

INTERACTIVE EFFECTS OF ZINC APPLICATION METHODS AND PHOSPHORUS SOURCES ON GROWTH YIELD AND QUALITY OF FINE AND COARSE RICE CULTIVARS

IQTIDAR HUSSAIN¹, MUHAMMAD SALEEM, MUHAMMAD JAWAD NAZIR² AND RASHID KHAN^{1*}

¹Department of Agronomy, Faculty of Agriculture, Gomal University, D.I. Khan, Khyber Pakhtunkhwa, Pakistan

²Plant Genetic Resources Institute (PGRI) National Agri Research Centre, Islamabad, Pakistan

Corresponding author's email: iqtidarhussain453@yahoo.com

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Abstract

Investigating how zinc application methods interact with phosphorus source types represents a crucial strategy for refining rice yield and grain quality in nutrient-impooverished soils. This field experiment was executed across two consecutive rice-growing seasons (2015–2016) rice season in Tibba Hamid Shah Bhakkar District, Punjab, Pakistan. The study sought to quantify the cumulative effects of three Zn application methods, soil application at 15 kg Zn ha⁻¹, a 1.5% foliar spray, and 1.5% seed priming with three P sources, diammonium phosphate, single super phosphate and nitrophos across two rice cultivars, Basmati-515 (fine grain) and IRRI-6 (coarse grain). A split-plot arrangement with four replicates was employed. Measurements encompassed leaf emergence and tiller emergence rates, days to heading, and allometric variables including leaf area index, leaf area duration, crop growth rate, and net assimilation rate. Yield determinants such as plant height, total tiller count, number of panicles bearing tillers, kernel count per panicle, 1000-kernel weight, grain and straw yield, and harvest index were recorded. The study further evaluated panicle sterility, kernel protein concentration, and Zn concentration in both grains and leaves, thereby correlating nutrient management strategies with both quantitative and qualitative yield outcomes. The study documented that soil-applied Zn at 15 kg ha⁻¹ combined with DAP as the P component markedly enhanced physiological, agronomic, and quality metrics relative to all alternative treatments. Basmati-515 consistently exceeded IRRI-6 regarding LAI, CGR, final yield, and Zn concentration in the grain. The Zn soil placement augmented yield through increased tiller number, stature, and visible radiation use efficiency, diminished panicle sterility and elevated both grain protein and Zn levels. Foliar applications delivered moderate yield response while seed priming principally fostered seedling vigor and advanced maturity by a few days. Collectively, the data advocate soil Zn placement with DAP as the superior tactic for rehabilitating yield in soils deficient in both Zn and P. The analyses further confirm that the Zn application technique and phosphorus modality jointly modulate rice productivity and grain nutrient profiles, informing strategies for agronomic sustainability and for producing biofortified rice on a wider scale.

Keywords: zinc application, phosphorus sources, biofortification, growth parameters, yield traits, grain quality

INTRODUCTION

Rice (*Oryza sativa* L.) is a global dietary cornerstone that currently contributes 35–60% of caloric intake for more than three billion individuals necessitating an average production increase of roughly

1% annually for sustainable supply (Khush, 2005; Cui *et al.*, 2020).

Phosphorus (P) is an irreplaceable macronutrient that underpins bioenergetics, nucleic acid metabolism, and root system architecture (Shenoy and Kalagudi, 2016; Vance *et al.*, 2003; Mitchell *et al.*, 2012).

Nevertheless, tropical and subtropical soils frequently contain less than 1% of total soil P in bioavailable forms, constraining attainable yield ceilings (Kaur *et al.*, 2010). Zinc is a critical micronutrient requisite for cofactor activity, auxin biosynthesis, and plasma membrane stability. Approximately 50% of the world's cereal-growing soils exhibit Zn deficiency, whose physiological ramifications yield lower biomass, diminished grain output, and suboptimal grain micronutrient density (Alloway, 2008).

Phosphorus and zinc interact in agronomic systems with opposing and complementary elements. Surplus P decreases Zn solubility by forming ZnP precipitates and by depressing mycorrhizal transport (Fageria *et al.*, 2011; Kaur *et al.*, 2010), whereas Zn starvation hinders P by disrupting energy-dependent root processes (Alloway, 2008; Zhang *et al.*, 2011). Nevertheless, judicious combined P and Zn applications typically exhibit greater overall efficacy. Meta-analyses of multisite trials reveal that regimen applications 80 kg P₂O₅ and 10 kg Zn ha⁻¹ for example, can elevate rice biomass and grain Zn concentrations by over 20% each (Mondal *et al.*, 2020; Mayadunne *et al.*, 2024; Memon *et al.*, 2020).

Despite clear evidence of the agronomic interdependence of phosphorus and zinc, current fertilization practices in South Asian rice-based systems remain largely generalized, with limited consideration of soil-plant-nutrient interactions in alkaline, Zn-deficient soils. Farmers frequently rely on uniform fertilizer recommendations that do not account for the antagonistic P-Zn dynamics, cultivar-specific nutrient demand, or the differential efficiency of Zn delivery methods. These constraints result in poor nutrient use efficiency, suppressed biomass accumulation, and inadequate grain Zn enrichment. Therefore, there is a critical need for field-validated nutrient management

strategies that integrate multiple Zn application techniques with diverse P fertilizer sources to optimize both productivity and biofortification outcomes under real-world rice-growing conditions.

Contrast in Zn application routes, soil, foliar, and seed priming results in distinct uptake efficiencies and agronomic outcomes. The soil route provides a reservoir of Zn, yet resilience may be compromised in high P profiles since competition can sequester Zn. Foliar applications target Zn supply to sensitive growth intervals, overcoming soil matrix limitations, while seed priming pretreats the seed with a low concentration Zn solution, fostering rapid root and shoot development. Cumulatively, these approaches yield substantial agronomic dividends and nutrient stacking (Phattarakul *et al.*, 2012; Rehim *et al.*, 2014; Farooq *et al.*, 2018; Upadhyay *et al.*, 2022). Consistent with these findings a combination of pot and in situ field experiments documented grain Zn concentrations rising by as much as 30% coincident with foliar Zn and verified concomitant increases in protein concentration attributed to stimulated N metabolic pathways (Fageria *et al.*, 2011; Chatterjee *et al.*, 2022; Upadhyay *et al.*, 2022).

Deliberate selection between fine-grain and coarse cultivars, exemplified by Basmati-515 and IRRI-6, respectively, reveals intrinsic disparities in growth dynamics, nutrient demand profiles, and Zn biofortification ceilings. Multi-season trials in Pakistan consistently demonstrated that coarse germplasm such as Pukhraj consistently yielded superior responses to co-applied P and Zn, manifesting as statistically significant increments in crop growth rate (CGR), biomass accumulation, and total Zn uptake compared with fine germplasm (Memon *et al.*, 2020; Mayadunne *et al.*, 2024). The results underscore genotype-dependent nutrient performance, reinforcing a need to

match cultivar selection to fertility strategy to fully exploit biofortification targets.

This study is distinct from previous research in its comprehensive evaluation of three zinc application methods (soil, foliar, and seed priming) in combination with three phosphorus fertilizer sources (DAP, SSP, and Nitrophos) across two contrasting rice cultivars (fine-grained Basmati-515 and coarse-grained IRRI-6). Unlike earlier studies that typically focused on single nutrient sources or isolated application routes, our experiment implements a rigorous factorial split-plot design over two cropping seasons and quantifies a wide spectrum of traits including phenology, LAI, CGR, NAR, yield attributes, and grain quality. Such a multidimensional, integrated nutrient assessment has not been previously reported in rice agronomy literature.

The literature on phosphorus and zinc interactions in rice is extensive yet studies rarely examine the simultaneous impact of three zinc application techniques, soil, foliar and seed priming, combined with three distinct phosphorus sources, DAP, SSP, and Nitrophos across two concomitant rice cultivars employing a split plot experimental design of substantial rigor. Moreover, the residual studies seldom quantify the multi trait outcomes, including phenology, leaf area index, crop growth rate, net assimilation rate, yield and grain quality.

Consequently, this research was designed to evaluate the interactive ramifications of the zinc application method and the phosphorus fertilizer source on growth, yield and grain quality of fine-grained Basmati 515 and coarse-grained IRRI 6 rice cultivars over two complete cropping seasons (2015–16) within a factorial split- plot framework. This investigation directly contributes to the agronomic viability of

integrated nutrient management protocols directed at the dual goals of sustained biofortification and enhanced productivity within rice agrosystems characterized by concomitant zinc and phosphorus limitation.

MATERIALS AND METHODS

Experimental Site and Climatic Conditions

This field experiment was executed across two consecutive kharif seasons (2015–2016) at the Tibba Hamid Shah farm, located in Tehsil Darya Khan, District Bhakkar, Punjab, Pakistan (31.62° N, 71.07° E). The experimental site lies within a transitional arid to semi-arid agro-ecological zone, characterized by hot summers, low annual precipitation, and high evaporative demand. The altitude of the site is approximately 161 m above sea level.

Meteorological data were obtained from an automated weather station (Davis Vantage Pro2, Davis Instruments, USA) installed near the site, supplemented with records from the Pakistan Meteorological Department. During the cropping season, the mean maximum temperature ranged from 32 to 45 °C, while the minimum temperature varied between 18 and 28 °C. The relative humidity fluctuated between 40 and 68%, with annual rainfall confined to 150– 250 mm, the majority occurring during the monsoon period (July–September). These conditions reflect the semi-arid environment under which the experiment was performed.

The soil of the experimental site was classified as sandy loam (USDA classification), moderately alkaline with a pH of 8.1, and low in organic matter content (0.23%). The Olsen method determined an available phosphorus concentration of 10 mg kg⁻¹, categorizing the soil as moderately supplied with

phosphorus. Zinc availability, extracted using DTPA, was found to be 0.6 mg kg⁻¹, which is below the critical threshold of 0.8 mg kg⁻¹, indicating Zn deficiency.

Soil Sampling and Analysis

Prior to sowing, composite soil samples were collected from two depth intervals (0–15 cm and 15–30 cm) using a motorized soil auger (Eijkelkamp Agrisearch Equipment, Netherlands) to ensure representative sampling. The collected samples were air-dried, ground, and sieved through a 2 mm mesh before analysis.

The following analytical procedures and instruments were employed:

Soil pH was determined in a 1:2.5 (w/v) soil-to-water suspension using a digital pH meter (Hanna Instruments HI2211, USA).

Electrical conductivity (EC) was measured with a conductivity meter (DDS-307A, INESA Scientific Instrument Co., China).

Organic carbon content was analyzed by the Walkley–Black wet oxidation method using a titration setup.

Available phosphorus was extracted with 0.5 M NaHCO₃ (Olsen's method) and quantified by a UV–Visible spectrophotometer (Shimadzu UV-1800, Japan).

Available zinc was extracted using DTPA solution (0.005 M DTPA, 0.01 M CaCl₂, 0.1 M TEA, pH 7.3) and measured with an Atomic Absorption Spectrophotometer (PerkinElmer AAnalyst 400, USA).

Baseline soil analysis confirmed that the experimental field was sandy loam, moderately

alkaline, low in organic matter, moderately supplied with phosphorus, and deficient in plant-available zinc.

Experimental Design and Treatments

The experiment was conducted under a split–split plot design (three-factor factorial arrangement) within a randomized complete block design (RCBD) comprising four replications. The hierarchical structure of experimental factors was as follows:

Main plot (Cultivars):

Basmati-515 (fine-grain, aromatic)

IRRI-6 (coarse-grain, non-aromatic)

Sub-sub plot (Phosphorus Application Methods):

Di-ammonium phosphate (DAP)

Single superphosphate (SSP)

Nitrophos (NP)

Sub-sub plot (Zinc Application Methods):

Soil-applied Zn: Basal incorporation of ZnSO₄·7H₂O at 15 kg Zn ha⁻¹.

Foliar Zn: Application of 1.5% ZnSO₄ spray at tillering and panicle initiation, using a knapsack sprayer (*Solo 425, Germany*).

Seed Priming with Zn: Pre-sowing priming in 1.5% ZnSO₄ solution (1:3 seed-to-solution, 10 h soak), followed by air-drying.

Each sub-sub plot measured 5.0 m × 1.4 m. Treatments were randomized within each block to avoid positional bias.

Agronomic Management

Seedling Transplantation

Thirty-day-old seedlings were transplanted on 25 June at 22.5 cm (intra-row) × 20 cm (inter-row) spacing,

with two seedlings per hill.

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Nutrient Management

A uniform basal dose of 100 kg P₂O₅ ha⁻¹ (according to P source) and 70 kg K₂O ha⁻¹ was incorporated at transplanting. Nitrogen was applied as urea at 160 kg N ha⁻¹ in three equal splits at 15, 30, and 45 DAT. Zinc was supplied strictly according to treatment protocols.

Crop Husbandry

Weeds were removed manually by hoeing and hand weeding. Irrigation was scheduled to maintain optimal soil moisture, avoiding drought stress and

excess water conditions. All other agronomic practices were implemented uniformly following local recommendations for transplanted rice.

Treatment Structure

**Data Acquisition and Observational Approaches
Phenological and Morphological Indicators**

Phenological traits were recorded following standard agronomic protocols. The number of days from transplanting to 50% heading and physiological maturity was noted by direct field observation. Weekly counts of tiller and leaf emergence were performed between 15 and 45 days after transplanting (DAT) using five pre-marked representative plants per subplot to capture growth dynamics.

Table 1: Experimental Design

Factor Level	Treatments	Details
Main Plot	Rice Cultivars	Basmati-515 (aromatic fine-grain), IRRI-6 (coarse non-aromatic)
Sub Plot	Phosphorus Sources	DAP, SSP, NP
Sub-sub- Plot	Zinc Application	Soil-applied ZnSO ₄ ·7H ₂ O @ 15 kg Zn ha ⁻¹ Foliar spray with 1.5% ZnSO ₄ at tillering and panicle initiation (Solo 425 sprayer) Seed priming with 1.5% ZnSO ₄ solution (10 h, 1:3 ratio)

Allometric Metrics

Leaf Area Index (LAI)

The CI-202 Portable Leaf Area Meter (CID Bio-Science, USA) was employed to measure leaf area at 45, 60, 75, and 90 DAT. LAI was calculated as:

$$LAI = (\text{Leaf area of sample plant} / \text{Ground area occupied by the plant})$$

Leaf Area Duration

LAD was derived following Watson’s (1947) formula:

$$LAD = [(LAI_1 + LAI_2) / 2] \times (t_2 - t_1)$$

where LA₁ and LA₂ represent successive observations of leaf

Leaf Area Duration

LAD was derived following Watson's (1947) formula:

$$LAD = \frac{(LAI_1 + LAI_2)}{2} \times (t_2 - t_1)$$

where LA₁ and LA₂ represent successive observations of leaf area index at times t₁ and t₂, respectively.

Crop Growth Rate (CGR)

Sequential destructive sampling was undertaken within a 1 m² quadrat at pre-defined intervals. Harvested samples were oven-dried at 70 °C until constant weight using a Memmert UF55 drying oven (Germany). CGR was then estimated as

$$\text{Crop growth rate (CGR)} = \frac{W_2 - W_1}{t_2 - t_1} \times \frac{1}{A}$$

Where W₁ and W₂ are dry weights (g) at times t₁ and t₂, and A is the ground area (m²).

Net Assimilation Rate (NAR)

NAR was calculated as:

$$NAR = \frac{(W_2 - W_1)(\ln LA_2 - \ln LA_1)}{(t_2 - t_1)(LA_2 - LA_1)}$$

Where W is plant dry weight and LA is leaf area at corresponding sampling times.

Yield and Yield-Associated Variables

Plant height, fertile tillers (m⁻²), and panicle length were measured from five randomly selected plants per plot using a digital vernier caliper (Mitutoyo 500-196-30, Japan).

Grain and straw yields were obtained by harvesting each plot separately, threshing, and adjusting grain moisture to 14% with a grain moisture meter (Dickey-John GAC® 2500, USA).

1000-grain weight was determined using an electronic balance (Shimadzu ATX224, Japan).

Grains per panicle were counted from five randomly selected panicles per plot.

Grain Quality Indices

Panicle sterility (%) was estimated using the protocol of Subedi *et al.* (1997).

Grain protein concentration (%) was determined via the micro-Kjeldahl method. Total nitrogen was measured with a Kjeltect™ 8200 Auto Distillation Unit (Foss, Denmark) and converted to protein using a factor of 5.95.

Zinc concentration in leaf and grain tissues was quantified following wet acid digestion (Jones and Case, 1990) using an Atomic Absorption Spectrophotometer (PerkinElmer AAnalyst 400, USA). Standard Zn solutions (0.5–2.5 mg L⁻¹) were used for calibration and regression curve generation.

Statistical Analysis

Data underwent analysis of variance (ANOVA) in a split plot framework with Statistix 8.1. Treatment means were distinguished by the least significant difference (LSD) at $\alpha = 0.05$. Interaction effects were considered significant when $p \leq 0.05$. Graphical and descriptive statistics were generated by MS Excel and Origin Pro 2023.

RESULTS AND DISCUSSION

Time to reach 50% heading was clearly shaped by zinc application methods and the phosphorus source with differences between the two rice cultivars also standing out. Basmati-515 always headed earlier than IRRI-6 for every treatment combination in the fig 1. The greatest advance occurred when seed priming with zinc was coupled with DAP application pointing to a possible synergy between better phosphorus supply and faster micronutrient uptake through the seed treatment. The earlier heading of Basmati-515 is likely linked to faster metabolic processes and heightened physiological activity induced by seed priming which enhances

seedling vigor and promotes more uniform early growth. DAP with its high solubility and quick phosphorus release probably strengthened root growth and nutrient acquisition during the seedling period helping the plants to reach critical developmental milestones on schedule.

Islam *et al.* (2021) reported parallel trends showing that micronutrient treatments applied to seeds notably hastened heading in fine rice cultivars by boosting early seedling vigor and tiller proliferation. Similarly, Singh *et al.* (2020) demonstrated that integrating seed priming with phosphorus enriched fertilization raised phenological advancement and underscore the promise of concurrently using zinc seed priming alongside phosphorus dense fertilizers such as DAP aiming to fine tune the timing of sensitive fine rice genotypes that respond markedly to variations in micronutrient and macronutrient supply. Application of soil applied zinc along with Diammonium Phosphate substantially benefited the allometric development of the fine rice cultivar Basmati-515.

The corresponding rise in Leaf Area Index and Leaf Area Duration illustrates both an expanded canopy and an extended metabolic window for photosynthesis processes that cumulatively foster a sustained increase in biomass. Concurrently, observed gains in Crop Growth Rate and Net Assimilation Rate reveal an enhanced physiological trajectory characterised by improved resource mobilisation and carbon fixation.

The data imply that the complementary action of zinc and phosphorus optimised the interplay between source strength and sink demand, key determinants of the cultivar's growth ceiling mentioned in fig 2. These trends corroborate results published by Farooq *et al.* (2018) who documented increased dry matter and growth metrics when micronutrient and macronutrient inputs were finely tuned within an integrated nutrition framework. Likewise, Sharma *et al.* (2019) confirmed that the strategic co-application of soil zinc and phosphorus fostered an extended canopy life, improved leaf retention and elevated growth parameters in rice thus reinforcing the current findings.

The integration of soil applied zinc and diammonium phosphate markedly elevated grain yield with Basmati-515 exceeding IRRI-6 in total production in the fig 3. The superior performance of Basmati-515 was ascribed to enhanced fertile tiller numbers optimized panicle architecture and more efficient grain setting. The composite treatment presumably optimized both macro and micronutrient availability during decisive growth windows thereby promoting advantageous assimilate distribution to reproductive structures. Conversely, IRRI-6 exhibited a greater tiller count but a reduced kernel number per panicle when juxtaposed with Basmati-515.

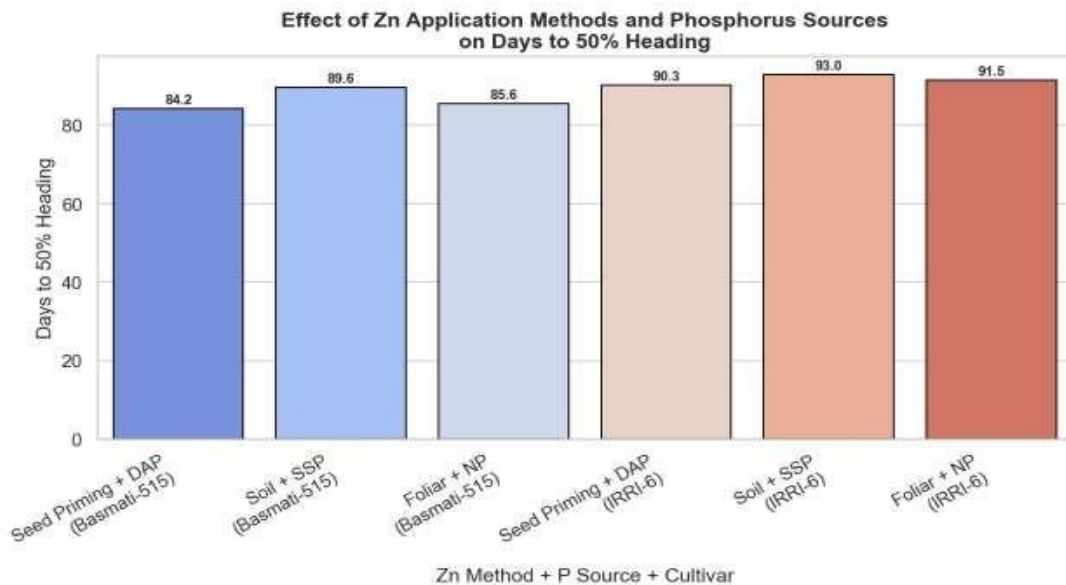


Figure 1. Effect of Zn application Methods and Phosphorus Sources on Days to 50% Heading

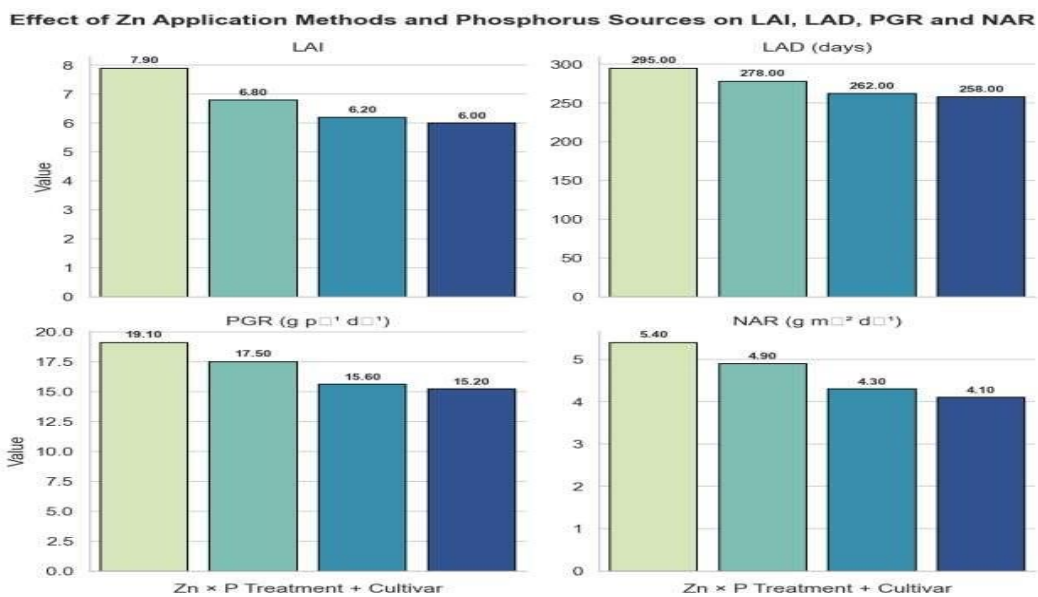


Figure 2. Effect of Zn application Methods and Phosphorus Sources on LAI, LAD, PGR and NAR

Effect of Zn Application Methods and Phosphorus Sources on Rice Yield Components

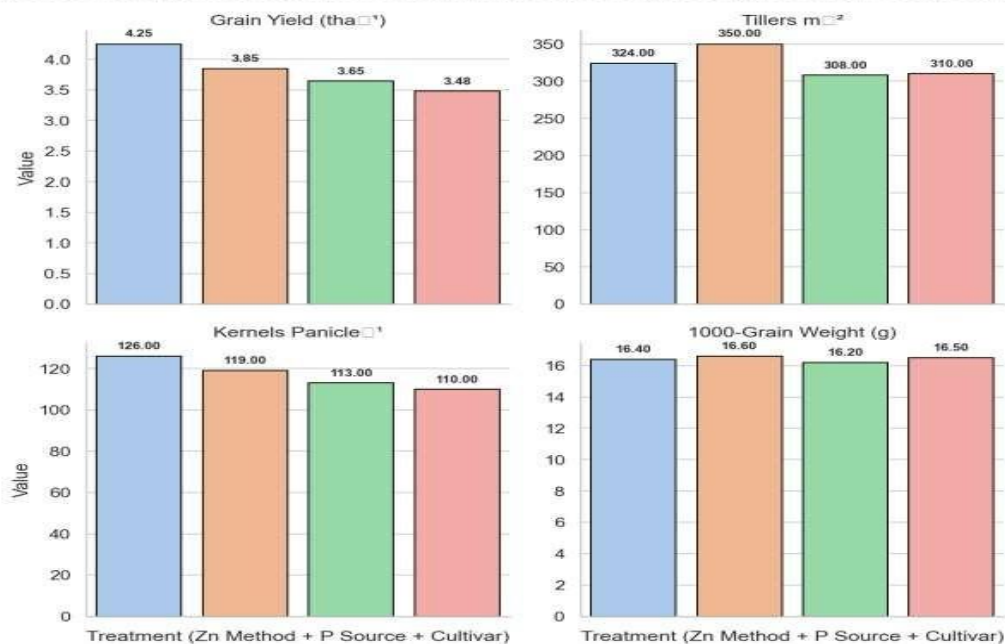


Figure 3. Effect of Zn application Methods and Phosphorus Sources on Rice Yield Components

Effect of Zn Application Methods and Phosphorus Sources on Grain Protein, Zn Content & Sterility

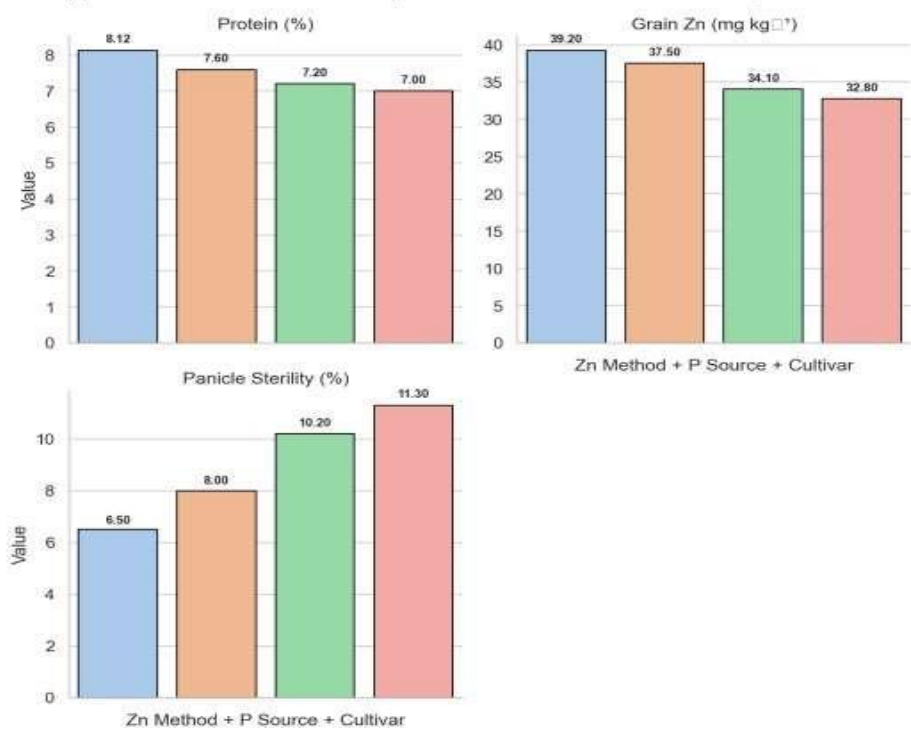


Figure 4. Effect of Zn application Methods and Phosphorus Sources on Grain Protein, Zn and Sterility

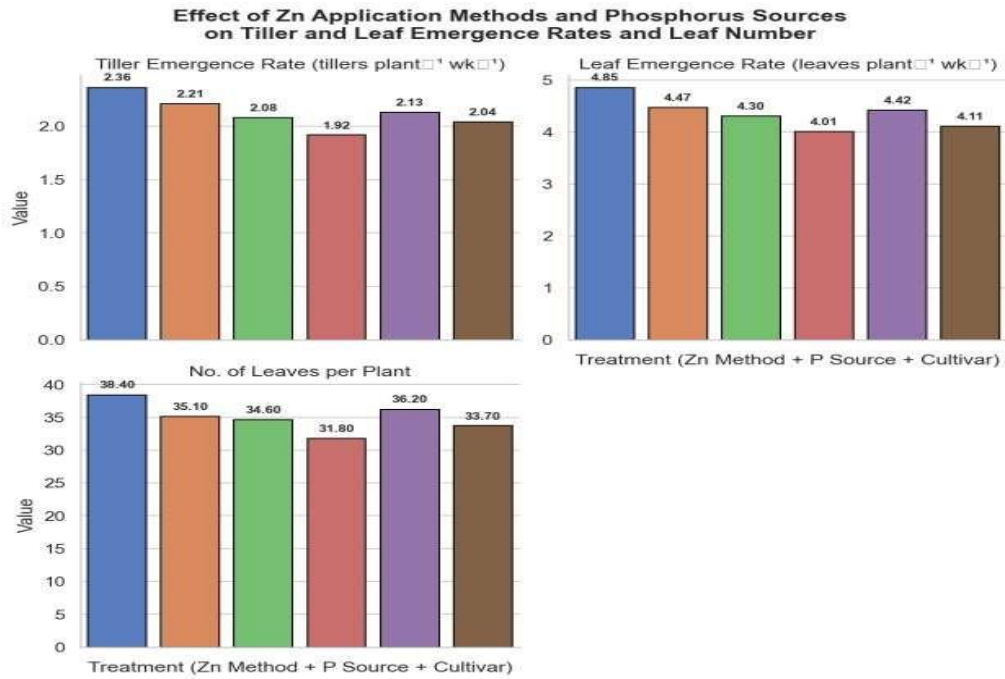


Figure 5. Effect of Zn application Methods and Phosphorus Sources on Tiller and Leaf Emergence Rates and Leaf Number

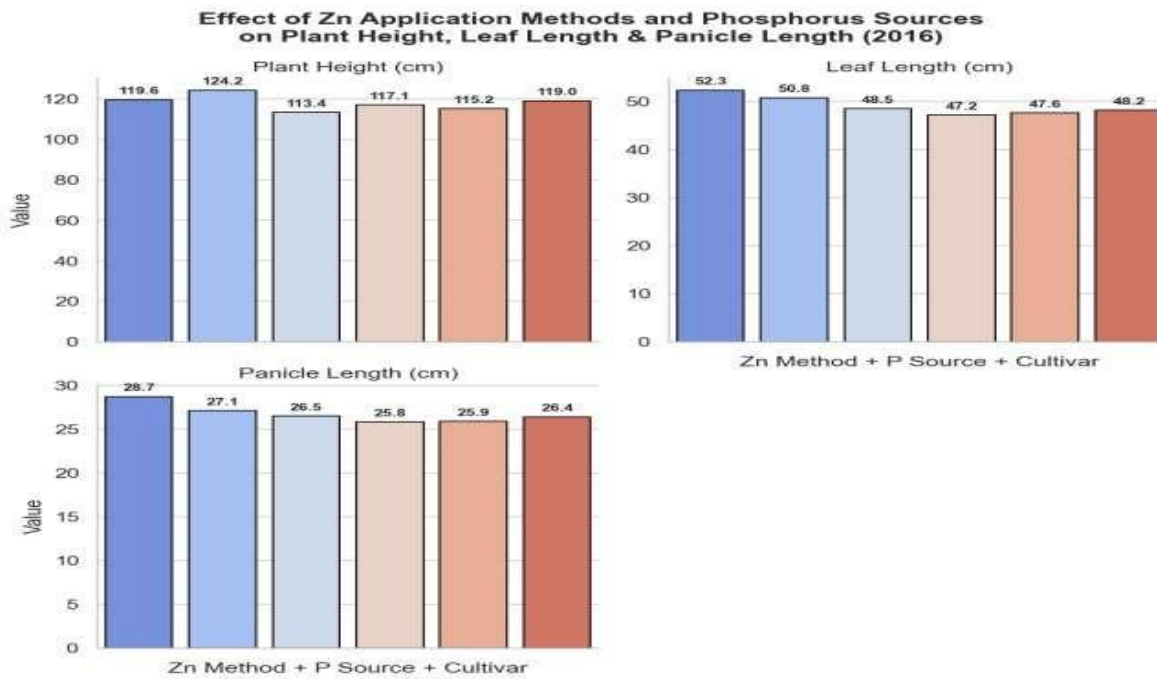


Figure 6. Effect of Zn application Methods and Phosphorus Sources on Plant Height, Leaf Length and Panicle length

This discrepancy may indicate a non-ideal source sink balance wherein excessive vegetative biomass limited reproductive success in fig 3. Such variations underscore that nutrient use efficiency and assimilate partitioning are at least in part genetically determined particularly when zinc and phosphorus are co-applied. The observations corroborate Zhang *et al.* (2023), who documented that basal zinc application bolstered tillering and grain filling in rice. Additionally, Yadav *et al.* (2022) found that combining zinc and phosphorus fertilization enhanced panicle fertility and yield in fine rice cultivars thereby reinforcing reproductive success and sink capacity.

Both rice cultivars showed significant gain in both grain quality and overall physiological vigor when soil applied zinc was paired with diammonium phosphate (DAP) fig 4. This dual nutrient protocol raised both protein and zinc concentrations in the grains and lowered the incidence of panicle sterility, an important determinant of grain set and final productivity. Of the two cultivars, Basmati 515 evidenced the highest nutritional quality which may arise from its genetic endowment for efficient nutrient accumulation and superior translocation from source tissues to developing grains.

The concomitant rise in protein and zinc concentrations can be traced to zinc's catalytic function in critical enzymes and its facilitation of amino acid biosynthesis (fig 4). Phosphorus when co-administered may have augmented the long distance transport of these nutrients especially during the critical grain filling interval thus bolstering the nutritional density of the final yield. These results align with Mayadunne *et al.* (2024) who documented that zinc and phosphorus co-fertilization boosts both rice biofortification and yield. Kumar *et al.* (2021) also found that zinc particularly in

tandem with phosphorus curbed panicle sterility and enhanced the nutritional profile of rice grains corroborating the findings presented here.

The interaction between zinc application techniques and phosphorus sources markedly affected the initial vegetative stage in both rice cultivars. Seed priming with zinc coupled with diammonium phosphate (DAP) application yielded superior tiller initiation and leaf emergence rates particularly in Basmati-515 mentioned in fig 5. Such a response indicates a pronounced physiological interaction whereby zinc treated seeds benefit from the immediate phosphorus solubilization thereby ensuring robust establishment during the sensitive early growth phase. The enhancements recorded under this particular treatment can be delineated to heightened seed vigor, amplified enzymatic pathways and modulated hormone levels all influenced by zinc.

The nutrient has been shown to elevate indole 3 acetic acid concentrations and to promote cellular elongation whereas DAP supplies readily bioavailable phosphorus essential for continued mitotic and meristematic activity at the root apex in the fig 5. The resulting phenotypic expression of the reinforced root to shoot ratio at the moment of emergence, likely facilitated early water and nutrient acquisition thereby accelerating the formation of a dense and uniform canopy.

The emerging leaf number per plant exhibited comparable patterns further corroborating the proposition that initial vegetative development marked by leaf and tiller proliferation serves as a dependable indicator of subsequently attained biomass and ultimate yield potential in fig 5. The current observations align with the observations of Islam *et al.* (2021) who documented that the concomitant application of zinc

seed priming and phosphorus enhanced soils and markedly advanced rice vegetative phases. Similarly, Das *et al.* (2020) documented that pairing seed applied micronutrient priming with phosphorus supply fostered accelerated shoot elongation, increased leaf area index and heightened tillering in fine rice cultivars.

The application of soil-applied zinc in tandem with DAP induced marked enhancements in plant morphology and structural traits with the coarse cultivar IRRI-6 achieving a maximum height of 124.2 cm in the fig 6. This outcome underscores the cultivar's pronounced capacity for vegetative adjustment to foundational nutrient delivery where zinc accelerates both cell division and elongation while phosphorus fortifies root and shoot architecture.

The recorded height increase is predominantly the result of pronounced internode elongation and a more expansive canopy parameters critical for optimizing light capture and total biomass accumulation (fig 6). Conversely the fine cultivar Basmati-515 developed both longer leaf blades and a more pronounced panicle under the identical nutrient regimen revealing its slender framework and a reproductive edge in Zn- and P-rich environments. Within fine rice genetic backgrounds the elongation of panicles maintains a strong positive correlation with the capacity to host grains thereby raising the threshold for genetic yield potential.

These gains are mediated by sustained meristematic activity directed nutrient allocation to reproductive organs and a balanced hormonal milieu the latter of which is finely tuned by the presence of zinc (fig 6). Leaf length exhibited marked divergence across cultivars while displaying a uniform positive response to Zn and DAP applications incorporated into the soil. This uniformity implies a likely enhancement

in nitrogen metabolic pathways and chlorophyll biosynthetic capacity both prerequisite to the efficient light harvesting and assimilatory processes underpinning grain yield in high-value aromatic rice.

The attendant structural refinements in both cultivars corroborate the observations of Farooq *et al.* (2018), who demonstrated that synergistic Zn and P supply ameliorates shoot morphology, panicle articulation, and holistic plant spatial arrangement in fig 6. Parallel patterns were recorded by Sharma *et al.* (2020) who documented that a composite regimen of micronutrient and P nutrition significantly advanced canopy morphology and the ontogeny of reproductive organs in rice cultivated across heterogeneous agro ecological domains.

Results indicated that biomass allocation in rice was markedly governed by the cultivar \times nutrient interaction, with soil-applied zinc and diammonium phosphate acting in concert. In that scenario, IRRI-6 exhibited the apex straw biomass of 6.34 t ha⁻¹, underscoring the cultivar's propensity for extensive vegetative growth when both principal and trace nutrients are optimally supplied (fig 7). The data imply that IRRI-6 diverts a greater fraction of photosynthate into structural components, a strategy evidently strengthened by nutrient-driven tiller multiplication and enhanced internode elongation.

Conversely, Basmati-515, manifesting a marginally lower straw yield, nonetheless registered the zenith harvest index of 42.2%. Such performance underscores its proficiency in converting total biomass into marketable grain. The elevated HI is attributable to a genetically encoded source sink equilibrium which, when coupled with sufficient zinc and phosphorus, accelerates the movement of assimilates into the panicles mentioned in fig 7. The concomitant structural

redistribution favoring a higher panicle to leaf ratio augments grain filling rates and ultimately total yield efficiency (fig 7). These observations align with Zhang *et al.* (2023) who reported that zinc fertilization accelerates grain-filling rate through elevated enzyme activity and more effective assimilate translocation, while phosphorus boosts structural biomass through expanded root and shoot development. Singh *et al.* (2022) added that simultaneous Zn and P application markedly raises harvest index, reinforcing vegetative scaffolding and reproductive grain set contingent upon the underlying physiology of the cultivar.

Moreover this segment emphasizes that Zn-P synergies elevate both grain and straw yield while finely regulating biomass allocation among plant parts (fig 7). The cultivar-specific divergence indicates that smooth and coarse rice forms may demand customized nutrient regimens to maximize yield while sustaining resource use efficiency. The cultivar-specific divergence indicates that smooth and coarse rice forms may demand customized nutrient regimens to maximize yield while sustaining resource use efficiency.

In a similar context, the application of beneficial rhizobacterial strains has been shown to improve soil physicochemical properties and enhance wheat (*Triticum aestivum* L.) productivity, reinforcing the importance of integrating biological and mineral nutrient management strategies for sustainable cereal production (Khan *et al.*, 2025a). Collectively, this segment emphasizes that Zn-P synergies elevate both grain and straw yield while finely regulating biomass allocation among plant parts. Similar evidence from

maize (*Zea mays* L.) demonstrates that combined application of organic and inorganic fertilizers improves both productivity and soil health (Khan *et al.*, 2025b), highlighting the broader significance of integrated nutrient management across cereal crops.

Joint application of soil applied zinc and diammonium phosphate (DAP) markedly reduced chalky kernel incidence and elevated the share of translucent kernels in Basmati-515 (fig 8). Chalkiness is a pivotal quality defect in rice tied to disordered starch granule organization, impaired assimilate mobilization during filling and heightened spikelet sterility. Sufficient zinc and phosphorus at pivotal reproductive phases ameliorate these factors by bolstering assimilate flow, lowering sterility and facilitating the enzymatic cascades governing endosperm maturation.

Zinc is crucial for starch polymerization and the coordination of protein carbohydrate deposition during the final kernel formation phase yielding firmer translucent endosperm. Phosphorus in contrast strengthens metabolic energy gradients and increases the assimilate sink capacity. Consequently, fine-quality cultivars such as Basmati-515 already predisposed to premium grain traits demonstrated a pronounced quality gain under the combined Zn and DAP regime with chalkiness reduced to around 5.9%. These findings underscore that fine-tuned nutrient supply micronutrient and macronutrient can carry grain traits beyond the limits suggested merely by genetic background. IRRI-6 exhibited a beneficial response to soil-applied zinc with a decrease in chalky grain percentage nevertheless chalkiness levels remained greater than in Basmati-515.

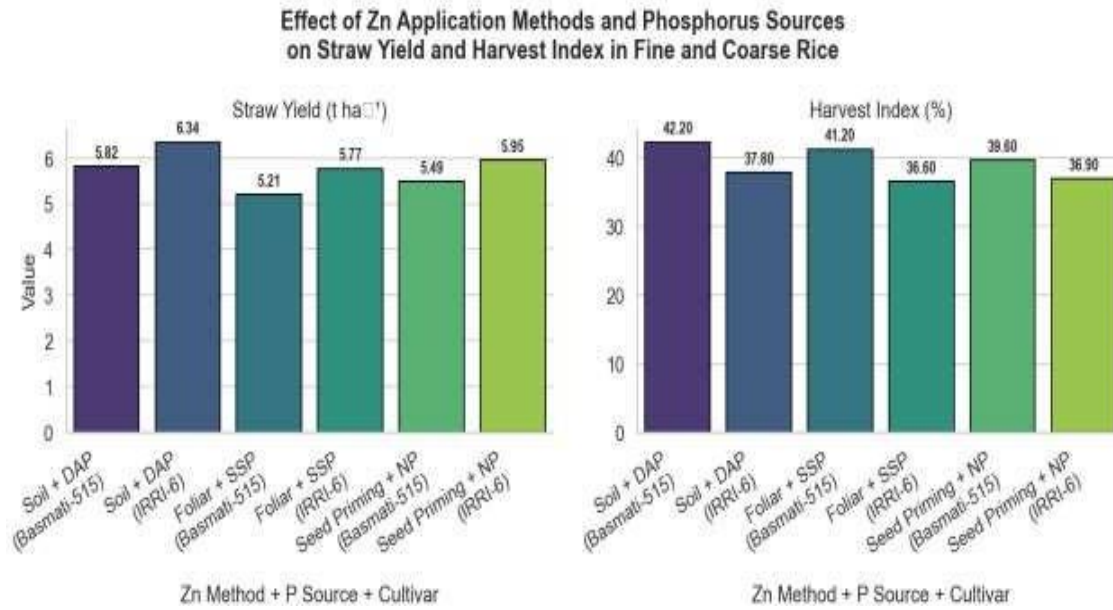


Figure 7. Effect of Zn application Methods and Phosphorus Sources on Straw Yield and Harvest Index in Fine and Coarse Rice

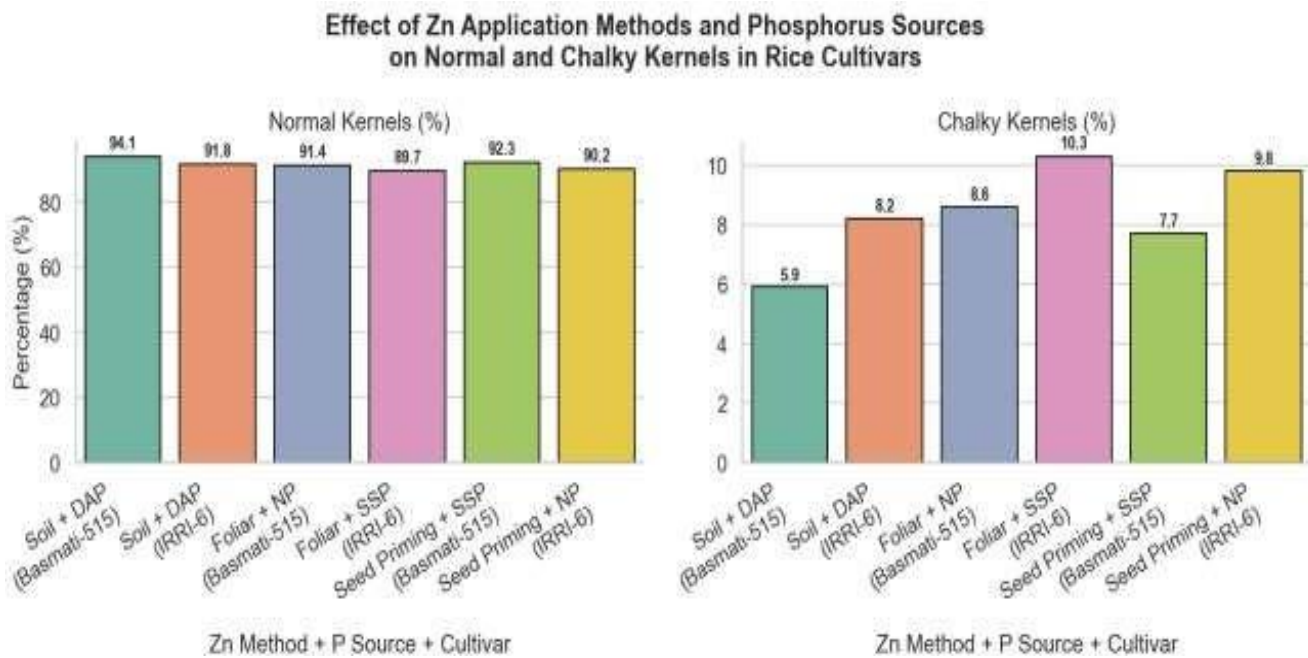


Figure 8. Effect of Zn application Methods and Phosphorus Sources on Normal and chalky kernels in Rice Cultivars

This difference likely arises from IRRI-6's coarser grain morphology and a larger endosperm surface area which heightens susceptibility to erratic starch deposition and to abiotic stresses during the critical grain filling period (fig 8). These observations are consistent with those of Mayadunne *et al.* (2024) who reported marked reductions in grain chalkiness and gains in grain uniformity when Zn P nutrition was applied in a complementary regimen. Gupta *et al.* (2022) noted that zinc intervention not only enhanced grain translucency but also mitigated endosperm disorders in commercially valuable rice lines, a response attributed to fortified starch protein matrix interactions and enhanced filling dynamics.

Conclusion

This study demonstrated that the combined application of soil-applied Zn (15 kg ha⁻¹) with DAP significantly enhances growth, yield, and grain nutritional quality in both fine and coarse rice cultivars, particularly Basmati-515. The synergistic Zn-P interaction improved LAI, CGR, grain protein, and grain Zn concentration while reducing panicle sterility and chalkiness. These results highlight the importance of integrated nutrient management for improving nutrient-use efficiency, enhancing biofortification outcomes, and sustaining productivity in Zn- and P-deficient rice agroecosystems.

Recommendations

Deliver ZnSO₄ at a rate of 15 kg ha⁻¹ alongside a DAP application totaling 100 kg P₂O₅ ha⁻¹ to maximize yield and enhance grain quality, particularly within fine rice types such as Basmati-515. Initiate Zn seed priming to accelerate early seedling vigor, yet integrate phosphorus inputs to prolong biomass accumulation across the cropping cycle. Direct

attention to biomass refinement in coarse varieties such as IRRI-6 by aligning Zn and P applications so that grain quality and nutrient storage are simultaneously advanced. Conduct additional experiments that quantify the agronomic cost benefit, probe the lingering effect of Zn and P in the soil and secure results across diverse pedoclimatic zones. Translate these outcomes into structured farmer education modules emphasizing nutrient-efficient applications within evolving climate-smart rice cultivation systems.

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