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Effect of Zinc Bio-Fortification on Yield and Quality of Pigmented Rice Varieties (*Oryza sativa* L.)

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Abstract

A field experiment was carried out during the *Kharif* season of 2023 at the Agricultural College Farm, Bapatla, to evaluate the influence of foliar zinc application on the yield and quality attributes of coloured rice (*Oryza sativa* L.). The study employed a split plot design (SPD) with four main plot treatments comprising coloured rice varieties M_1: Navara, M2: BPT-2858, M3: BPT-2841, and M_4: Kujipatalia and four sub-plot treatments involving foliar application of $ZnSO_4$ at 0.2% concentration at different growth stages: S_1 - no zinc application, S_2 - application at the tillering stage, S_3 - application at both tillering and panicle initiation stages, and S_4- application at tillering, panicle initiation, and booting stages. Each treatment combination was replicated thrice. The findings indicated that the Kujipatalia variety (M_4) produced the highest grain and straw yields. In terms of physical quality traits, milling percentage was maximized in Kujipatalia, kernel length in BPT-2841, kernel breadth in Navara, and overall physical quality was superior in BPT-2858. Regarding chemical quality parameters, BPT-2841 exhibited the highest levels of total phenols, carbohydrates, amylose, crude fiber, antioxidant activity, and anthocyanin content. BPT-2858 recorded the highest crude ash, crude fat, and zinc content in grain, whereas Kujipatalia showed the greatest crude protein and zinc content in straw. Among the zinc application treatments, the foliar application of $ZnSO_4$ at 0.2% during tillering, panicle initiation, and booting stages (S_4) consistently resulted in the most favourable outcomes across all measured parameters. Consequently, the combination of Kujipatalia, BPT-2841, and BPT-2858 varieties with the S_4 zinc application schedule proved to be the most effective in enhancing both yield and quality traits. In contrast, the Navara variety without zinc supplementation (S_1) demonstrated the lowest performance in yield and quality, although it recorded the highest kernel breadth.

Key words: Coloured rice, Zinc fertilization, yield, quality

Introduction

Rice serves as the primary food for more than half of the world's population and plays a critical role in meeting over 90% of the world's dietary energy needs. India is the world's second largest producer of rice, accounting for 20 percent of world rice production. Asia accounts for 60% of the total global population, approximately 92% of worldwide rice production, and 90% of global rice consumption (Anonymous, 2012). In 2023-24, projections indicate that the global rice market will produce 520.5 million metric tons of rice. In India, rice cultivation covers an extensive area of 46.3 million hectares, resulting in an annual yield of 1357.55 lakh tonnes. An area of 22.9 lakh hectares in Andhra Pradesh cultivates rice, yielding an annual production of 77.6 lakh metric tons and a productivity of 3,392 kilograms per hectare (Ministry of Agriculture and Farmer Welfare, GOI, 2022).

For people who rely on rice as their main source of sustenance, the quality of rice is critical. In the past few years, the demand for high-quality rice has risen as a result of social progress and improved living conditions. Consumers now prioritise high-quality rice above high-yielding varieties (Tang *et al.*, 2019). In addition to traditional criteria for selecting high-quality rice, such as ease of processing, nice appearance, and outstanding taste, the market and consumers also consider rich nutrition and robust flavour as crucial elements in assessing rice quality. As a result, there has been a surge in research focused on improving the nutritional content and fragrance, making it a popular subject of study. Contemporary nutritional research has demonstrated that coloured rice variants possess higher nutritional value compared to white rice, even after the milling process. Applying mineral elements in moderate amounts can increase the mineral content in rice grains, enhancing the nutritional quality of rice and meeting the mineral needs of the human body (Xu *et al.*, 2022). Consequently, some prominent rice research programmes are now shifting their attention to the matter of nutritional quality, which includes enhancing the levels of micronutrients and antioxidants.

Black rice is a type of rice that contains pigments called cyanidin-3-glucosidase and peonidin-3-glucosidase anthocyanin molecules, which give it its dark colour. Black rice has had a profound impact on culinary traditions and cultural activities, starting from its roots in Asia and continuing to its current comeback in world cuisine. Black rice has gained significant interest among coloured rice varieties due to its sensory attributes, high nutritional content, and particularly its advantageous health benefits (Kushwaha, 2016; Ito *et al.*, 2019). The substance is comprised of a variety of beneficial substances, such as vital amino acids, functional lipids, anthocyanins, phenolic compounds, γ-oryzanols, tocopherols, tocotrienols, phytosterols, and phytic acid. It is also abundant in antioxidants and has the ability to decrease chronic inflammation. Historically, the affluent enjoyed red rice as an exclusive type due to its exceptional nutritional content and distinct flavour. Additionally, it possesses a more pronounced nutty taste and a slightly resilient consistency, rendering it a preferred option in numerous customary recipes. The composition of this substance includes anthocyanins, proanthocyanidins, GABA (Gamma-Aminobutyric acid) and phytosterols. These components have the potential to decrease cholesterol levels and mitigate the likelihood of developing heart disease.

Conversely, rice has a naturally low content of micronutrients such as zinc. In developing nations where polished rice is the primary dietary staple, zinc deficiency poses a significant problem of malnutrition. Zinc is a crucial mineral for maintaining human health. Insufficient levels of zinc can lead to a range of illnesses, including a weakened immune system, stunted growth and development, and heightened susceptibility to cancer (Nriagu, 2019). Because the human body is unable to synthesize zinc, it must be obtained from external sources. Plant-based meals, such as rice, have a reduced zinc level compared to animal diets (Rahman *et al*., 2012). Indeed, rice has a notably lower zinc concentration compared to other plant-based meals like wheat, maize, and potatoes (Cakmak *et al.*, 2017). Long-term consumption of refined white rice may lead to an increased risk of insufficient zinc intake. Hence, the judicious utilisation of zinc fertiliser is vital for raising the quality of rice, specifically by augmenting the zinc concentration and fragrance of rice. Zinc (Zn) is the second most abundant trace element, and it is essential for the survival of all living species. Zinc (Zn) stimulates several enzymes and protein synthesis, as well as enhancing the breakdown of sugar, hence enhancing the overall quality of rice kernels (Kheyri *et al.*, 2019). Additionally, the outer layer of leaves rapidly detects zinc when administered through foliar feeding. The phloem transports the redistributed zinc to developing seeds (**Table 1**). This process ultimately leads to the formation of larger grains and increased grain yield (Hassan *et al.*, 2019).

Table 1: Yield of coloured rice varieties influenced by zinc fertilization

Treatments	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})
Coloured rice varieties		
M_1:Navara	3318	4116
M_2: BPT-2858	3868	4801
M_3: BPT-2841	4187	5255
M_4: Kujipatalia	4480	5374
SEm(±)	100.9	94.6
CD (P=0.05)	349	327
CV (%)	8.8	8.9
Foliar application of $ZnSO_4$ @ 0.2%		
S_1: No zinc	3484	4559
S_2:Tillering stage	3869	4695
S_3:Tillering and PI stages	4172	5071
S_4:Tillering, PI and booting stages	4328	5221
SEm(±)	103.3	98.9
CD (P=0.05)	302	289
CV (%)	9.0	9.2
Interaction		
SEm (±)	178.0	169.4
CD (P=0.05)	493	470

Materials and Methods

The present experiment was conducted during *kharif,* 2023 at the Agricultural College Farm of Acharya N. G. Ranga Agricultural University (80.30˚E longitude and 15.54˚ N latitude with an altitude of 5.49 m above mean sea level) Bapatla, Andhra Pradesh. The soil of the experimental field was sandy clay loam, neutral in reaction (pH 7.2), normal in EC (0.21 dS/m), medium in organic carbon (0.45%), low in available nitrogen (235.2 kg/ha), medium in available phosphorus (38.2 kg/ha) and available potassium (309.12 kg/ ha) and low in available zinc (0.29 ppm). The mean maximum temperature during the cropping period was 33.2ºC and mean minimum temperature was 23.7ºC. The total rainfall received during the cropping period was 900.8mm, in 2023. The experiment was conducted in a split-plot design (SPD) with 3 replications. In main plot, coloured rice varieties: M_1- Navara, M_2- BPT-2858, M_3- BPT-2841 and M_4- Kujipatalia and in sub-plots – application of $ZnSO_4$ @ 0.2% at different stages: S_1- no zinc; S_2- application of $ZnSO_4$ @ 0.2% at tillering stage; S_3- application of $ZnSO_4$ @ 0.2% at tillering and panicle initiation stages and S_4- application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages were tested. The varieties had duration of (M_1)120, (M_2)130, (M_3)130-135 and (M_3)120-130 days and were sown on 8th August 2023. The seedlings were uprooted on 25th day in the nursery and transplanted into the main field with a row spacing of 20 cm × 15 cm. In order to facilitate the good seed germination, irrigation was provided immediately after sowing. The fertilizer schedule recommended for rice cultivation in Krishna Agro Climatic zone is 120:60:40 kg NPK/ha. Full dose of phosphorus was applied as basal. Nitrogen was applied in 3 split doses, 1/3rd at basal, 1/3rd at tillering and 1/3rd at panicle initiation stage and potassium was appliedin 2 split doses, half at basal and half at panicle initiation. Pre emergence herbicide pyrazosulfuran-ethyl @ 80 g ac^{-1} was applied followed by post emergence herbicide application of bispyribac sodium @ 30 g *a.i* ha^{-1} applied at 20 DAT and manual weeding was done at 45 DAS and 70 DAS. Need based irrigations were given throughout the crop period. Treatment with $ZnSO_4$ @ 0.2% was carried out based on the different stages in all the plots except in the control. The yield was recorded after the harvest of the crop while the physical quality parameters were recorded using the Satake huller, milling and head rice recovery machine and dial micrometer while chemical quality parameters were done in the laboratory by the standard procedures: The data are subjected to statistical analysis using Fisher's method of analysis of variance as outlined by Panse and Sukhatme (1978) for the design adopted in this research study and wherever statistical significance was observed, the critical difference (CD) at P=0.05 level of probability was calculated for comparison of mean data.

Results and Discussion

The grain and straw yields were significantly influenced by coloured rice varieties and zinc fertilization, and their interaction effect was also significantly affected by varieties and zinc fertilization. Data reveal that the Kujipatalia variety recorded significantly the highest grain yield (4480 kg ha^{-1}) and straw yield (5374 kg ha^{-1}) which was on par with BPT-2841 variety while the significantly lowest grain yield was recorded with Navara variety grain yield (3318 kg ha^{-1}) and straw yield (4116 kg ha^{-1}). The maximum grain and straw yield was recorded with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages. Grain yield (4328 kg ha^{-1}) and straw yield (5221 kg ha^{-1}) were found to be on par with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation grain yield (4172 kg ha^{-1}) and straw yield (5071 kg ha^{-1}). Minimum grain yield (3484 kg ha^{-1}) and straw yield (4559 kg ha^{-1}) were noticed with no zinc application. The highest grain and straw yield were recorded with the Kujipatalia variety coupled with application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages and the lowest grain yield was recorded with Navara variety combined with no zinc application. The foliar application of zinc (Zn) significantly improved grain yield by increasing number of spikelets per panicle, filled grain percentage and 1000 grain weight stated by Wang *et al.,* (2023). Similar findings were reported by Xia *et al*., (2018) and Chen *et al*., (2022).

Physical quality parameters

Results of the data on hulling percentage of coloured rice were found to be non-significant in both the varieties and upon zinc fertilization. There was also no significant interaction between varieties and zinc application at different stages on hulling percentage of coloured rice. The experimental data reveals that the milling percentage was found to be significant for coloured rice varieties and zinc fertilization. Significantly higher milling percentage was recorded with Kujipatalia variety (71.0%) which was on par with BPT-2841 (70.5%) and BPT-2858 (68.7%) variety and lowest was recorded with Navara variety (67.0%). Significantly higher milling percent was recorded with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages (71.1%) which was on par with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation stages (70.0%) and significantly lowest milling percent was recorded with no zinc application (67.3%). Data on head rice recovery of coloured rice was found to be non-significant among the varieties and zinc fertilization. The interaction effect among the two factors (varieties and zinc fertilization) was also found to be non-significant on head rice recovery percent of coloured rice. El-Hissewy *et al.,* (2016) stated that the effect of zinc fertilization on increased milling value may be due to improved growth, photosynthetic assimilates and grain filling (**Table 2**).

Table 2: Physical quality parameters of coloured rice varieties influenced by zinc fertilization

Physical quality parameters					
Treatments	Hulling (%)	Milling (%)	Head rice recovery (%)	Kernel length (mm)	Kernel breadth (mm)
Coloured rice varieties					
M_1:Navara	74.1	67.0	63.8	6.3	2.7
M_2: BPT-2858	75.8	68.7	65.0	6.5	2.2
M_3: BPT-2841	76.9	70.5	65.7	6.5	2.3
M_4:Kujipatalia	77.2	71.0	66.6	6.5	2.4
SEm(±)	1.24	1.02	0.96	0.03	0.01
CD (P=0.05)	NS	3.0	NS	0.09	0.03
CV (%)	5.6	5.1	5.1	1.4	1.2
Foliar application of $ZnSO_4$ @ 0.2%					
S_1: No zinc	75.1	67.3	63.7	6.4	2.4
S_2:Tillering stage	75.6	68.8	64.4	6.4	2.4
S_3:Tillering and PI stages	76.4	70.0	65.3	6.5	2.4
S_4:Tillering, PI and booting stages	6.8	71.1	67.7	6.5	2.4
SEm(±)	0.57	0.68	1.13	0.03	0.01
CD (P=0.05)	NS	1.9	NS	NS	NS
CV (%)	2.6	3.4	6.0	1.8	1.3
Interaction					
SEm (±)	5.6	1.35	1.89	0.70	0.01
CD (P=0.05)	NS	4..2	5.6	NS	0.03

Results of the experimental data on kernel length of coloured rice were significantly influenced by varieties. Significantly the highest kernel length was recorded with BPT-2858, BPT-2841 and Kujipatalia varieties (6.5 mm) and the lowest was recorded with Navara variety (6.3 mm). Experimental results showed that kernel length of coloured rice varieties was not significantly influenced by zinc fertilization. There was no significant interaction among the coloured rice varieties and zinc fertilization on kernel length. While the kernel breadth of coloured rice showed significant effect only for the varieties and non-significant for the zinc fertilization. Significantly the highest kernel breadth was achieved with Navara variety (2.7 mm) and the lowest was achieved with BPT-2858 variety (2.2 mm). There was no significant influence of coloured rice varieties with zinc fertilization. The interaction effect among these two factors was shown to be significant on the kernel breadth of coloured rice. Wahane *et al.,* (2022) reported that the kernel length and breadth were not affected by Zn fertilization.

Chemical quality parameters

Total phenols (mg/g):

The total phenol content was influenced significantly by both the coloured rice varieties and zinc fertilization. With respect to varieties, significantly the higher phenol content was recorded with BPT-2841 variety (74.2 mg/100g) which was found to be on par with Kujipatalia (71.6 mg/100g) variety and significantly the lower phenol content was recorded with Navara variety (65.7mg/100g). In the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages (73.8 mg/100g) has recorded significantly the higher phenol content which was on par with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation stages (70.2mg/100g) and lower phenol content was recorded with no zinc application (67.3mg/100g). There was significant interaction effect among the varieties and zinc application at different stages on total phenol content. The highest phenol content was recorded with BPT-2841 variety coupled with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages and the lower phenol content was recorded in Navara variety with no zinc application. Seleiman *et al.,* (2023) reported that the foliar application of Zn improved total phenol content by 30% compared to the control by enhancing the different enzymatic activity like superoxide-dismutase. Ali *et al.,* (2020) observed that the maximum phenol contents were found in foliar application compared with soil application which indicates that foliar zinc application increases the phenolic contents. Similar findings were corroborated by Bassi and Sharma (1993). Wahane *et al.,* (2022) observed that the amylose content was significantly influenced by Zn fertilization **(Table 3).**

Amylose content (%)

Data on amylose content of the grain reveals that the highest amylose content in the grain was recorded with BPT-2841 variety (23.2%) which was found to be on par with the BPT-2858 (22.9%) and Kujipatalia variety (22.4%) while, Navara variety (18.9%) recorded significantly lowest amylose content in the grain. In case of zinc fertilization, the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages (26.7%) has recorded significantly superior amylose content in the grain and the lowest was recorded with no zinc application (16.1%). There was significant interaction among the varieties and zinc application at different stages on amylose content of the grain. The highest amylose content was recorded with BPT-2858 variety combined with application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages and the lower amylose content was recorded with Navara variety combined with no zinc application **(Table 3).**

Carbohydrate content (%)

Carbohydrate content was significantly influenced with both the coloured rice varieties and zinc fertilization. Data indicated that significantly higher carbohydrate content was recorded with BPT-2841 variety (72.2%). Lower carbohydrate content was recorded with Navara variety (50.3%). Significantly superior carbohydrate content was recorded with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages (73.7%) and no zinc application recorded significantly lower carbohydrate (52.4%) content **(Table 3)**. Zn plays an important role in several plant physiological processes such as carbohydrate metabolism. Zn exerts a positive effect on carbohydrate metabolism through photosynthesis and sugar transformations (Alloway, 2004). Barak and Helmke (1993) reported that zinc is involved in starch formation.

Antioxidant activity (mg/100g)

The antioxidant activity was significantly influenced by coloured rice varieties and zinc fertilization. Significantly the higher antioxidant activity was recorded with BPT-2841 variety (76.6 mg/100g) followed by BPT-2858 variety (74.5 mg/100g) and Kujipatalia variety (72.9 mg/100g) while significantly lower antioxidant activity was recorded with Navara variety (60.5 mg/100g).With respect to zinc fertilization, significantly higher antioxidant activity was recorded with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages (81.3 mg/100g) which was found to be significantly superior over rest of the treatments **(Table 3).** Lower antioxidant activity was recorded with no zinc application (62.9 mg/100g). Seleiman *et al.,* (2023) reported that the foliar application of Zn facilitated antioxidant defence mechanisms.

Anthocyanin content (mg/g)

Experimental data on anthocyanin content of coloured rice was significantly influenced by the varieties but not with zinc fertilization. Among the varieties, the highest was recorded with BPT-2841 variety (1.02 mg/g) followed by BPT-2858 variety (1.01 mg/g) and the lowest was recorded with Navara variety (0.87 mg/g). There was significant interaction effect among the varieties and zinc fertilization on anthocyanin content of coloured rice (**Table 3**).

Table 3: Effect of zinc fertilization on total phenol content, amylose, carbohydrate, antioxidant and anthocyanin content of coloured rice

Chemical quality parameters					
Treatments	Total phenols (mg/g)	Amylose content (%)	Carbohydrates (%)	Antioxidants (mg/g)	Anthocyanin (mg/g)
Coloured rice varieties					
M_1:Navara	65.7	18.9	50.3	60.5	0.87
M_2: BPT-2858	69.0	22.9	57.8	74.5	1.01
M_3: BPT-2841	74.2	23.2	72.2	76.6	1.02
M_4:Kujipatalia	71.6	22.4	67.0	72.9	0.95
SEm(±)	1.28	0.65	1.28	1.91	0.04
CD (P=0.05)	4.4	2.3	4.4	6.6	0.12
CV (%)	6.3	10.4	7.2	9.3	12.6
Foliar application of $ZnSO_4$ @ 0.2%					
S_1: No zinc	67.3	16.1	52.4	62.9	0.95
S_2:Tillering stage	69.2	20.7	57.7	68.1	0.96
S_3:Tillering and PI stages	70.2	23.9	63.5	72.3	0.96
S_4:Tillering, PI and booting stages	73.8	26.7	73.7	81.3	0.97
SEm(±)	1.31	0.81	1.78	1.47	0.03
CD (P=0.05)	3.8	2.4	5.2	4.3	NS
CV (%)	6.5	12.8	10.0	8.2	12.2
Interaction					
SEm (±)	2.26	1.34	2.88	2.76	0.06
CD (P=0.05)	6.6	4.3	8.3	7.9	0.17

Crude fiber content (%)

Data reveals that the coloured rice varieties and zinc fertilization had significant impact on the crude fiber content of the grain. Among the varieties, BPT-2841 variety (4.68 %) has recorded the highest crude fiber content which was significantly superior over the rest of the varieties tested and Navara variety recorded significantly the lowest crude fiber (3.33 %) content. The highest crude fiber content attained with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages (4.55%) was statistically significant over the rest of the treatments studied in this experiment and the lowest crude fiber content was recorded with no zinc application (3.95 %). Rasheed *et al*., (2022) stated that crude fiber in rice with more strength has been observed with response to zinc application **(Table 4).**

Crude protein content (%)

The crude protein content in the coloured rice was influenced by varieties and zinc fertilization. The highest crude protein content was recorded with Kujipatalia variety (9.8 %) which was on par with BPT- 2841 variety (9.5 %) and the lower crude protein was recorded with Navara variety (7.9 %). Among the zinc fertilization at different stages, application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages (9.6 %) recorded significantly superior to other varieties and the lower crude protein content was recorded with no zinc application (7.9%). Humaira *et al.,* (2015) reported that Zn-superoxide dismutase enzymatic activity is enhanced with Zn application due to this, more protein is produced. Obata *et al*., (1999) and Awad-Allah *et al.,* (2022) reported similar result in their studies **(Table 4)**.

Table 4: Effect of zinc fertilization on crude protein, crude ash, crude fiber and crude fat content of coloured rice

Chemical quality parameters				
Treatments	**Crude protein (%)**	**Crude ash (%)**	**Crude fiber (%)**	**Crude fat (%)**
Coloured rice varieties				
M_1:Navara	7.9	1.61	3.33	1.99
M_2: BPT-2858	8.6	1.72	3.66	2.13
M_3: BPT-2841	9.5	1.60	4.68	1.93
M_4:Kujipatalia	9.8	1.42	4.56	1.78
SEm(±)	0.22	0.05	0.02	0.05
CD (P=0.05)	0.8	0.18	0.07	0.19
CV (%)	8.4	11.5	1.8	9.6
Foliar application of $ZnSO_4$ @ 0.2%				
S_1: No zinc	7.9	1.35	3.95	1.58
S_2:Tillering stage	8.9	1.55	3.78	1.95
S_3:Tillering and PI stages	9.5	1.70	3.96	2.01
S_4:Tillering, PI and booting stages	9.6	1.74	4.55	2.29
SEm(±)	0.25	0.05	0.04	0.07
CD (P=0.05)	0.7	0.14	0.11	0.20
CV (%)	9.7	10.5	3.1	12.4
Interaction				
SEm (±)	0.42	0.09	0.06	0.11
CD (P=0.05)	2.6	0.27	0.18	0.33

Crude fat content (%)

Experimental results reveal that the crude fat content of coloured rice was significantly influenced by varieties and zinc fertilization. With respect to varieties, the highest crude fat content was recorded with BPT-2858 variety (2.13 %) followed by Navara variety (1.99 %) while, Kujipatalia variety (1.78%) recorded the lowest. In case of zinc fertilization, application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages (2.29 %) recorded superior crude fat content while, the lowest was recorded with no zinc application (1.58 %). Dhaliwal *et al.,* (2020) observed that the foliar application of Zn improved the mineral contents **(Table 4).**

Crude ash content (%)

Data reveals that the crude ash content in the coloured rice was influenced by varieties and zinc fertilization. Among the varieties, the highest crude ash content was recorded with BPT-2858 variety (1.72%) and the lowest was recorded with Kujipatalia variety (1.42%). Results of the data with respect to zinc fertilization, revealed that the highest crude ash content was recorded with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages (1.74 %) which was on par with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation stages (1.70%). The lowest was recorded with no zinc application (1.35%) **(Table 4).**

Zinc content in grain (ppm)

Zinc content in the grain was influenced by coloured rice varieties and zinc fertilization. Data shows that the highest zinc content in the rice grain was recorded with BPT-2858 variety (34.2 ppm) which was found to be on par with BPT-2841 (33.9 ppm) and Kujipatalia (32.4 ppm) variety. Navara variety recorded the lowest zinc content in the grain (28.3 ppm). With respect to zinc fertilization, the highest zinc content in the grain was recorded with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages (33.2 ppm) while no zinc (31.3 ppm) applied treatment recorded the lowest zinc content in the grain. The interaction effect between the coloured rice varieties and zinc fertilization was found to have significant impact on the zinc content in the grain. The highest zinc in the grain was recorded with the combination of BPT-2858 variety with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages whereas the lowest was recorded with Navara variety coupled with no zinc application. Xu *et al.,* (2022) observed that zinc applied by foliar spray is readily absorbed by the leaf epidermis and after remobilization, it is transferred via the phloem to developing seeds. Zulfiqar *et al.,* (2020) stated that foliar application of Zn at the early reproductive stage results in the translocation of the Zn to the reproductive structures of the plant and it is then accumulated in grains. Saha *et al*., (2017) reported that foliar application of Zn at the reproductive stages yielded more **(Table 5)**. In foliar application, Zn^{2+} ions enter the plant (leaf apoplast) directly through stomatal pores and increase Zn concentration in the phloem tissue of leaves, from where it can be directly translocated to grains (Gupta *et al.,* 2017).

Table 5: Effect of zinc fertilization on zinc content in the grain and straw of coloured rice

Treatments	Zinc content in grain (ppm)	Zinc content in straw (ppm)
Coloured rice varieties		
M_1:Navara	28.3	25.6
M_2: BPT-2858	34.2	27.6
M_3: BPT-2841	33.9	27.5
M_4:Kujipatalia	32.4	28.1
SEm(±)	0.54	0.53
CD (P=0.05)	1.9	1.8
CV (%)	5.8	6.7
Foliar application of $ZnSO_4$ @ 0.2%		
S_1: No zinc	31.3	24.9
S_2:Tillering stage	31.8	26.5
S_3:Tillering and PI stages	32.4	28.4
S_4:Tillering, PI and booting stages	33.2	28.8
SEm(±)	0.34	0.69
CD (P=0.05)	1.0	2.0
CV (%)	3.7	8.8
Interaction		
SEm (±)	0.69	1.13
CD (P=0.05)	2.7	3.8

Zinc content (%) in straw

Experimental results on zinc content in straw of coloured rice was influenced by varieties and zinc fertilization. Among the varieties, the highest zinc content in straw was recorded with Kujipatalia variety (28.1 %) followed by BPT-2858 variety (27.6 %) and the lowest was recorded with Navara variety (25.6%). In case of zinc fertilization, the highest zinc content in straw was recorded with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages (28.8 %) which was on par with the application of $ZnSO_4$ @ 0.2% at tillering and panicle initiation stages (28.4 %). The interaction effect was found to be significant on zinc content in straw among the varieties and zinc fertilization **(Table 5).** The highest zinc content in straw was recorded with BPT-2858 variety coupled with the application of $ZnSO_4$ @ 0.2% at tillering, panicle initiation and booting stages and lowest was recorded with the Navara variety combined with no zinc application. High Zn application produced a considerable improvement in Zn uptake in shoots, regardless of genotype (Himasri *et al.,* 2025 and Fageria *et al.,* 1997). Li *et al.,* (1999) reported that Zn application increased Zn concentrations and uptake in shoot, grain and straw with foliar application being most effective.

Conclusion

The highest yield was observed highest with Kujipatalia variety and incase of quality parameters *viz.*, total phenols, carbohydrate, antioxidant activity, amylose content, crude fiber were realized highest with BPT-2841 variety; while crude ash, crude fat, Zn in grain with BPT-2858 variety and crude protein, Zn in straw with Kujipatalia variety. The application of $ZnSO_4$ at specific growth stages namely tillering and panicle initiation resulted in a statistically significant improvement in both yield and quality parameters. Bio-fortification of coloured rice with Zn fertilization significantly influenced all the quality parameters which influences the overall health of an individual. Zinc content in grain reduces the problem of micronutrient malnutrition in the developing nations.

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