no significant interaction was found for other parameters, suggesting that the effects of zinc application and varieties act separately on most variables. The recap of the analysis of variance shows the effect of zinc application on the observed variables in the experiment with several rice varieties, as presented in Table 1.

Table 1. Summary of ANOVA results on the effect of Zn application on the growth and productivity of three rice varieties

No	**Observation variables**	**Zinc**		**Variety**		**Zinc × Variety**	
		p-value	Sig	*p*-value	Sig	*p*-value	Sig
1	Plant height (cm)	0.0000	**	0.0331	*	0.2599	ns
2	Tiller (seedlings) (stems)	0.0004	**	0.5037	ns	0.1263	ns
3	Productive tiller (stems)	0.0000	**	0.0200	*	0.2060	ns
4	Flowering time (DAP)	0.0000	**	0.0000	**	0.4900	ns
5	Number of grains per panicle	0.0000	**	0.0902	ns	0.0578	ns
6	1000-grain weight (g)	0.0000	**	0.0000	**	0.0005	**
7	Percentage of empty grains (%)	0.0000	**	0.0336	*	0.2719	ns
8	Percentage of filled grains (%)	0.0309	**	0.0000	*	0.2484	ns
9	Harvest dry grain (HDG) (%)	0.0044	**	0.0000	**	0.0053	**
10	Dry unhusked rice (DUR) (%)	0.0000	**	0.0049	**	0.0029	**

Note: ns = not significant at 5% level, * and ** denote significant at 5% and 1% levels, respectively.

3.1. Plant Height

Based on the ANOVA and the Least Significant Difference (LSD) test at the 5% level (Table 2), zinc (Zn) application (through seed priming and foliar spray) showed a significant effect on the plant height of rice. The treatment P4 (seed priming + foliar spray twice during the vegetative phase and twice during the generative phase) resulted in the highest plant height at 94.42 cm, followed by P3 (91.84 cm), P2 (91.13 cm), and P1 (90.02 cm). Plants without zinc treatment (P0) reached 88.35 cm in height. The variety response to plant height also showed variation, with Inpari 32 reaching an average height of 92.57 cm, Ciherang 91.25 cm, and Nutri Zinc 89.64 cm. Overall, treatment P4 showed the best effectiveness in increasing rice plant height, which can optimally support the photosynthesis process.

Crop yield is determined by biomass accumulation and harvest index at maturity, where increasing biomass is a key strategy for improving productivity. Biomass accumulation is strongly influenced by the ability of the canopy to intercept radiation and by radiation use efficiency (RUE), which is closely related to the rate of photosynthesis. Therefore, optimizing photosynthesis is a crucial factor in enhancing RUE and crop yield. Optimal plant height can support the development of a wider canopy, thereby improving light interception and photosynthetic efficiency (Huang *et al.,* 2025). In addition, the availability of nutrients such as zinc (Zn) plays an important role, as Zn functions as a cofactor of the enzyme carbonic anhydrase, enhancing photosynthetic efficiency and chlorophyll synthesis, and also contributes to hormonal regulation that supports cell division and elongation (Broadley *et al*., 2007). Therefore, zinc application during the vegetative and generative phases, especially in treatment P4, can contribute to optimal final harvest yields.

Table 2. The effect of zinc application and varieties on plant height, number of tillers, and productive tillers in rice plants

Zinc Application	**Plant Height (cm)**	**Number of Tillers (Stems)**	**Productive Tillers (Stems)**
P0 (Control)	88.35 d	17.71 c	9.33 e
P1 (Zinc Priming)	90.02 c	20.51 b	11.31 d
P2 (Zinc Priming + Foliar Spray 2x during Vegetative Phase)	91.13 bc	23.97 a	12.04 c
P3 (Zinc Priming + Foliar Spray 2x during Generative Phase)	91.84 b	19.80 bc	13.00 b
P4 (Zinc Priming + Foliar Spray 2x during Vegetative Phase + 2x during Generative Phase)	94.42 a	24.57 a	14.82 a
LSD Value 5%	1.7**	2.23**	0.426**
Rice Varieties			
Ciherang	91.25 a	21.60	12.46 a
Inpari 32	92.57 ab	20.93	12.22 a
Nutri Zinc	89.64 b	21.41	11.61 b
LSD Value 5%	0.66*	9.51 ns	1.50*

Note: ns = not significant at the 5% level, * and ** denote significant at the 5% and 1% levels, respectivel

The achievement of better plant height aligns with the description of superior varieties released by the Ministry of Agriculture, such as Inpari 32 and Ciherang, which are expected to grow to an optimal height to support good yields. According to the Directorate of Seed Production, Ministry of Agriculture (Direktorat Perbenihan, 2023), Inpari 32 and Ciherang varieties have a potential plant height of around 90–100 cm, which supports photosynthesis efficiency and spikelet filling. Thus, zinc application has been proven to increase plant height, which in turn contributes to improved rice yield and higher harvest potential. This shows that biofortification technology through zinc application can be a solution to increase rice productivity in Indonesia.

3.2. Number of Tillers (Stems)

Based on the analysis of variance and the Least Significant Difference (LSD) test at the 5% level (Table 2), zinc application significantly affected the number of tillers in the three rice varieties tested. Treatment P4 (combination of seed priming and foliar spray of zinc twice during the vegetative phase and twice during the generative phase) resulted in the highest number of tillers, with 24.57 stems per hill. This treatment was not significantly different from P2 (seed priming and foliar spray of zinc twice during the vegetative phase), which produced 23.97 stems, as both P2 and P4 received the same treatment of seed priming and foliar spray during the vegetative phase. Thus, P2 and P4 showed higher numbers of tillers compared to the other treatments. Treatment P1 (seed priming with zinc) resulted in 20.51 stems, while P3 (seed priming and foliar spray of zinc twice during the generative phase) produced 19.80 stems. The lowest number of tillers was recorded for the control (P0), with 17.71 stems.

The difference in rice varieties did not significantly affect the number of tillers. The average number of tillers for the Ciherang variety was 21.60 stems, Inpari 32 had 20.93 stems, and Nutri Zinc had 21.41 stems per hill. These results indicate that the increase in the number of tillers was more influenced by zinc application than by genetic differences between the varieties. Zinc application proved to increase the number of tillers by 38.7% compared to the control. This is consistent with previous studies which reported that zinc application can increase the number of tillers due to the strengthening of the source-sink mechanism, supporting meristematic tissue formation and the activation of growth hormones such as those involved in tiller formation (Cakmak, 2000; Broadley *et al*., 2007).

The results of this study indicate that zinc application through treatments P4 (seed priming and foliar spray twice during the vegetative phase and twice during the generative phase) and P2 (seed priming and foliar spray twice during the vegetative phase) significantly affected the increase in the number of rice tillers. Although they differ in the application stage during the generative phase, the observation of the number of tillers (vegetative phase) showed no significant difference between P4 and P2, as both treatments received the same seed priming and foliar spray during the vegetative phase. The increase in the number of tillers supports increased plant biomass, which plays a crucial role in expanding the plant's capacity to produce optimal yields. Thus, zinc application through P2 and P4 is effective in increasing the number of tillers, which has the potential to increase rice production.

3.3. Number of Productive Tillers

Based on the analysis of variance and the Least Significant Difference (LSD) test at the 5% level (Table 2), zinc application had a highly significant effect on the increase in the number of productive tillers in rice. Treatment P4 (seed priming and foliar spray of zinc twice during the vegetative and generative phases) resulted in the highest number of productive tillers, with 14.82 stems per hill, significantly different from the other treatments. Treatment P3 produced 13.00 stems, P2 12.04 stems, P1 11.31 stems, and the control (P0) produced 9.33 stems per hill.

The difference in rice varieties did not significantly affect the number of productive tillers. Varieties Ciherang (12.46 stems) and Inpari 32 (12.22 stems) did not differ significantly from each other, but they were significantly different from the Nutri Zinc variety (11.61 stems). This indicates that zinc application has a greater effect on the formation of productive tillers than genetic differences between varieties. Treatment P4 showed the best response in increasing the number of productive tillers, with an increase of 58.8%. The increase in the number of productive tillers is of significant importance, as a greater number of productive tillers supports the formation of more panicles, which in turn will increase the number of rice grains. This is consistent with the findings of Saikh *et al.* (2022), who reported that foliar application of zinc can increase the number of productive tillers by up to 46%, contributing to the efficiency of rice plant component formation.

Table 3. The effect of zinc application and variety differences on flowering time, number of grains, empty grains, and filled grains

Zinc Application	**Flowering Time (DAP)**	**Number of Grain (Seed)**	**Empty Grains (%)**	**Filled Grains (%)**
P0 (Control)	60.00 a	110.86 d	17.77 a	82.07 d
P1 (Zinc Priming)	57.88 b	126.48 c	15.83 b	83.80 c
P2 (Zinc Priming + Foliar Spray 2x during Vegetative Phase)	57.77 bc	137.11 b	11.62 c	88.06 b
P3 (Zinc Priming + Foliar Spray 2x during Generative Phase)	57.11 c	142.35 b	10.60 c	89.44 b
P4 (Zinc Priming + Foliar Spray 2x during Vegetative Phase + 2x during Generative Phase)	55.22 d	165.02 a	8.10 d	91.17 a
LSD Value 5%	0.69**	77.7*	1.66**	1.66**
Rice Varieties				
Ciherang	54.73 b	135.50	12.51 b	87.44 a
Inpari 32	55.06 b	141.90	11.80 b	87.81 a
Nutri Zinc	63.00 a	131.60	14.04 a	85.46 b
LSD Value 5%	0.66**	9.51 ns	1.50*	1.62*

Note: ns = not significant at the 5% level, * and ** denote significant at the 5% and 1% levels, respectivel

3.4. Flowering Time (DAP)

Based on the analysis of variance and Least Significant Difference (LSD) test at the 5% level (Table 3), zinc (Zn) application significantly accelerated the flowering time of rice plants. The P4 treatment (seed priming + two foliar sprays of zinc during the vegetative and generative phases) resulted in the fastest flowering time of 55.22 days after sowing (DAP), significantly different from all other treatments. The P3 treatment (seed priming + two foliar sprays of zinc during the generative phase) resulted in a flowering time of 57.11 DAP, which was faster than the control but significantly different from P1 and P2. The P2 treatment (seed priming + two foliar sprays of zinc during the vegetative phase) and P1 (seed priming) resulted in flowering times of 57.77 DAP and 57.88 DAP, respectively, while the control (P0) had the slowest flowering time at 60.00 DAP. The varietal effect on flowering time was also significant. The Ciherang variety (54.73 DAP) and Inpari 32 (55.06 DAP) had faster flowering times compared to Nutrizink, which showed the slowest flowering at 63.00 DAP, significantly different from the other two varieties.

Overall, the results of this study indicate that Zn application, especially in the P4 treatment, significantly accelerated the flowering time, potentially supporting an increase in rice productivity by speeding up the transition to the generative phase. This indicates that Zn is an essential trace element for both plants and humans, playing important roles in various physiological functions, including maintaining protein synthesis, regulating gene expression, forming and stabilizing enzyme structures, supporting energy production, and participating in carbohydrate metabolism, photosynthesis, auxin metabolism, and pollen formation (Boonchuay *et al*., 2013; *Suganya et al*., 2020). Zinc plays a key role in speeding up the transition from the vegetative to the generative phase in plants (Ahmed *et al*., 2022).

3.5. Number of Grains of Panicle

Based on the results of the Least Significant Difference (LSD) test at the 5% significance level (Table 3), zinc (Zn) application significantly increased the number of grains of panicle in rice. The P4 treatment (seed priming + two foliar sprays of zinc during the vegetative and generative phases) resulted in the highest number of grains per panicle, with 165.02 grains, significantly different from other treatments. The P3 treatment (seed priming + two foliar sprays of zinc during the generative phase) produced 142.35 grains, P2 (seed priming + two foliar sprays of zinc during the vegetative phase) produced 137.11 grains, P1 (seed priming) produced 126.48 grains, and the control (P0) produced the fewest grains, 110.86 per panicle. The effect of variety on the number of grains of panicle did not show significant differences. The average number of grains per panicle in the Inpari 32 variety was 141.90 grains, followed by Ciherang with 135.50 grains, and Nutri Zinc with 131.60 grains. This indicates that while there are variations in the variety response to zinc application, the increase in the number of grains was more influenced by the zinc application than by the genetic differences between varieties.

Zinc application supports the formation of more and higher-quality panicles, which in turn increases the number of grains formed. Zinc plays a role in enhancing plant metabolism efficiency and supporting hormonal regulation, particularly in the formation of generative organs like panicles and spikelets (Broadley *et al*., 2007; Saikh *et al*., 2022). Research by Saikh *et al*. (2022) also reported that foliar application of zinc at a 0.5% concentration increases the number of spikelets per panicle in rice by activating metabolism and regulating plant hormones.

The increase in the number of grains per panicle in the P4 treatment showed a 47.7% increase compared to the control, indicating that zinc application is highly effective in increasing the number of grains in rice. This study also showed that the P4 treatment provided the best results for all the tested varieties, with Inpari 32 recording the highest number of grains, followed by Ciherang and Nutri Zinc. This difference highlights genetic variation in the varieties' ability to efficiently utilize zinc, which affects panicle development and spikelet formation. Therefore, integrated zinc application, as in the P4 treatment, not only increases the quantitative yield potential but also supports the physiological performance of rice varieties in forming more productive and uniform grains.

3.6. Percentage of Filled and Empty Grains (%)

Based on the analysis of variance and Least Significant Difference (LSD) test at the 5% significance level (Table 3), zinc (Zn) application showed a highly significant effect on increasing the percentage of filled grains and reducing the percentage of empty grains in rice. The P4 treatment (seed priming + two foliar sprays of zinc during both the vegetative and generative phases) resulted in the highest percentage of filled grains, 91.17%, and the lowest percentage of empty grains, 8.10%. This treatment was significantly different from all other treatments. The P3 treatment (seed priming + two foliar sprays of zinc during the generative phase) and P2 treatment (seed priming + two foliar sprays of zinc during the vegetative phase) resulted in filled grains of 89.44% and 88.06%, and empty grains of 10.60% and 11.62%, respectively. Meanwhile, the control (P0) showed the lowest filled grains at 82.07% and the highest empty grains at 17.77%. The P1 treatment (seed priming) only increased the percentage of filled grains to 83.80% and reduced the percentage of empty grains to 15.83%.

The effect of variety on the percentage of filled and empty grains also showed significant differences. The Inpari 32 variety (87.81%) and Ciherang (87.44%) had a higher percentage of filled grains compared to Nutrizink (85.46%). On the other hand, the Nutrizink variety showed the highest percentage of empty grains (14.04%), while Ciherang

(12.51%) and Inpari 32 (11.80%) had lower percentages of empty grains. This suggests that, besides the influence of zinc application, the genetic traits of the variety also play a significant role in the efficiency of grain filling.

Overall, the continuous application of zinc, both through seed priming and foliar sprays during the vegetative and generative phases, proved to be the most effective in improving the quality of filled grains and reducing empty grains. Zinc is a vital micronutrient for plant growth. It indirectly enhances rice yield by improving biochemical pathways within the plant and plays a key role in promoting auxin synthesis and chlorophyll formation. Therefore, both directly and indirectly, zinc plays a significant role in increasing rice yield (Joshi *et al.,* 2023), as well as increasing the activity of carbohydrate metabolism enzymes that support seed filling (Alloway, 2008; Cakmak, 2000; Broadley *et al*., 2007). The application of zinc in the P4 treatment significantly increased the harvest yield and the quality of grain filling. The increase in filled grains (from 82.07% to 91.17%) and the reduction in empty grains (from 17.77% to 8.10%) show that zinc application supports better panicle formation and maximizes grain filling. The 54.4% reduction in empty grains also indicates that zinc plays an important role in reducing the formation of empty seeds, contributing to optimal harvest yield improvement.

3.7. Thousand Grain Weight (g)

Based on the results of the Least Significant Difference (LSD) test at the 5% level (Table 4), zinc (Zn) application significantly affected the thousand grain weight of rice across various rice varieties. The P4 treatment (seed priming + foliar spray of Zn twice during the vegetative phase and twice during the generative phase) resulted in the highest thousand grain weight, which was 29.15 g for the Inpari 32 variety, higher than the other treatments. The thousand grain weight for the P4 treatment of the Ciherang variety was 27.58 g, while for Nutri Zinc, it was only 24.59 g. This shows that the combination of continuous zinc application improves the efficiency of grain filling, which proved to be the most effective compared to other treatments.

Table 4. Effect of zinc application and varietal differences on the weight of 1000 grain (g)

Varieties	1.000 grain weight (g)				
	P0	P1	P2	P3	P4
V1	25.07 c A	24.42 d B	25.41 cb B	26.42 b A	27.58 a B
V2	25.43 d A	26.06 c C	26.40 c A	27.73 b A	29.15 a A
V3	21.67 d B	22.71 c A	23.50 b C	23.73 b B	24.59 a C
LSD 5%			0.5004		

Note: V1 = Ciherang variety; V2 = Inpari-32 variety; V3 = Nutri Zinc variety; P0 = Control; P1 = Zinc priming; P2 = Zinc priming + Foliar spray 2x during the vegetative phase; P3 = Zinc priming + Foliar spray Zinc 2x during the generative phase; P4 = Zinc priming + Foliar spray 2x during the vegetative phase + 2x during the generative phase. Lowercase letters indicate differences between treatments within the same variety, while uppercase letters indicate differences between varieties within the same treatment.

The P4 treatment also resulted in a significant increase in the thousand grain weight for all tested varieties. For example, the Inpari 32 variety showed an increase of 14.63% (from 25.43 g in P0 to 29.15 g in P4), while Ciherang increased by 9.99% (from 25.07 g to 27.58 g). The Nutri Zinc variety showed an increase of 13.47% (from 21.67 g to 24.59 g). These results indicate that zinc application increased the thousand grain weight across all varieties, with the most significant increase in Inpari 32. When compared to the potential thousand grain weight values in the variety descriptions (Direktorat Perbenihan, 2023), the results of P4 for Inpari 32 (29.15 g) and Ciherang (27.58 g) surpassed their potential values, which are 27.1 g and 27–28 g, respectively, while Nutri Zinc is within the range of its descriptive weight (±24.6 g). Foliar application of zinc (Zn) can enhance both the formation and efficient utilization of carbohydrates in plant tissues. This leads to improved grain quality, as indicated by a reduction in unfilled grains, a decrease in dull-colored grains, and a lower proportion of abnormal grains. Consequently, this treatment contributes to an increase in grain weight (Hamam *et al.,* 2017). Zinc also increases the source capacity by enhancing photosynthesis and carbohydrate synthesis and enlarges the sink capacity through increased size and activity of endosperm cells, as well as associated enzyme activities (Alloway, 2008; Kumar *et al*., 2022).

3.8. Harvest Dry Grain (HDG)

Based on the results of analysis of variance and Least Significant Difference (LSD) test at the 5% significance level (Table 5), zinc (Zn) application significantly affected the harvest dry grain (HDG) yield in the three tested rice varieties. The control treatment (P0) resulted in HDG of 6.4 kg for the Ciherang variety, 7.8 kg for Inpari 32, and 6.8 kg for Nutrizink. The P1 treatment (zinc priming) increased the yield to 11.4 kg (Ciherang), 10.6 kg (Inpari 32), and 8.9 kg (Nutri Zinc). The P2 treatment (zinc priming + foliar spray zinc twice during the vegetative phase) resulted in 11.6 kg (Ciherang), 13.5 kg (Inpari 32), and 9.9 kg (Nutri Zinc), while the P3 treatment (zinc priming + foliar spray zinc twice during the generative phase) resulted in 13.8 kg (Ciherang), 14.0 kg (Inpari 32), and 12.6 kg (Nutri Zinc). The best treatment, P4 (zinc priming + foliar spray zinc twice during both vegetative and generative phases), produced 20.2 kg (Ciherang), 19.7 kg (Inpari 32), and 15.2 kg (Nutri Zinc). When HDG yield is converted to tons per hectare, the control treatment (P0) is equivalent to 5.7 tons ha^{-1} (Ciherang), 6.5 tons ha^{-1} (Inpari 32), and 5.7 tons ha^{-1} (Nutri Zinc). In contrast, the P4 treatment resulted in 16.9 tons ha^{-1} for Ciherang, 16.4 tons ha^{-1} for Inpari 32, and 12.7 tons ha^{-1} for Nutri Zinc. These findings indicate that zinc application through a combination of priming and foliar spray can increase yields by more than 100% compared to the control, with the highest increase observed in Ciherang variety (more than 196%) and Inpari 32 (more than 150%). This increase in HDG reflects not only the effectiveness of zinc as a micronutrient but also its close association with the plant's physiological mechanisms, particularly the source-sink efficiency. Zinc acts as a cofactor for various important enzymes, such as carbonic anhydrase, alcohol dehydrogenase, and RNA polymerase, supporting photosynthesis, nitrogen metabolism, and cell division (Cakmak, 2000; Marschner, 2012). In the context of the source-sink mechanism, zinc strengthens the source (leaf) capacity to produce assimilates through enhanced photosynthetic activity and accelerates the mobilization of photosynthates to the sink (grains) by increasing the activity of sugar transporters and starch storage enzymes (Alloway, 2008; Hafeez *et al*., 2013).

Table 5. Effect of zinc application and varietal differences on harvest dry grain (HDG)

Varieties	**Harvest dry grain (kg/plot)**				
	P0	**P1**	**P2**	**P3**	**P4**
V1	6.4 c A	24.42 d B	25.41 cb B	26.42 b A	27.58 a B
V2	7.8 d A	26.06 c C	26.40 c A	27.73 b A	29.15 a A
V3	6.8 d A	22.71 c A	23.50 b C	23.73 b B	24.59 a C
LSD 5%			1.59		

Explanation: V1 = Ciherang variety; V2 = Inpari-32 variety; V3 = Nutri Zinc variety; P0 = Control; P1 = Zinc priming; P2 = Zinc priming + Foliar spray 2x during the vegetative phase; P3 = Zinc priming + Foliar spray Zinc 2x during the generative phase; P4 = Zinc priming + Foliar spray 2x during the vegetative phase + 2x during the generative phase. Lowercase letters indicate differences between treatments within the same variety, while uppercase letters indicate differences between varieties within the same treatment.

3.9. Milled Dry Grain (MDG)

Based on the analysis of variance and Least Significant Difference (LSD) test at a 5% significance level (Table 6), zinc (Zn) application has a highly significant effect on the milled dry grain (MDG) yield of the three rice varieties tested. The control treatment (P0) resulted in MDG yields of 5.3 kg (Ciherang), 6.3 kg (Inpari 32), and 5.4 kg (Nutri Zinc). The P1 treatment (priming Zn) increased the yields to 9.1 kg (Ciherang), 8.6 kg (Inpari 32), and 7.1 kg (Nutri Zinc). The P2 treatment (priming Zn + foliar spray twice during the vegetative phase) resulted in 9.6 kg (Ciherang), 11.1 kg (Inpari 32), and 8.1 kg (Nutri Zinc). The P3 treatment (priming Zn + foliar spray twice during the generative phase) yielded 11.4 kg (Ciherang & Inpari 32) and 10.1 kg (Nutri Zinc). The best treatment, P4 (priming Zn + foliar spray twice during both the vegetative and generative phases), resulted in MDG yields of 16.3 kg (Ciherang), 16.0 kg (Inpari 32), and 12.1 kg (Nutri Zinc). When converted to tons per hectare, P0 corresponds to 4.46 t ha^{-1} (Ciherang), 5.29 t ha^{-1} (Inpari 32), and 4.57 t ha^{-1} (Nutri Zinc), while P4 reached 13.64 t ha^{-1} (Ciherang), 13.35 t ha^{-1} (Inpari 32), and 10.14 t ha^{-1} (Nutri Zinc). These findings indicate that integrated zinc application can more than double the harvest yield compared to the control conditions. When compared to the potential yield of superior rice varieties issued by the Directorate of Seedling, Ministry of Agriculture (Direktorat Perbenihan, 2023), such as Inpari 32 and Ciherang, which have a potential yield of around 8-8.5 tons per hectare, the P4 treatment on Inpari 32 (13.35 t/ha) and Ciherang (13.64 t/ha) surpassed the set potential. This shows that the application of P4 zinc not only significantly improves yield but also allows for yields beyond the potential of the designated superior varieties. Thus, proper zinc application can maximize the genetic potential of rice varieties, thereby optimally increasing productivity.

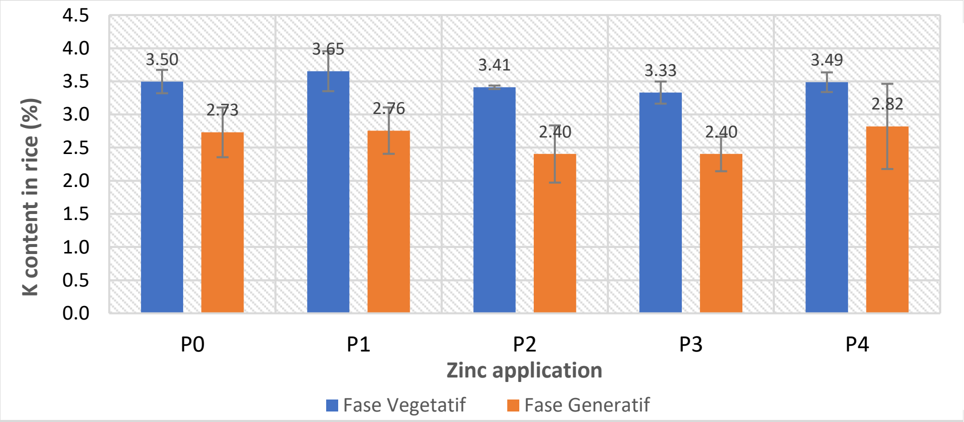
Table 6. The effect of zinc application and varietal differences on dry unhusked rice (DUR)

Varieties	**Dry unhusked rice (kg/plot)**				
	P0	**P1**	**P2**	**P3**	**P4**
V1	5.3 c A	24.42 d B	25.41 cb B	26.42 b A	27.58 a B
V2	6.3 d A	26.06 c C	26.40 c A	27.73 b A	29.15 a A
V3	5.4 d A	22.71 c A	23.50 b C	23.73 b B	24.59 a C
LSD 5%			1.20		

Explanation: V1 = Ciherang variety; V2 = Inpari-32 variety; V3 = Nutri Zinc variety; P0 = Control; P1 = Zinc priming; P2 = Zinc priming + Foliar spray 2x during the vegetative phase; P3 = Zinc priming + Foliar spray Zinc 2x during the generative phase; P4 = Zinc priming + Foliar spray 2x during the vegetative phase + 2x during the generative phase. Lowercase letters indicate differences between treatments

3.10. Potassium Content Due to Zinc Treatment

Based on the analysis of potassium content in rice biomass during the vegetative and generative phases, the Least Significant Difference (LSD) test was not applied in this analysis as the samples analyzed were taken from 45 treatment plots and then composited and analyzed in the laboratory. Therefore, while the results obtained are representative of all treatments, no statistical testing using LSD was performed. However, based on the composite sample analysis, the potassium content in the biomass for treatment P4 (priming Zn and foliar spray twice during the vegetative and generative phases) showed a higher tendency compared to other treatments (Figure 2).



Description:

P0 = Control;
P1 = Zinc Priming;
P2 = Zinc Priming + Foliar Spray 2x Vegetative Phase;
P3 = Zinc Priming + Foliar Spray 2x Generative Phase;
P4 = Zinc Priming + Foliar Spray 2x Vegetative Phase + 2x Generative Phase

Figure 2. Potassium (K) content in the vegetative and generative phases of several rice varieties

During the vegetative phase, the highest potassium content was recorded in treatment P1 (priming Zn) with an average of 3.65%, followed by the control (P0) at 3.50%, P4 at 3.49%, P2 at 3.41%, and P3 at 3.33%. During the generative phase, the highest potassium content was observed in treatment P4, with an average of 2.82%, followed by P1 at 2.76%, P0 at 2.73%, and P2 and P3 at 2.40% each. Regarding varieties, Inpari 32 showed the highest potassium content during the generative phase, at 3.56% in treatment P4, while Nutri Zinc recorded the lowest content at 1.92% in treatment P2.

Treatment P4 (priming Zn+ foliar spray twice during both vegetative and generative phases) showed a better tendency to maintain potassium levels in plant tissues. During the generative phase, treatment P4 experienced a decrease of about ±19.2% (from 3.49% in the vegetative phase to 2.82% in the generative phase), which is lower than the decrease observed in other treatments, ranging from 20% to 45%. This reduction in potassium content is a natural physiological process due to the remobilization of nutrients from vegetative organs (source) to generative organs (sink) (Marschner, 2012). Potassium (K) plays an important role in the translocation of water, essential nutrients, and other substances from the roots through the stem to the leaves. This element is also involved in various metabolic processes and biochemical reactions within plant cells (Rengel & Damon, 2008; White, 2013), including regulatory mechanisms and transport systems (Adams & Shin, 2014). In addition, potassium plays a role in regulating stomatal opening and closing and enhances photosynthesis by regulating CO_2 uptake. K is also important in photosynthesis, translocation, and carbohydrate metabolism, which are produced as a result, ultimately contributing to increased crop yield and improved grain quality (Pettigrew, 2008; Zorb *et al*., 2014; Lu *et al*., 2016). Potassium (K) plays an important role in activating various enzymes related to plant growth. This element is also required in the synthesis of protein and starch in plants. Furthermore, K supports carbohydrate metabolism and is involved in enzyme activation, where almost every stage of these metabolic processes depends on the presence of K, including the activation of enzymes involved in these processes (Rawat *et al*., 2022).

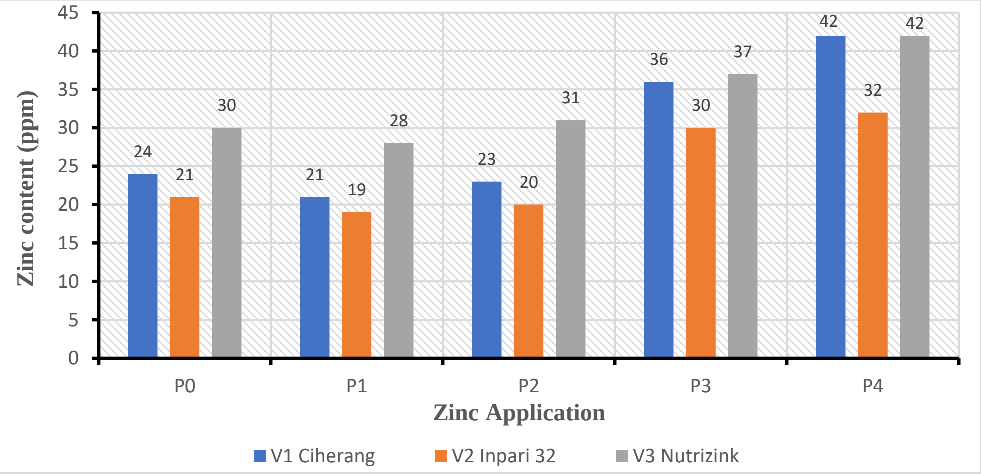
The success of treatment P4 in maintaining potassium content through to the generative phase can be explained by the increased physiological efficiency of the plants supported by zinc. Zinc enhances the activity of ion transport enzymes, including potassium ions, and supports auxin synthesis and membrane permeability, which strengthens the efficiency of potassium absorption and retention (Alloway, 2008; Cakmak, 2008). Additionally, zinc helps maintain membrane integrity and reduces potassium leakage, especially during the critical grain-filling phase (Rehman *et al*., 2018). For the Inpari 32 variety, treatment P4 showed optimal results with a relatively small decrease in potassium content (about 2.5%), from 3.65% to 3.56%. This suggests that Inpari 32 has better physiological efficiency in retaining potassium during the generative phase compared to Nutri Zinc, which experienced a potassium decrease of nearly 45% in some treatments. In the context of agricultural success, according to Linquist (2020), the optimal potassium level in rice stem tissues during the generative phase is between 2.0-2.6%. All varieties under treatment P4 managed to maintain potassium levels in the tissue above this critical threshold, with Inpari 32 at 3.56%, Ciherang at 2.40%, and Nutri Zinc at 2.50%. This demonstrates that integrated zinc fertilization strategies can maintain potassium at optimal levels during crucial physiological periods, which in turn supports the efficiency of the source-sink mechanism, enhances productivity, and improves harvest quality.

Overall, the results of this study show that treatment P4 (Priming Zinc + Foliar Spray 2× during vegetative and 2× during generative phases) significantly contributes to maintaining potassium levels in rice plant tissues, which is crucial in supporting efficient growth and yield. The synergy between zinc and potassium has been proven to support a more efficient sink mechanism, improving grain filling, and enhancing rice yield.

3.11. Zinc Content in Rice (ppm)

Based on the analysis of zinc content in rice during the vegetative and generative phases, the Least Significant Difference (LSD) test was not applied in this analysis because the samples analyzed were taken from 45 experimental plots, which were then composited and analyzed in the laboratory. Therefore, although the results obtained are representative of the entire treatment, statistical testing using LSD was not performed. However, based on the composite sample analysis, the zinc content in rice for the P4 treatment (zinc priming and foliar spray twice during the vegetative and generative phases) showed a higher trend compared to the other treatments (Figure 3).

The zinc content in rice revealed that integrated zinc fertilization through a combination of seed priming and foliar spraying significantly increased the zinc content in rice. For the Ciherang variety, the initial zinc content in the control treatment (P0) was 24 ppm, with a significant increase in the P4 treatment (zinc priming and foliar spray twice during the vegetative and generative phases), which reached 42 ppm. The P3 treatment (zinc priming and foliar spray twice during the generative phase) also showed a moderate increase to 36 ppm. For the Inpari 32, a similar increase was recorded with zinc content in P0 at 21 ppm, and increased to 32 ppm in P4. Meanwhile, the Nutri Zinc variety, which has high genetic capacity, showed an initial zinc content of 30 ppm in P0 and increased to 42 ppm in P4. Overall, the P4 treatment resulted in the highest average zinc content of 39 ppm, followed by P3 with 34 ppm, P0 with 25 ppm, P1 with 23 ppm, and P2 with 25 ppm. These results show that timely and continuous zinc fertilization can improve zinc content in rice, especially in varieties with high genetic potential. The P4 treatment showed the best trend in increasing the zinc content in rice, with an significant increase of 54.68% compared to the control (P0).



Description:

P0 = Control;
P1 = Zinc Priming;
P2 = Zinc Priming + Foliar Spray 2x Vegetative Phase;
P3 = Zinc Priming + Foliar Spray 2x Generative Phase;
P4 = Zinc Priming + Foliar Spray 2x Vegetative Phase + 2x Generative Phase

Figure 3. The effect of different rice varieties and zinc application on the zinc content in rice (ppm)

The increase in zinc content is closely related to the physiological role of zinc in supporting the activity of important enzymes such as RNA polymerase, carbonic anhydrase, and alcohol dehydrogenase, which are involved in plant metabolism. In addition, zinc plays a crucial role in regulating cell membranes and protein metabolism that support assimilate transport and seed filling (Alloway, 2008; Marschner, 2012). llness in young children may result in the depletion of essential nutrients required for optimal growth and development. Under such conditions, the available nutrient intake is predominantly allocated to support immune function in combating infections. Therefore, zinc (Zn) plays a crucial role in enhancing immune system performance and is important in the prevention of stunting, as it can reduce the risk of infectious diseases (Asiah *et al*., 2020). Zinc (Zn) also plays an important role in the process of bone growth and development (Molenda & Kolmas, 2023).

This study emphasizes that although P4 is the best treatment, P3 and P2 also contribute significantly to fulfilling the daily zinc requirements, especially for populations vulnerable to zinc deficiency, such as infants and pregnant women. Consuming zinc-fortified rice through optimal treatments can help prevent stunting, The nutritional status of children under five with a classification of very short stature is defined as stunting.

4. CONCLUSION

Based on the results of the study, the application of zinc ($ZnSO_4$ 0.5%) through seed priming and foliar spray during the vegetative and generative phases significantly affected the improvement of various growth and yield parameters in rice plants, including plant height, tiller number, productive tiller number, flowering time, number of grains per panicle, 1,000-grain weight, percentage of empty grains, percentage of filled grains, harvest dry grain (HDG), and dry unhusked rice (DUR). The P4 treatment (seed priming and Zn application during both the vegetative and generative phases) showed the best response in improving growth, yield, and zinc content in rice, with an average increase of 56% compared to the control. Furthermore, the P4 treatment was also effective in maintaining potassium content in the rice biomass during the generative phase, which is crucial for supporting growth efficiency and grain filling. The variety factor also significantly affected yield parameters, with the Nutri Zinc variety showing the highest potassium uptake and zinc content in the rice. The Ciherang variety showed the highest response to the P4 treatment, with a 75% increase in zinc content in rice, followed by Inpari 32 (52%) and Nutri Zinc (40%). The interaction between zinc application and variety had a highly significant effect on 1,000-grain weight, HDG, DUR, and the ability to maintain potassium content in plant tissues during the generative phase. These findings indicate that zinc biofortification can significantly enhance both production yield and zinc content in rice, with the variety playing a key role in determining the response to zinc application. Further research is needed to evaluate the effectiveness of combining zinc application with macro fertilizers, as well as to perform planting during the same season (simultaneous planting) in a single rice field.

AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
KM	✓					✓	✓	✓	✓	✓	✓		✓	
MMK	✓	✓		✓	✓		✓	✓		✓	✓	✓	✓	
EP	✓	✓		✓	✓			✓		✓	✓	✓	✓	
RADW	✓	✓		✓	✓					✓	✓	✓		
MSH				✓	✓					✓	✓			

C: Conceptualization
M: Methodology
So: Software
Va: Validation
Fo: Formal Analysis
I: Investigation
D: Data Curation
R: Resources
O: Writing - Original Draft
E: Writing - Review & Editing
Vi: Visualization
Su: Supervision
Fu: Funding Acquisition
P: Project Administration

REFERENCES

Adams, E., & Shin, R. (2014). Transport signaling and homeostasis of potassium and sodium in plants. *Journal of Integrative Plant Biology*, ***56***, 231-249. https://doi.org/10.1111/jipb.12159

Ahmed, N., Hussain, H.Z., Ali, M.A., Rahi, A.A., Saleem, M., & Ahmad, F. (2022). Effect of zinc on chlorophyll contents, gas exchange attributes and zinc concentration in rice. *Pakistan Journal of Botany*, ***54***(1), 17–24. https://doi.org/10.30848/PJB2022-1(14)

Alloway, B.J. (2008). *Zinc in Soils and Crop Nutrition*. International Zinc Association (IZA) and International Fertilizer Industry Association (IFIA), Brussels, Belgium and Paris, France.

Asiah, A., Yogisutanti, G., & Purnawan, A.I. (2020). Asupan mikronutrien dan riwayat penyakit infeksi pada balita stunting di UPTD Puskesmas Limbangan Kecamatan Sukaraja Kabupaten Sukabumi. *Journal of Nutrition College*, ***9***(1), 6–11. https://doi.org/10.14710/jnc.v9i1.24647

Badan Meteorologi, Klimatologi, dan Geofisika [BMKG]. (2023). *Buletin Pemantauan Musiman Indonesia: Q3 (Juli-September) 2023*. Jakarta.

Badan Pangan Nasional. (2023). *Statistik Konsumsi Pangan Tahun 2023*. Kementerian Pertanian Indonesia, Jakarta.

Barman, H., Das, S., & Roy, A. (2018). Zinc in soil environment for plant health and management strategy. *Universal Journal of Agricultural Research*, ***6***(5), 149-154. https://doi.org/10.13189/ujar.2018.060501

Boonchuay, P., Cakmak, I., Rerkasem, B., & Prom-U-Thai, C. (2013). Effect of different foliar zinc application at different growth stages on seed zinc concentration and its impact on seedling vigor in rice. *Soil Science and Plant Nutrition, **59***(2), 180–188. https://doi.org/10.1080/00380768.2013.763382

Broadley, M.R., White, P.J., Hammond, J.P., Zelko, I., & Lux, A. (2007). Zinc in plants. *New Phytologist*, ***173***(4), 677–702. https://doi.org/10.1111/j.1469-8137.2007.01996.x

Cakmak, I. (2000). Possible roles of zinc in protecting plant cells from damage by reactive oxygen species (Tansley Review No. 111). *New Phytologist*, ***146***(2), 185–205. https://doi.org/10.1046/j.1469-8137.2000.00630.x

Das, S., Avasthe, R., Singh, S., Dutta, S., & Roy, A. (2018). Zinc in plant-soil system and management strategy. *Agrica*, ***7***(1), article #4. https://doi.org/10.5958/2394-448X.2018.00001.9

Direktorat Perbenihan, Kementerian Pertanian. (2023). *Deskripsi Varietas Unggul Baru Padi*. Dinas Pertanian dan Ketahanan Pangan DIY (Gebyar Perbenihan Tanaman Pangan 2023).

Hafeez, B., Khanif, Y.M., & Saleem, M. (2013). Role of zinc in plant nutrition: A review. *Asian Journal of Experimental Agriculture*, ***3***(2), 374–391. https://doi.org/10.9734/AJEA/2013/2746

Hamam, M., Pujiasmanto, B., & Supriyono. (2017). Peningkatan hasil padi (*Oryza sativa* L.) dan kadar zink dalam beras melalui aplikasi zink sulfat heptahidrat. *Jurnal Agronomi Indonesia*, ***45***(3), 243–248. https://doi.org/10.24831/jai.v45i3.12287

Huang, J., Chai, Y., Yang, S., Cao, Y., Yang, L., Wang, M., Meng, X., & Guo, S. (2025). Integrated innovation and application of green high-yield and high-efficiency technologies of rice in China. *Frontiers of Agricultural Science and Engineering, **12***(3), 530–544. https://journal.hep.com.cn/fase/EN/10.15302/J-FASE-2025636

Joshi, Y. R., Lamichhane, S. K., Paudel, A., Aryal, M., & Adhikari, S. (2023). Effect of different methods of zinc application on the performance of spring rice (Hardinath-1) in Banke, Nepal. *Russian Journal of Agricultural and Socio-Economic Sciences*

(RJOAS), ***2***(134), 151–158. https://doi.org/10.18551/rjoas.2023-02.17

Khan, M.W., Rab, A., Ali, R., Sajid, M., Khan, M.N., Ali, A., Khan, M.A., Pervez, W., & Amin, F. (2018). Improving growth and yield of potato through potassium and zinc fertilization. *Pure and Applied Biology*, ***7***(3), 992–997. http://dx.doi.org/10.19045/bspab.2018.700117

Kumar, S., Sarangthem, I., Devi, N.S., Devi, K.N., & Singh, N.G. (2022). Effect of zinc nutrition on economic productivity of rice (*Oryza sativa*) and soil biological properties. *The Indian Journal of Agricultural Sciences*, ***92***(3), 420-423. https://doi.org/10.56093/ijas.v92i3.122732

Linquist, B. (2020). *Optimal and Critical Nutrient Concentrations in Rice Tissue (Fact Sheet)*. University of California, Agriculture and Natural Resources — UCCE Rice Specialist & Farm Advisors.

Lu, Z., Lu, J., Pan, Y., Lu, P., Li, X., Cong, R., & Ren, T. (2016). Anatomical variation of mesophyll conductance under potassium deficiency has a vital role in determining leaf photosynthesis. *Plant, Cell & Environment*, ***39***(11), 2428-2439. https://doi.org/10.1111/pce.12795

Marschner, P. (Ed.). (2012). *Marschner's Mineral Nutrition of Higher Plants* (3rd ed.). Academic Press, Amsterdam. https://doi.org/10.1016/C2009-0-63043-9

Molenda, M., Kolmas, J. (2023). The role of zinc in bone tissue health and regeneration – A review. *Biological Trace Element Research*, ***201***, 5640–5651. https://doi.org/10.1007/s12011-023-03631-1

Pettigrew, W.T. (2008). Potassium influences on yield and quality production for maize wheat soybean and cotton. *Physiologia Plantarum*, ***133***(4), 670-681. https://doi.org/10.1111/j.1399-3054.2008.01073.x

Rengel, Z., & Damon, P.M. (2008). Crops and genotypes differ in efficiency of potassium uptake and use. *Physiologia Plantarum*, ***133***(4), 624-636. https://doi.org/10.1111/j.1399-3054.2008.01079.x

Rawat, J., Pandey, N., & Saxena, J. (2022). Role of potassium in plant photosynthesis, transport, growth and yield. In N. Iqbal & S. Umar (Eds.), *Role of Potassium in Abiotic Stress*. Springer Nature Singapore. https://doi.org/10.1007/978-981-16-4461-0_1

Rehman, H., Aziz, T., Farooq, M., Wakeel, A., & Rengel, Z. (2012). Zinc nutrition in rice production systems: a review. *Plant and Soil*, ***361***, 203-226. https://doi.org/10.1007/s11104-012-1346-9

Saikh, R., Murmu, K., Sarkar, A., Mondal, R., & Jana, K. (2022). Effect of foliar zinc application on growth and yield of rice (*Oryza sativa*) in the Indo-Gangetic Plains of India. *Nusantara Bioscience*, ***14***(2), 182–187. https://doi.org/10.13057/nusbiosci/n140208

Salem, E.M.M., Kenawey, M.K.M., Saudy, H.S., & Hafez, E.M. (2022). Influence of silicon forms on nutrients accumulation and grain yield of wheat under water deficit conditions. *Gesunde Pflanzen*, ***74***, 539–548. https://doi.org/10.1007/s10343-022-00629-y

Suganya, A., Saravanan, A., & Manivannan, N. (2020). Role of zinc nutrition for increasing zinc availability, uptake, yield, and quality of maize (*Zea mays* L.) grains: An overview. *Communications in Soil Science and Plant Analysis,* ***51***(16), 2001–2021. https://doi.org/10.1080/00103624.2020.1820030

UNICEF Indonesia. (2022). *Menuju Masa Depan Indonesia Bebas Masalah Kekurangan Gizi*. UNICEF Indonesia.

Winarso, S. (2005). *Kesuburan Tanah, Dasar Kesehatan dan Kualitas Tanah*. Gava Media, Yogyakarta.

White, P.J. (2013). Improving potassium acquisition and utilisation by crop plants. *Journal of Plant Nutrition and Soil Science*, ***176***(3), 305-316. https://doi.org/10.1002/jpln.201200121

Zorb, C., Senbayram, M., & Peiter, E. (2014). Potassium in agriculture-status and perspectives. *Journal of Plant Physiology*, ***171***(9), 656-669. https://doi.org/10.1016/j.jplph.2013.08.008