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THE ENHANCEMENT OF BIOMASS ACCUMULATION, SEED YIELD, AND ZINC (Zn) CONTENT IN SEVERAL RICE (Oryza sativa L.) VARIETIES THROUGH ZINC (ZnSO4) APPLICATION

PENINGKATAN AKUMULASI BIOMASSA, HASIL BIJI, DAN KANDUNGAN ZINC (Zn) BEBERAPA VARIETAS PADI SAWAH (*Oryza sativa* L.) MELALUI APLIKASI ZINC (ZnSO4)

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ABSTRACT

This study aimed to evaluate the effects of $ZnSO_4$ application on biomass accumulation, grain yield, and Zn content in three rice varieties. The research was conducted in paddy fields located in Maja Village, Margapunduh Subdistrict, Pesawaran District, Lampung. The treatments were arranged in a factorial design using a strip plot with three replications. The treatments were arranged by a factorial design (4×3) using a strip plot in a completely randomized block design (CRBD) with three replications. The first factors were four application methods of $ZnSO_4$, consisting of: control (P0), seed priming with 0.25% $ZnSO_4$ (P1), seed priming with 0.25% $ZnSO_4$ and foliar spray with 0.5% $ZnSO_4$ at the vegetative stage (P2), seed priming with 0.25% $ZnSO_4$ and foliar spray with 0.5% $ZnSO_4$ at the generative stage (P3), and seed priming with 0.25% $ZnSO_4$ and foliar spray with 0.5% $ZnSO_4$ at both vegetative and generative stages (P4). The second factors were three rice varieties, consisting of Ciherang (V1), Inpari-32 (V2), and Inpari IR Nutrizinc (V3). The observed variables included fresh and dry biomass at vegetative and harvest stages, weight of 100 grains, harvest index, and milled dry grain. The results showed that the combination of $ZnSO_4$ seed priming and foliar spray at both vegetative and generative stages significantly increased biomass accumulation, grain yield, and Zn content. Ciherang and Inpari-32 varieties produced higher yields compared to Inpari IR Nutrizinc. This study indicates that agronomic biofortification through $ZnSO_4$ application is effective in improving rice yield and nutritional quality, particularly Zn content, which plays a vital role in addressing stunting.

KATA KUNCI:
Biofortifikasi, hasil panen, mikronutrien, padi sawah, varietas, zinc

ABSTRAK

Penelitian ini bertujuan untuk mengevaluasi pengaruh aplikasi $ZnSO_4$ terhadap akumulasi biomassa, hasil biji, dan kandungan Zn pada tiga varietas padi sawah. Penelitian dilaksanakan di lahan sawah Desa Maja, Kecamatan Margapunduh, Kabupaten Pesawaran, Lampung. Perlakuan disusun secara faktorial menggunakan rancangan strip plot. Faktor pertama adalah aplikasi $ZnSO_4$ yang terdiri dari kontrol (P0), priming $ZnSO_4$ 0,25% (P1), priming $ZnSO_4$ 0,25% dan foliar spray ZnSO4 0,5% pada fase vegetatif (P2), priming ZnSO4 0,25% dan foliar spray $ZnSO_4$ 0,5% pada fase generatif (P3), dan priming ZnSO4 0,25% dan foliar spray ZnSO4 0,5% pada fase vegetatif dan fase generatif (P4). Faktor kedua adalah varietas padi yang terdiri dari varietas Ciherang (V1), Inpari-32 (V2), dan Inpari IR Nutrizinc (V3). Variabel yang diamati meliputi biomassa segar dan kering pada fase vegetatif dan panen, bobot 100 butir gabah, indeks panen, dan gabah kering giling. Hasil penelitian menunjukkan bahwa aplikasi $ZnSO_4$ secara priming dan foliar spray pada fase vegetatif dan generatif meningkatkan akumulasi biomassa, hasil gabah, dan kandungan Zn, sementara varietas Ciherang dan Inpari-32 memberikan hasil lebih tinggi dibandingkan Inpari IR Nutrizinc. Penelitian ini menunjukkan bahwa biofortifikasi agronomis melalui aplikasi $ZnSO_4$ efektif meningkatkan hasil dan kualitas gizi beras. Khususnya kandungan Zn yang dapat membantu dalam mengatasi stunting.

1. INTRODUCTION

Rice (*Oryza sativa* L.) is one of the important food crops and strategic commodities having a central role in maintaining food security in Indonesia. As the staple food of the majority of the population in Indonesia, the adequate availability of rice is an important indicator in fulfilling the basic needs of the community. In 2024, BPS reported that national rice production reached 53.14 million tons of milled dry grain (MDG). The percentage decreased slightly by 1.55% compared to 2023. This decline in production is due to several factors such as genetic factors, land use change, climate change including drought and flooding, decreased soil fertility, and lack of micro-nutrient management.

Efforts to increase productivity to achieve success can be supported by the role of using superior varieties that can increase yield potential, optimizing land use, application of optimum fertilizer, improving resistance to biotic and abiotic stresses, and improving quality which includes taste and nutritional content in the rice produced (Aristya and Taryono, 2019). Rice contains approximately 360 kcal of energy, 6.6 g of protein, 0.58 g of fat, and 79.34 g of carbohydrates per 100 g of grain (USDA, 2011). Despite its substantial contribution to daily energy intake, rice contains relatively low levels of essential micronutrients required for optimal human health. Consequently, populations that depend heavily on rice-based diets may be at an increased risk of inadequate micronutrient intake. This issue is particularly important in developing countries, where rice constitutes a significant proportion of the daily diet. As a result, malnutrition remains a major public health challenge, encompassing undernutrition, overnutrition, and micronutrient deficiencies (Arif *et al*., 2020).

Micronutrient deficiencies remain a major public health concern worldwide, particularly among children and pregnant women (WHO, 2024). Among these deficiencies, Zn deficiency is one of the most prevalent and has received considerable attention because of its essential role in growth, immune function, and cellular metabolism. In children, inadequate Zn intake can impair growth and development by reducing growth hormone activity, thereby increasing the risk of stunting (Fatimah *et al.,* 2020). Given that rice is the primary staple food for a large proportion of the population, enhancing Zn concentration in rice grains represents a promising strategy to improve dietary Zn intake and contribute to stunting prevention.

Zinc is one of the essential micronutrients that has an important role in plant metabolism and contributes to several cellular and physiological activities of plants thereby increasing plant growth, development, and yield (Hamzah *et al*., 2022). Zinc plays an important role in N metabolism in plants and is needed to activate enzymes that convert nitrate into ammonia, so that N can be absorbed by plants (Cakmak *et al*., 2010). Zinc deficiency causes disruption of metabolic processes, stunted growth and leaf chlorosis, thereby interfering with the absorption of nutrients and contributing to food source deficiencies in humans (Hamzah *et al*., 2022). Adequate Zn availability in plants can increase N uptake, thereby increasing growth and biomass production (Cakmak *et al*., 2010).

Plant biomass is the total dry matter accumulated from all organic components produced during the plant's life cycle. In rice, high biomass accumulation plays an important role in increasing yield. Greater biomass reflects sufficient energy and organic compounds to support grain formation and filling (Andesmora *et al*., 2023). Ji *et al*. (2022) reported that Zn availability promotes the uptake, translocation, and distribution of nitrogen in rice, while N supply increases Zn uptake and translocation.

Biofortification is a strategy to improve the nutritional content of rice for wider consumption. It involves enhancing the concentration of bioavailable elements in edible plant parts through plant breeding, genetic engineering, or agronomic practices (Singh *et al*., 2016; Bouis & Saltzman, 2017; Garg *et al*., 2018). Exogenous biofortification can be applied by soil fertilization, seed priming, or foliar spraying (Farooq *et al*., 2012).

Yamuangmorn *et al*. (2022) reported that priming treatment of rice seeds using 0.5% $ZnSO_4$ solution can increase seedling vigor and Zn accumulation in grain. The results of research by Sisodiya *et al*. (2021) showed that foliar spray treatment with a concentration of 0.5% $ZnSO_4$ applied to rice plants aged 30 and 60 day after planting (DAP) produced better growth, yield components, and uptake of Zn, N, P and K in shoots, roots, grain and straw compared to the control. Saikh *et al*. (2022) also reported the application of zinc on the leaves at a concentration of 0.5% ($ZnSO_4 \cdot 7H_2O$) at panicle initiation and one week after flowering was able to increase grain yield, biomass accumulation, N availability in the soil compared to other treatments, especially the control. In addition, Zn in rice grains can be effectively increased by foliar application of Zn, especially when Zn is sprayed after flowering.

The use of improved varieties such as Ciherang, Inpari 32, and Inpari IR Nutrizinc plays an important role in efforts to increase rice production in Indonesia. Ciherang has high yield potential and good adaptation to various conditions. This variety is popular among farmers because of its high productivity and taste that is favored by the wider community. Inpari 32 was developed with the advantage of high potential and resistance to leaf blight. Chairuman et al. (2022) mentioned that Inpari IR Nutrizinc has competitive yield potential, is adaptive in sub-optimal land, and has a nutritional content rich in zinc produced from the Agricultural Research and Development Agency and was released in 2019. This study aimed to determine the effectiveness of $ZnSO_4$ application to increase biomass accumulation, seed yield, and Zn content in three varieties of paddy rice.

2. MATERIALS AND METHOD

2.1 Materials and methods

This research was conducted in the paddy field of Maja Village, Marga Punduh District, Pesawaran Regency, Lampung Province from July to November 2024. The materials used in this study were Zinc sulfate heptahydrate ($ZnSO_4.7H_2O$), rice seeds of Ciherang, Inpari 32, and Inpari IR Nutrizinc varieties, Urea, SP-36, and KCl fertilizers, insecticides, and fungicides, while the tools used in this study were trays, hoes, buckets, measuring cups, meters, and stationery.

2.2 Experiment Design

The treatments were arranged by a factorial design (4x3) using a strip plot in a completely randomized block design (CRBD) with three replications. The first factor were four applications of Zinc which consists of priming with distilled water for 12 hours (P_0), Priming Zn 0.25% for 12 hours (P_1), Priming Zn 0.25% for 12 hours + Foliar spray Zn 0.5% Early Vegetative Phase (21-25 DAP) and Late Vegetative Phase (40–50 DAP) (P_2), Priming Zn 0.25% for 12 hours + Foliar spray Zn 0.5% Generative Phase of grain filling (65 DAP) and milk ripening phase (75 DAP) (P_3), and Priming Zn 0.25% for 12 Hours + Foliar spray Zn 0.5% Early Vegetative Phase (21–25 DAP) and Late Vegetative Phase (40–50 DAP) + Generative Phase of grain filling (65 DAP) and milk ripening phase (75 DAP) (P_4). The second factor were rice varieties consisting of Ciherang (V_1), Inpari-32 (V_2), and Inpari IR Nutrizinc (V_3).

The observation variables included fresh and dry biomass in the vegetative and harvest phases, 100-grain weight, harvest index, milled dry grain, and Zn content in the husk. Zinc content in the husk was tested following the procedure of the Technical Manual of the Soil and Fertilizer Instrument Standard Testing Center (2023). The husk samples were deconstructed using the wet deconstruction method with nitric acid (HNO_3), and the Zn content was analyzed using an Atomic Absorption Spectrophotometer (AAS). The data obtained from the observations were analyzed using RStudio software, followed by Tukey's Honestly Significant Difference (HSD) test at the 5% significant level.

3. RESULT AND DISCUSSION

Zinc application improved biomass accumulation and yield performance in the evaluated rice varieties (Table 1). Plants supplied with Zn produced greater fresh and dry biomass during both vegetative and harvest phases, which was accompanied by increases in 100-grain weight, harvest index, and milled dry grain yield. Differences among varieties were observed mainly in yield-related traits, indicating variation in their productive potential. The response to Zn application also varied among varieties, particularly for 100-grain weight and milled dry grain yield, suggesting that some genotypes were more responsive to Zn fertilization than others. These results demonstrate that Zn application can enhance rice productivity, although the magnitude of improvement depends on varietal characteristics.

3.1 Fresh and dry biomass in the vegetative phase

The results showed that application had a very significant effect on the accumulation of fresh and dry biomass in the vegetative phase, while varietal differences had no significant effect (Table 2). Zinc application by priming and foliar spray in the vegetative phase (P_2), priming and foliar spray in the generative phase (P_3), priming and foliar spray in the vegetative and generative phases (P_4) produced higher vegetative phase fresh and dry biomass than the control (P_0) (Table 2). Compared to the control (P_0), the increase in vegetative phase fresh and dry biomass was between 25.5–64.7% and 25.6–50.5%.

Table 1**.** Summary of variance analysis of zinc application effects on biomass and yield in rice varieties

Variable	Zn	Variety	Zn x Variety
Vegetative fresh biomass (g/plant)	**	ns	ns
Vegetative dry biomass (g/plant)	**	ns	ns
Harvest fresh biomass (g/plant)	**	ns	ns
Dry biomass harvest (g/plant)	**	ns	ns
100 Grain (g)	**	**	**
Harvest Index (%)	**	*	ns
Milled Dry Grain (g/m^2)	**	**	**

Notes: ** = highly significant at 5%; * = significant at 5%; ns = non-significant at 5%

Table 2. Effect of zinc application and rice varieties on fresh and dry biomass during vegetative phase

Treatment	Fresh biomass (g)	Dry biomass (g)
Zinc application		
P_0 (Control)	256,88 b	89,94 d
P_1 (*Zinc Priming*)	308,44 b	103,33 cd
P_2 (*Priming Zn + Foliar spray* Vegetative Phase)	423,14 a	129,81 ab
P_3 (*Priming Zn + Foliar spray* Generative Phase)	322,45 a	112,99 bc
P_4 (*Priming Zn + Foliar spray* Vegetative Phase + Generative Phase)	416,77 a	133,89 a
	**	**
Rice varieties		
Ciherang	352,12	116,68
Inpari 32	333,08	112,32
Inpari IR Nutrizinc	356,78	112,96
	ns	ns
HSD value 5%	**97,00**	**44,11**

Note: ** and * indicate highly significant and significant effects at the 5% level, respectively. Means followed by the same letter in the same column indicated not significant difference with the HSD test at the 5% level.

According to Khongchiu *et al*. (2025), zinc has an important role in the process of photosynthesis, especially in enzymatic reactions involving the enzyme carbonic anhydrase. Photosynthesis is the main process producing biomass, Zn application can enhance biomass accumulation by stimulating photosynthesis. Furthermore, Zn activates RNA polymerase, protects ribosomal RNA, and supports chlorophyll and starch synthesis, thereby enhancing photosynthesis and energy storage. It also regulates auxin synthesis, stabilizes cell membranes, and improves stress tolerance, making it indispensable for plant growth and productivity (Rudani *et al*., 2018). Singh *et al*. (2014) also stated that biomass is a reliable indicator of plant productivity, as higher biomass reflects improved photosynthetic efficiency, nutrient uptake, and environmental adaptation.

3.2 Fresh and dry biomass during generative phase

Zinc application also increased the accumulation of fresh and dry biomass in the generative phase (Table 3). The increases in fresh and dry biomass during the generative phase due to Zn application ranged from 24.1–67.2% and 18.1–22.6%, respectively. The highest increase in fresh and dry biomass in the generative phase due to Zn application consistently occurred in the priming and foliar spray Zn treatments in the vegetative and generative phases (P4). The increase in biomass accumulation due to Zn application is related to the role of Zn in the photosynthesis process as previously described (Khongchiu *et al*., 2025). According to Nayak *et al*. (2025), Zn also plays a role in the biosynthesis of indole-3-acetic acid (IAA), and its application influences auxin production, thereby supporting the initiation of reproductive organ primordia. Tuiwong *et al*. (2024) reported that Zn application through foliar spray during the vegetative phase can increase leaf and stem biomass growth and activate the expression of Zn transporter genes such as OsZIP3, OsZIP4, and OsZIP9, which are involved in the absorption and translocation of Zn from leaves to seeds.

3.3 Weight of 100 Grains

The results showed that the response of 100-grain weight to Zn application depends on the different varieties. The three varieties of paddy rice, Ciherang, Inpari 32, and Inpari IR Nutrizinc showed a consistent increase in 100-grain weight due to Zn treatment (Table 4). In the Ciherang variety, Zn treatment by priming and foliar spray in the vegetative and generative phases (P_4) produced the highest 100-grain weight of 2.76 g, or an increase of 9.96% compared to the control (P_0).

Table 3. Effect of zinc application and rice varieties on fresh and dry biomass during vegetative phase

Treatment	Fresh biomass (g)	Dry biomass (g)
Zinc application		
P_0 (Control)	253,35 c	87,76 ab
P_1 (*Zinc Priming*)	292,06 bc	93,00 ab
P_2 (*Priming Zn + Foliar spray* Vegetative Phase)	374,31 a	103,67 ab
P_3 (*Priming Zn + Foliar spray* Generative Phase)	314,55 ab	80,81 b
P_4 (*Priming Zn + Foliar spray* Vegetative Phase + Generative Phase)	405,67 a	107,63 a
	**	**
Rice varieties		
Ciherang	319,85	103,92
Inpari 32	314,05	90,4
Inpari IR Nutrizinc	350,07	89,41
	ns	tn
HSD value 5%	**76,29**	**25,27**

Note: ** and * indicate highly significant and significant effects at the 5% level, respectively. Means followed by the same letter in the same column indicated not significant difference with the HSD test at the 5% level.

Table 4. Effect of zinc application on 100-grain weight in different varieties of paddy rice

Rice varieties	Zinc application				
	P_0	P_1	P_2	P_3	P_4
	………………………………(g)………………………………				
Ciherang	2,51 cd A	2,44 d B	2,54 c B	2,64 b B	2,76 a B
Inpari 32	2,54 d A	2,61 cd A	2,64 c A	2,74 b A	2,92 a A
Inpari IR Nutrizinc	2,17 d B	2,27 c C	2,35 b C	2,37 b C	2,46 a C
HSD value 5%	**216,93**				

Notes: P_0 = Control; P_1 = Priming Zinc; P_2 = Priming Zinc + Foliar Spray at the Vegetative Phase; P_3 = Priming Zinc + Foliar Spray at the Generative Phase; P_4 = Priming Zinc + Foliar Spray at the Vegetative and Generative Phases. Numbers followed by uppercase letters are compared vertically, numbers followed by lowercase letters are compared horizontally, and numbers followed by the same letter indicate no significant difference according to the HSD test at the 5% significance level.

In the Inpari 32 variety, Zn treatment through priming and foliar spray during the vegetative and generative phases (P_4) increased the 100-grain weight by 14.96% compared to the control (P_0). Meanwhile, the Inpari IR Nutrizinc variety also experienced an increase in 100-grain weight of up to 13.36% through Zn treatment by priming and foliar spray in the vegetative and generative phases (P_4). Although the resulting weight is lower than the other two varieties, the increase shown is still significant and consistent.

Zn application has a positive impact on increasing the weight of 100 grains, but the amount varies depending on the variety. This can be attributed to the increase in biomass in the vegetative and generative phases. In addition, this also indicates that the effectiveness of Zn application in increasing yield is also influenced by the genetic characteristics of each variety. Inpari 32 variety showed the most optimal response to Zn application by priming and foliar spray in the vegetative and generative phases (P_4). This variety produced 100-grain weight 5.80% higher than Ciherang and 18.70% higher than Inpari IR Nutrizinc. According to Jumakir *et al*. (2024), varieties that have high yield potential tend to have larger grain size and weight, depending on the efficiency of photosynthate transport to the grain during the filling phase.

In addition, the genetic factor of the Inpari 32 variety is thought to have better grain filling ability. With Zn treatment by priming and foliar spray in the vegetative and generative phases (P4), it can maximize the potential of the variety. Supported by Iman *et al*. (2013), varietal response to Zn is highly dependent on the ability of each variety to absorb and distribute Zn to seed tissue, especially for genotypes that are tolerant of Zn deficiency.

3.4 Harvest Index

The results showed that Zn application gave a very significant effect, while the difference in varieties showed a significant effect on the harvest index value produced (Table 1). Zinc application increased the harvest index from 16.41% to 31.36%. Zinc treatment by priming and foliar spray in the vegetative and generative phase (P_3), and priming and foliar spray in the vegetative and generative phases (P_4), showed the highest harvest index compared to other treatments, with harvest index values of 31.36% and 31.15%, respectively (Table 5).

The results showed that Zn application through priming and foliar spray during the generative phase had the most significant effect on the efficiency of photosynthate translocation to the grain. This is in accordance with the physiological needs of plants, in which assimilates produced during the vegetative phase are transferred to the generative phase for grain filling.

Table 5. The effect of Zn application on the grain yield index of several paddy rice varieties

Treatment	Harvest index
Zinc application	
P_0 (Control)	16,41 c
P_1 (*Zinc Priming*)	20,98 b
P_2 (*Priming Zn + Foliar spray* Vegetative Phase)	20,92 b
P_3 (*Priming Zn + Foliar spray* Generative Phase)	31,36 a
P_4 (*Priming Zn + Foliar spray* Vegetative Phase + Generative Phase)	31,15 a
	**
Rice Variety	
Ciherang	26,08 a
Inpari 32	26,24 a
Inpari IR Nutrizinc	20,17 b
	*
HSD 5%	**1,23**

Note: ** and * indicate highly significant and significant effects at the 5% level, respectively. Means followed by the same letter in the same column indicated not significant difference with the HSD test at the 5% level.

According to Safriani *et al*. (2018), the harvest index reflects the proportion of photosynthate that is successfully translocated to the generative organs of the plant, especially in the form of grain. The efficiency of photosynthate translocation from vegetative tissues to seeds greatly affects the harvest index value. This is supported by the research of Saikh *et al*. (2022), which showed that Zn treatment during the generative phase (panicle initiation and flowering) increased the harvest index to 42.52% compared to the control. This indicates that the greater the translocation of photosynthate from source to sink, the higher the harvest index value achieved.

The differences among varieties showed different harvest index values. Inpari 32 showed the highest harvest index value of 26.24% compared to Ciherang and Inpari IR Nutrizinc. It is suspected that the varieties differ in the efficiency of photosynthate translocation to the grains and in their physiological responses to the environment and fertilization. Although the Inpari IR Nutrizinc variety has a high Zn content, in this study the variety produced a lower ratio of grain yield to total biomass than the other varieties.

3.5 Milled Dry Grain

The results showed that the response of milled dry grain to Zn application also depended on varietal differences (Table 1). Zinc treatment by priming and foliar spray in the vegetative and generative phases (P_4) consistently increased the milled dry grain produced in the three varieties (Table 6). In the Ciherang variety, zinc treatment by priming and foliar spray in the vegetative and generative phases (P_4) increased the milled dry grain by up to 198.98% compared to the control (P_0). Through the same zinc application, milled dry grain also consistently increased by up to 152.33% and 121.70% compared to the control (P_0) in the Inpari 32 and Inpari IR Nutrizinc varieties, respectively. This finding is supported by the research of Saikh *et al*. (2022), who reported that zinc application through foliar spray repeated during the growth phase can increase the efficiency of plant nutrient use, resulting in optimal grain formation and increased grain yield.

The Ciherang and Inpari 32 varieties produced 34.46% and 31.64% higher milled dry grain yields than Inpari IR Nutrizinc. Although Inpari IR Nutrizinc is a biofortified variety that genetically has a higher Zn content, the results showed that this variety produced lower grain yields than Ciherang and Inpari 32. It is suspected that this variety has a high efficiency of internal Zn use, so it does not respond significantly to additional Zn from external sources.

Table 6. Effect of zinc application on milled dry grain in several varieties of paddy rice

Rice varieties	Zinc application				
	P_0	P_1	P_2	P_3	P_4
	……………………………….(g/m²)…………………………………				
Ciherang	456,33 d A	761,33 c A	805,00 c AB	953,00 b A	1364,33 a A
Inpari 32	529,33 d A	717,33 c AB	929,33 b A	955,00 b A	1335,67 a A
Inpari IR Nutrizinc	457,67 d A	595,67 c B	681,33 c B	849,67 b A	1014,67 a B
HSD 5%	**121,50**				

Notes: P_0 = Control; P_1 = Priming Zinc; P_2 = Priming Zinc + Foliar Spray at the Vegetative Phase; P_3 = Priming Zinc + Foliar Spray at the Generative Phase; P_4 = Priming Zinc + Foliar Spray at the Vegetative and Generative Phases. Numbers followed by uppercase letters are compared vertically, numbers followed by lowercase letters are compared horizontally, and numbers followed by the same letter indicate no significant difference according to the HSD test at the 5% significance level.

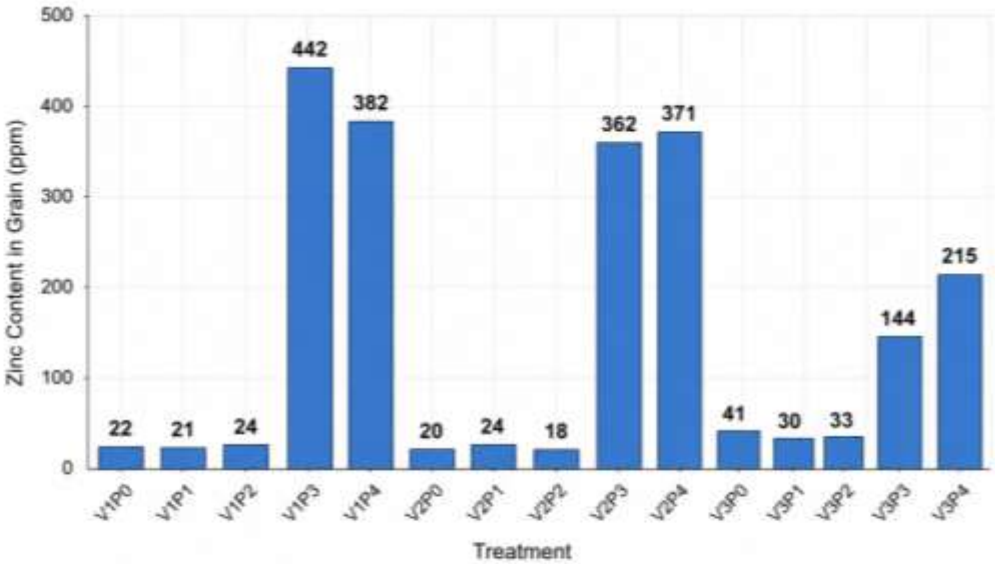

Figure 1. Zinc concentration in rice husks as affected by zinc application and rice variety

In line with Hafeez *et al*. (2019), varieties that have high internal Zn content do not always respond significantly to external Zn fertilization in terms of yield, but rather in terms of Zn content in the grain. Kamran *et al*. (2023) reported that foliar spraying is the application of micronutrients to leaves and is considered the most effective method for applying Zn, as Zn can be directly absorbed through the leaf surface, transported via the phloem, and translocated to developing seeds.

3.6 Zinc Content in Rice Husk

The results of Zn content analysis in rice husks are presented in Figure 1. Zn application through seed priming combined with foliar spraying during the generative stage (P_3) and during both the vegetative and generative stages (P_4) consistently increased Zn concentration in the husks across all rice varieties. The highest Zn concentration was recorded in the Ciherang variety under the P_4 treatment, reaching 442 ppm, whereas the lowest concentration (18 ppm) was observed in the Inpari 32 variety under the P2 treatment.

This indicates that Zn application through seed priming combined with foliar spraying during the generative phase (P_3) or during both the vegetative and generative phases (P_4) effectively satisfied the physiological demand for Zn uptake and translocation to the grains. Wu *et al.* (2010) reported that Zn applied through foliar spraying was absorbed directly by the epidermal tissues of the leaves without undergoing the root absorption process. Zinc that entered the leaf tissues was subsequently mobilized and distributed to all parts of the plant through the phloem network. This translocation process allowed Zn to reach actively developing sink organs, such as panicles and rice grains.

The increased Zn concentration in rice husks observed in this study is consistent with previous findings. Denre *et al*. (2017) reported that Zn fertilization increased Zn accumulation in rice grains, husks, and straw through enhanced uptake and distribution of Zn throughout the plant. Similarly, Phuphuong *et al*. (2018) demonstrated that foliar Zn application during panicle initiation, flowering, and milk stages effectively increased grain Zn concentration. Das *et al*. (2019) further reported that foliar application of 0.5% $ZnSO_4$ at the tillering and milk stages significantly improved Zn biofortification in rice. Collectively, these findings indicate that combining seed priming with foliar Zn application, particularly during reproductive growth stages, is an effective strategy for increasing Zn accumulation in rice tissues.

4. CONCLUSIONS

Zinc application is effective in enhancing biomass accumulation, harvest index, seed yield, and zinc content in rice. The combination of 0.25% $ZnSO_4$ seed priming and 0.5% foliar application at both vegetative and generative stages was identified as the most effective treatment for improving rice growth, productivity, and zinc enrichment. Among the tested varieties, Ciherang and Inpari 32 exhibited greater responsiveness to zinc application than Inpari IR Nutrizinc. This approach has the potential to increase zinc availability in rice-based diets and may contribute to efforts aimed at alleviating zinc deficiency and reducing the risk of stunting.

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