**Influence of Zinc Fertilization Methods and Varietal Response on Paddy Yield and Zinc Bioavailability**

**Abstract:** Malnutrition is a major global health concern, especially in underdeveloped and developing regions, where diets often lack essential nutrients. Poor dietary diversity and limited access to nutrient-rich foods contribute significantly to this issue. Addressing malnutrition is vital for achieving global food and nutritional security. A field experiment was conducted for *Kharif* season (2021-22) at Regional Agricultural Research Station, Nandyala, Andhra Pradesh by using split plot design to study the Influence of Zinc Fertilization Methods and Varietal Response on Paddy Yield and Zinc Bioavailability.

In an experimental study, the rice variety NDLR-8 produced the highest grain yield (6,379 kg/ha) and straw yield (6,751 kg/ha), closely followed by the NDLR-7 variety. The study highlighted a strong positive response of rice to zinc fertilization in a low-rainfall region, particularly at application rates between 50 and 100 kg/ha. In terms of nutritional quality, NDLR-8 also showed significantly higher iron (42.35 mg/kg) and zinc (7.81 mg/kg) content compared to other varieties. Importantly, zinc application did not significantly alter the levels of potassium, copper, or manganese in the soil, relative to its initial condition. However, even small increases in zinc levels led to a noticeable rise in total zinc uptake by the plants. These findings underscore the potential of targeted zinc fertilization and nutrient-rich crop varieties like NDLR-8 to combat widespread zinc deficiency, improve soil health, and support the fight against malnutrition through improved crop nutrition.

**Key words**: Paddy Crop, Grain yield , Straw yield, Zinc content and Zinc fortification studies

**Introduction:** The Green Revolution significantly improved food security in many countries by increasing cereal production. However, its primary focus was on maximizing crop yields rather than enhancing the nutritional quality of food. This yield-centric approach led to a decline in soil health and a reduction in the nutrient content of food grains. As a result, micronutrient malnutrition remains a critical issue, affecting over two billion people worldwide primarily among low-income families in developing nations (Majumder *et al*., 2019). Deficiencies in iron, iodine, zinc, and vitamin A are among the most widespread forms of malnutrition (Kennedy et al., 2003). Each year, more than five million children die from complications related to micronutrient deficiencies. According to White and Broadley (2009), over 60% of the global population is iron-deficient, over 30% lacks sufficient zinc, and around 30% suffers from iodine deficiency.In India, the situation is particularly severe. The 2020 report of The State of Food Security and Nutrition in the World' estimates that 14% of India’s population is undernourished, translating to 189.2 million people. Alarmingly, 34.7% of Indian children under the age of five are stunted, indicating chronic undernutrition, while 20% suffer from wasting, meaning they have a dangerously low weight for their height. These figures highlight that India continues to face some of the highest rates of child malnutrition globally, underscoring the urgent need for nutrition-focused agricultural strategies.

According to the Global Hunger Index (2020), which measures hunger based on undernourishment, child stunting, wasting, and child mortality—India ranks 94th out of 107 countries, highlighting the serious state of food and nutritional insecurity in the country.Zinc (Zn) is a vital micronutrient for both plants and humans. In plants, it plays a crucial role in various biochemical processes, including protein synthesis, gene expression, and maintaining the structural and functional integrity of biological membranes (Kambe et al., 2015). However, more than half of the major crop species are affected by zinc deficiency (Swamy et al., 2016; Lee et al., 2017), making zinc management critical for agricultural productivity.

In rice, zinc can be efficiently applied through foliar sprays, which are cost-effective and yield promising results in terms of plant growth and grain quality (Guo et al., 2016). Foliar fertilization has also been successfully used to biofortify rice seeds with zinc, improving not only seed quality but also ensuring better zinc availability in the early growth stages of the next crop season.Proper nutrient management in autumn rice is essential for achieving optimal yields. Alongside major nutrients, zinc is indispensable for plant development, and its deficiency severely impacts plant growth and grain enrichment. Precise scheduling and application techniques are necessary to enhance zinc uptake and accumulation in rice grains.

From a human nutrition perspective, zinc deficiency affects about 30% of the global population and is particularly prevalent in developing countries. Diets in rural areas are predominantly cereal-based, supplying up to 75% of daily calorie intake, yet these cereals are low in both zinc content and bioavailability (Cakmak, 2012). A typical cereal-based diet provides only 4–6 mg Zn/day from rice and 11–18 mg Zn/day from wheat, whereas optimal human health requires cereal grains to contain 40–60 mg Zn/kg. However, current levels are typically between 10–30 mg Zn/kg—well below the requirement.Zinc deficiency is linked to serious health consequences, including stunted growth, impaired immune function, reproductive issues, and delayed neuro-behavioral development. It is estimated to contribute to the deaths of about 450,000 children under five years of age annually. Therefore, enhancing the zinc content in staple foods like rice and wheat is a major public health priority.Zinc biofortification in rice can be significantly improved by optimizing the timing, placement, and form of zinc application, as well as through careful selection of responsive cultivars. Ensuring adequate zinc availability during critical stages of crop development directly influences zinc concentration in grains, contributing to better plant health and improved human nutrition (Yadava *et al*., 2020).

**Materials & Methods:**

The field experiments were conducted during the *kharif* season of year 2021-22 at Regional Agricultural Research Station, Nandyala, Andhra Pradesh, under Irrigated conditions. The soil of experimental site was medium deep black, low in organic carbon (0.36%), low in Nitrogen (116 kg/ha) high in available P2O5 (69.5 kg ha-1) and available K2O (536 kg ha-1). A composite soil sample was collected from 0-20 cm depth during the study years, processed and analysed in laboratory for pH and Electrical Conductivity(EC) (1:2 soil : water suspension), by pH and Ec meters, respectively (Jackson 1973) . Organic Carbon percentage (OC) was estimated by rapid titration method (Walkley and Black method 1934). Available nitrogen was estimated by alkaline permanganate method (Subbaiah and Asija 1956). Available phosphorus by Olsens method (Olsen *et al.*1954). Available potassium by ammonium acetate extraction method (Jackson 1973). Available Zinc, Copper, Iron and Manganese were extracted with DTPA and estimated by using AAS as described by Lindsay and Norvell (1978). The experiment was laid out in Split plot design with 16 treatments **Main plots: Paddy Varieties**: 4, V1 - BPT 5204,V2 - NDLR -7, V3 - NDLR -8, V4 - NLR 34449 **Sub plots: Zinc levels : 4** Zn0 – Control,Zn1 - 50 Kg/ha , Zn2 – 100 Kg/ha ,Zn3 – Foliar spray of ZnSO4 @ 0.2% and replicated in three times. Rice variety NDLR-7 was sown during second week of July, transplanted in second week of August by adopting 15x15cm spacing with three seedlings per hill and fertilizers applied as per the treatments protocol. The crop cultural practices were carried out according to the standard practices in the rice fields and harvested at 145 days after sowing. The grain and straw samples were collected at harvest, oven dried at 700C processed and analysed for total content of N, P, K, Zn, Cu, Fe and Mn following standard procedures. The data related to plant height and yield attributes was recorded on ten randomly selected plants in each plot. Net grain and straw yield were recorded for net plot and computed as kg ha-1. Soil and plant samples were collected in each treatment and analysed by following standard procedures. All the data was subjected to statistical analysis.

**Results and Discussion:**

Data present in Table 1 shows that there is no significant difference between any treatment for yield attributes like plant height, production tillers per hill and no of grians per panicle. Highest panicle length (23.02 cm) was observed in NDLR-8 variety, which is on par with variety (21.00 cm). Lowest panicle length (18.87 cm) was observed in BPT-5204 variety. may be due to lower zinc fertilization than recommended dose of fertilization. These results were in accordance with the findings of Prasada Rao *et al*. (2013).

**Grain yield and Straw yield**

*Kharif* rice grain yields were significantly enhanced with Zinc fertilization, which ensures nutrient supply according to crop requirements. The application of higher fertilizer doses resulted in grain yields ranging from 4,868 to 6,379 kg/ha (Table 1). Among the tested varieties, the lowest yields were observed in NLR-34449 (5,944 kg/ha) and BPT-5204 (5,958 kg/ha). This lower performance may be attributed to suboptimal zinc application compared to the recommended levels.In contrast, the NDLR-8 variety recorded the highest grain yield (6,379 kg/ha) and straw yield (6,751 kg/ha), followed closely by NDLR-7, indicating that both varieties responded well to optimized nutrient management. The experiment demonstrated a strong positive response of rice to zinc fertilization under scarce rainfall conditions, particularly with application rates ranging from 50 to 100 kg/ha.

The observed increase in growth and yield parameters is likely due to enhanced cell division and elongation stimulated by sufficient nitrogen supply, which supports better panicle development, a higher number of grains per panicle, and extended greenness of leaves even during maturity. This prolonged photosynthetic activity contributes to efficient carbohydrate translocation to the grains, resulting in a higher number of filled grains per panicle. These findings are consistent with those reported by Prasada Rao *et al.* (2013) and Amal Jose *et al* (2021).

. Further, the increase in zinc application rates significantly improved both grain and straw yields, which was also accompanied by a marked increase in total zinc uptake. This can be attributed to the combined effect of increased biomass and improved nutrient assimilation. Keram *et al*. (2013) and Prom-u-thai *et al*. (2020) reported that the application of 10 kg Zn/ha was statistically at par with 20 kg Zn/ha in terms of grain and straw yields. The lowest yields were recorded in the control (no zinc application), confirming the importance of zinc in rice productivity. The increase in yields due to zinc fertilization may be linked to zinc's critical role in indole-3-acetic acid (IAA) biosynthesis and primordia initiation of reproductive structures, as well as its overall positive impact on metabolic activities in the plant.

Maximum zinc uptake was recorded with the application of 20 kg Zn/ha, which was significantly higher than the control, aligning with the findings of Boonchuay et al. (2013) and Ramulu Ch. and Raghu Rami Reddy P. (2018). Additionally, Alvarez et al. (2019) reported that increased leaf zinc accumulation is associated with decreased amino acid concentrations and enhanced protein content, contributing to higher dry matter production.

**Soil Nutrient Status after Crop Harvest**

According to data presented in Table 2, the highest levels of available nitrogen (192 kg/ha) and phosphorus (50.12 kg/ha) in soil were recorded under the NDLR-8 variety treated with 100 kg/ha of zinc. This increase can likely be attributed to the application of higher doses of nitrogen and phosphorus fertilizers, which enhanced the nutrient status of the soil.Among the micronutrients measured in post-harvest soils, NDLR-8 also recorded significantly higher iron (42.35 mg/kg) and zinc (7.81 mg/kg) concentrations than the other rice varieties. However, zinc fertilization had no significant effect on the availability of potassium, copper, and manganese when compared to the initial soil properties at the experimental site.A significant and positive correlation was observed between the applied levels of nitrogen (N), phosphorus (P), and potassium (K), and their respective available forms in the soil. These findings are consistent with the results reported by Gebremedhin et al. (2015).

The application of Recommended Dose of Fertilizers (RDF) combined with zinc also improved the availability and bioavailability of major nutrients (NPK) and zinc, while the addition of farmyard manure (FYM) contributed to an increase in soil organic matter (SOM), further enhancing nutrient availability (Pooniya et al., 2019; Biswakarma et al., 2021).

As shown in Table 3, the rice variety NDLR-8 had higher zinc and iron content, while NDLR-7 and BPT-5204 were richer in protein and iron. Even small increases in zinc concentration resulted in a marked improvement in total zinc uptake, which may be biologically significant in combating widespread zinc deficiency in soils and plants (Choudhary *et al*., 2022).

**Table 1: Influence of Zinc fortification on Yield and yield attributing characters of different Paddy varieties.**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Treatments** | **Plant height (cm)** | **No.of production tillers per hill** | **No.of grains per panicle** | **Panicle length (cm)** | **Grain yield (kg/ha)** | **Straw yield (kg/ha)** |
| Main plots |  |  |  |  |  |  |
| V1 - BPT 5204 | 79.3 | 17.33 | 187 | 18.87 | 5958 | 6182 |
| V2 - NDLR -7 | 93.1 | 18.25 | 192 | 22.38 | 6023 | 6261 |
| V3 - NDLR -8 | 95.9 | 17.66 | 192 | 23.02 | 6379 | 6751 |
| V4 - NLR 34449 | 70.8 | 17.75 | 193 | 21.00 | 5924 | 6392 |
| SEm+ | 1.66 | 0.72 | 5.7 | 0.81 | 145 | 162 |
| CD @0.05 | 5.75 | NS | NS | 2.81 | 362 | 402 |
| CV (%) | 4.80 | 9.94 | 7.2 | 9.3 | 11.46 | 5.63 |
| Subplots |  |  |  |  |  |  |
| Zn0 – Control | 82.2 | 17.08 | 182 | 20.8 | 4868 | 5012 |
| Zn1 - 50 Kg/ha | 85.7 | 18.17 | 193 | 22.08 | 5275 | 5643 |
| Zn2 – 100 Kg/ha | 85.8 | 18.17 | 200 | 21.02 | 6299 | 6773 |
| Zn3 – Foliar spray of ZnSO4 @ 0.2% | 85.6 | 17.58 | 191 | 21.39 | 5044 | 5261 |
| SEm+ | 2.22 | 0.72 | 4.9 | 0.87 | 135 | 172 |
| CD @0.05 | NS | NS | 14.2 | NS | 374 | 440 |
| CV (%) | 6.43 | 9.90 | 6.3 | 10.1 | 8.42 | 10.16 |
| Interaction VXZn | NS | NS | NS | NS | NS | NS |
| Interaction VXZn | NS | NS | NS | NS | NS | NS |

Table 2. Effect of zinc fortification on Post harvest Soil Fertility status in paddy crop

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Treatments** | **Avail N (Kg/ha)** | **P2O5 (kg/ha)** | **K2O (kg/ha)** | **Fe**  **(mg kg-1)** | **Zn**  **(mg kg-1)** | **Cu**  **(mg kg-1)** | **Mn**  **(mg kg-1)** |
| **Main plots** |  |  |  |  |  |  |  |
| V1 - BPT 5204 | 180 | 48.35 | 476 | 40.68 | 6.74 | 4.44 | 8.54 |
| V2 - NDLR -7 | 167 | 44.17 | 482 | 38.54 | 5.75 | 2.50 | 5.86 |
| V3 - NDLR -8 | 192 | 50.12 | 472 | 42.35 | 7.81 | 3.68 | 9.22 |
| V4 - NLR 34449 | 178 | 43.67 | 488 | 35.62 | 4.81 | 2.70 | 5.26 |
| SEm+ | 3.52 | 2.14 | 4.22 | 1.22 | 0.43 | 0.11 | 0.21 |
| CD @0.05 | 9.12 | **5.78** | **NS** | **3.16** | 1.18 | **NS** | **0.56** |
| CV (%) | 10.58 | 8.82 | 7.2 | 8.2 | 6.3 | 6.8 | 6.2 |
| **Subplots** |  |  |  |  |  |  |  |
| Zn0 – Control | 182 | 52.53 | 482 | 42.70 | 7.20 | 2.82 | 6.09 |
| Zn1 - 50 Kg/ha | 173 | 43.34 | 476 | 38.62 | 4.82 | 2.61 | 6.03 |
| Zn2 – 100 Kg/ha | 188 | 47.82 | 482 | 49.20 | 8.50 | 2.55 | 6.10 |
| Zn3 –Foliar spray of ZnSO4 @ 0.2% | 166 | 48.12 | 464 | 38.71 | 6.78 | 2.63 | 6.28 |
| SEm+ | 3.15 | 0.72 | 6.3 | 1.87 | 0.73 | 0.21 | 0.12 |
| CD @0.05 | **8.42** | **2.10** | **NS** | **5.24** | 2.14 | **NS** | **NS** |
| CV (%) | 6.45 | 8.12 | 6.5 | 7.1 | 8.42 | 5.16 | 5.3 |
| Interaction VXZn | **NS** | **NS** | **NS** | **NS** | NS | **NS** | **NS** |
| Interaction VXZn | **NS** | **NS** | **NS** | **NS** | NS | **NS** | **NS** |

Table 3. Iron & Zinc concentrations in Paddy grain samples at the time of harvest in Kharif 2021

|  |  |  |
| --- | --- | --- |
| **Treatments** | **Fe**  **(mg kg-1)** | **Zn**  **(mg kg-1)** |
| **Main plots** |  |  |
| V1 - BPT 5204 | 29.42 | 18.12 |
| V2 - NDLR -7 | 24.45 | 14.14 |
| V3 - NDLR -8 | 30.25 | 18.85 |
| V4 - NLR 34449 | 18.65 | 16.17 |
| SEm+ | 3.22 | 0.43 |
| CD @0.05 | 8.47 | 1.22 |
| CV (%) | 8.2 | 6.3 |
| **Subplots** |  |  |
| Zn0 – Control | 14.38 | 10.14 |
| Zn1 - 50 Kg/ha | 25.47 | 17.88 |
| Zn2 – 100 Kg/ha | 28.38 | 18.22 |
| Zn3 –Foliar spray of ZnSO4 @ 0.2% | 16.85 | 14.25 |
| SEm+ | 0.87 | 0.35 |
| CD @0.05 | **2.16** | 1.08 |
| CV (%) | 8.5 | 7.14 |
| Interaction VXZn | **NS** | NS |
| Interaction VXZn | **NS** | NS |

**Conclusion:** In conclusion, the present study has shown that Zn in rice grain can be effectively raised by foliar Zn application, in particular when Zn was sprayed after flowering. Seeds with high Zn provide both agronomic and nutritional benefits. Since widespread occurrence of Zn deficiency in human populations is associated with low dietary Zn intake, special attention should be paid to foliar treatments of staple food crops with Zn. As shown in this paper for rice, this agronomic practice is highly effective and quick in increasing grain Zn.With proper planning, execution and implementation, bio fortified food crops will help India to address the malnutrition problem with minimum investment in research and it is going to improve the lives and health of so many needy people of our country.

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