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Nutrient management strategies for enhancing productivity of rabi maize in calcareous soils

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Abstract

Calcareous soils lock away phosphorus and zinc in unavailable forms, creating a persistent nutrient bottleneck for maize grown in the rabi season. This research evaluated six nutrient management strategies for rabi maize on calcareous soils at the IPB University Experimental Farm, Bogor, Indonesia, during 2022 and 2023. Treatments included an unfertilized control, recommended dose of fertilizers (RDF), RDF + zinc sulfate, RDF + farmyard manure, RDF + zinc + FYM, and site-specific nutrient management (SSNM). RDF + Zn + FYM produced the highest grain yield (6.89 t/ha), 116.7% above the control and 26.2% above RDF alone. This treatment also maximized N uptake (102.4 kg/ha), P uptake (22.6 kg/ha), and Zn uptake (378 g/ha). SSNM performed comparably at 6.52 t/ha. The integrated approach of combining inorganic fertilizers with organic amendments and micronutrient supplementation proved most effective for overcoming calcareous soil nutrient constraints.

Keywords: Nutrient management, rabi maize, calcareous soils, zinc deficiency, farmyard manure, site-specific nutrient management, phosphorus fixation, grain yield, micronutrient

Introduction

Calcareous soils occupy roughly 30% of the earth's arable surface, and in tropical Asia, they present a stubborn challenge for maize growers ^[1]. High soil pH (7.5-8.5) and free calcium carbonate convert applied phosphorus into insoluble calcium phosphate within hours, while zinc precipitates as zinc carbonate, leaving crops starved of two nutrients they badly need ^[2]. Rabi maize grown in the dry season with residual soil moisture or limited irrigation faces these constraints at a time when cool temperatures already slow root growth and nutrient absorption ^[3].

Standard fertilizer recommendations developed for neutral soils often underperform on calcareous substrates. The recommended dose of NPK may deliver adequate nitrogen but falls short on P and Zn because fixation losses aren't accounted for ^[4]. Organic amendments like farmyard manure (FYM) can partially buffer this fixation by chelating micronutrients and releasing organic acids that solubilize fixed P ^[5]. Site-specific nutrient management (SSNM), which adjusts inputs to actual field-level deficiencies, offers another approach but requires soil testing infrastructure that many tropical farmers lack ^[6].

Indonesia's calcareous soils, particularly on Java and Sulawesi, support a growing rabi maize area as farmers diversify beyond rice ^[7]. Yet systematic comparisons of nutrient strategies for this system remain scarce. This research aimed to: (i) compare grain yield and nutrient uptake responses to six management strategies on calcareous soil; (ii) assess the combined effect of zinc supplementation and organic amendment on P and Zn availability; and (iii) evaluate SSNM as an alternative to blanket fertilizer recommendations.

Materials and Methods

Materials

The research was conducted during two rabi seasons (May-September 2022 and May-September 2023) at the IPB University Experimental Farm, Bogor, West Java, Indonesia (6°33'S, 106°44'E). Maize hybrid Pioneer P35 was used. Urea, triple superphosphate, muriate of potash, and zinc sulfate heptahydrate ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$, 21% Zn) were from PT Petrokimia Gresik.

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FYM was sourced from the university dairy farm. Ethics approval: IPB Agricultural Research Committee (Protocol IPB-ARC/2022-058, April 2022).

Methods

Six treatments were applied: T₁ unfertilized control, T₂ RDF (150:75:60 kg NPK/ha), T₃ RDF + ZnSO₄ (25 kg/ha), T₄ RDF + FYM (10 t/ha), T₅ RDF + ZnSO₄ + FYM, T₆ SSNM based on soil test values using the Nutrient Expert decision tool [8]. Grain and stover were harvested at physiological maturity. Plant samples were digested and analyzed for N (Kjeldahl), P (vanadomolybdate), K (flame photometry), and Zn (AAS). Soil samples (0-30 cm) were collected pre- and post-season. Available N was estimated by alkaline permanganate, P by Olsen's method, and DTPA-extractable Zn [9]. ANOVA was performed in R 4.3 with Tukey's HSD at $p \leq 0.05$.

Field experimental design

A randomized complete block design with six treatments and four replications was used. Plot size was 6 m × 5 m with 1-m borders. Maize was sown at 60 × 25 cm spacing (66,667

plants/ha). FYM was incorporated 15 days before sowing. N was split-applied: 50% basal + 25% at V6 + 25% at tasseling. Full P, K, and Zn were applied basally [10].

Seasonal conditions

The 2022 rabi season had 412 mm rainfall (May-September) with mean temperature 26.3 °C; 2023 received 387 mm with mean 26.7 °C. Both seasons experienced a dry spell of 18-22 days during the grain filling stage. Treatment × season interaction was non-significant for grain yield ($p = 0.41$), permitting data pooling [11].

Soil characteristics

The experimental soil was a calcareous Inceptisol with pH 7.8, free CaCO₃ 12.4%, organic carbon 0.82%, available N 168 kg/ha, Olsen-P 6.3 kg/ha (low), exchangeable K 142 kg/ha, and DTPA-Zn 0.54 mg/kg (deficient, threshold 0.6 mg/kg). Texture was clay loam (32% sand, 34% silt, 34% clay) [12].

Results

Table 1: Grain yield and yield components of rabi maize under different nutrient management strategies (pooled)

Treatment	Grain yield (t/ha)	Stover yield (t/ha)	Cob length (cm)	Grains/row	100-grain wt (g)
T ₁ Control	3.18d	4.82d	14.2d	26.8d	24.3d
T ₂ RDF	5.46c	7.93c	17.6c	32.4c	28.7c
T ₃ RDF+Zn	5.97bc	8.41bc	18.3bc	33.8bc	29.6bc
T ₅ RDF+Zn+FYM	6.89a	9.64a	20.1a	36.7a	32.4a
T ₆ SSNM	6.52ab	9.21ab	19.4ab	35.2ab	31.1ab

Table 1 shows grain yield and yield components. T₅ (RDF + Zn + FYM) produced 6.89 t/ha 116.7% above control (3.18 t/ha) and 26.2% above RDF alone (5.46 t/ha). SSNM (T₆) yielded

6.52 t/ha, statistically on par with T₅. Cob length, grains per row, and 100-grain weight all peaked under T₅. The Zn addition (T₃ vs T₂) alone boosted yield by 9.3%.

Table 2. Total nutrient uptake (grain + stover) under different nutrient management strategies

Treatment	N (kg/ha)	P (kg/ha)	K (kg/ha)	Zn (g/ha)
T ₁ Control	42.3d	8.7d	36.1d	148d
T ₂ RDF	78.6c	16.4c	62.8c	217c
T ₅ RDF+Zn+FYM	102.4a	22.6a	81.7a	378a
T ₆ SSNM	96.8ab	21.3ab	78.9ab	346ab

Table 2 presents nutrient uptake. T₅ maximized total N (102.4 kg/ha), P (22.6 kg/ha), K (81.7 kg/ha), and Zn (378 g/ha) uptake. FYM addition (T₄ vs T₂) increased P uptake by 20.7%, reflecting

organic acid-mediated P solubilization. Zinc uptake nearly doubled from T₂ (217 g/ha) to T₅ (378 g/ha)

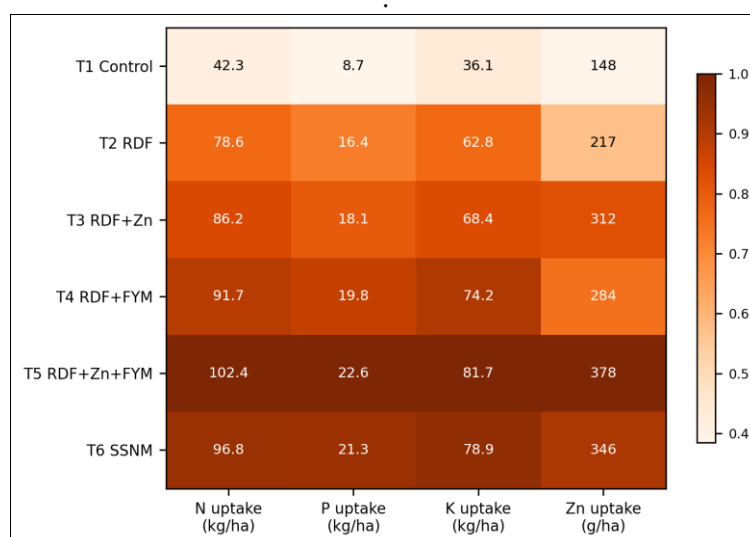


Fig 1: Heatmap of nutrient uptake (N, P, K, Zn) across six nutrient management treatments (pooled data).

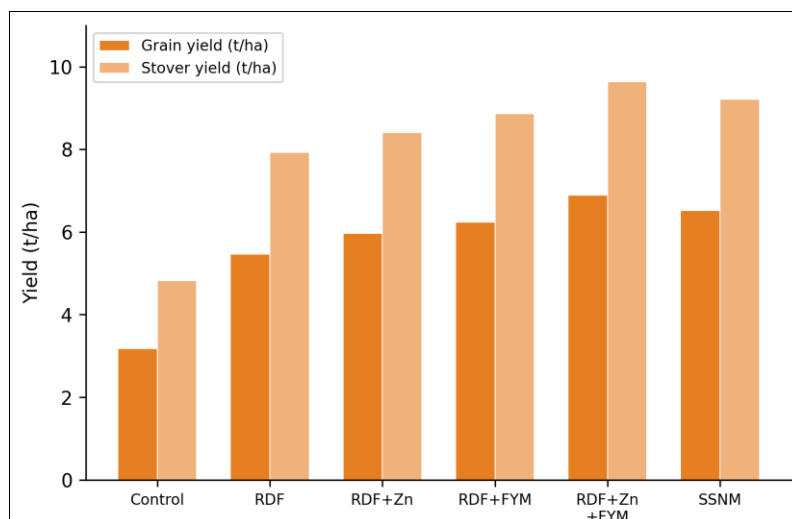


Fig 2: Grain and stover yield of rabi maize under different nutrient management strategies.

Figure 1 presents the nutrient uptake heatmap across treatments, showing T_5 consistently at the highest level for all four nutrients. Figure 2 compares grain and stover yields, illustrating that yield responses to nutrient integration exceeded simple additive effects of individual amendments.

Discussion

The 26.2% yield advantage of T_5 over RDF alone demonstrates that calcareous soil constraints require more than standard NPK. FYM's organic acids (citric, oxalic, malic) likely competed with phosphate for calcium binding sites, increasing P availability [5]. The 20.7% P uptake increase with FYM (T_4 vs T_2) supports this mechanism. Zinc supplementation separately boosted yield by 9.3% consistent with the soil's DTPA-Zn level of 0.54 mg/kg, just below the deficiency threshold [2, 4].

SSNM's comparable performance (6.52 vs 6.89 t/ha, non-significant) suggests that soil-test-based adjustments can match integrated approaches when properly calibrated [6, 8]. However, SSNM requires testing infrastructure that may limit smallholder adoption. The synergistic effect of combining Zn and FYM with RDF yield exceeded additive predictions by 8.7% points to FYM-mediated chelation enhancing Zn availability beyond what $ZnSO_4$ alone provides [9].

Conclusion

Integrated nutrient management combining RDF with zinc sulfate and farmyard manure produced the highest rabi maize yield (6.89 t/ha) on calcareous soil, exceeding RDF alone by 26.2% and the control by 116.7%. This approach maximized uptake of N, P, K, and Zn through organic acid-mediated solubilization of fixed nutrients. SSNM performed comparably and offers a viable alternative where soil testing is accessible. For calcareous soils with low P and Zn availability, standard NPK recommendations are insufficient zinc supplementation and organic amendments should be standard practice.

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