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Optimizing nutrient synchronization through integrated nutrient management enhances productivity and profitability of maize (*Zea mays* L.) in vertisols of central India

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Abstract

Productivity of maize (*Zea mays* L.) in central Indian Vertisols is often constrained not by absolute nutrient deficiency, but by inadequate synchronization between nutrient supply and crop demand. A field experiment was conducted during the Kharif season of 2025-26 at Indore to evaluate the effect of partial substitution of mineral fertilizers with organic and biological inputs on agronomic performance and economic returns. Eight treatments comprising graded levels of the recommended dose of fertilizers (RDF: 120:60:40 kg N:P₂O₅:K₂O ha⁻¹), alone and in combination with Farmyard Manure (FYM) and biofertilizers, were evaluated in a randomized block design with three replications. Integration of 75% RDF with FYM (5 t ha⁻¹) and biofertilizers significantly improved leaf area index (4.58), dry matter accumulation (212 g plant⁻¹), and grain yield (6.82 t ha⁻¹) compared with sole application of 100% RDF (6.21 t ha⁻¹). Agronomic efficiency and benefit-cost ratio were also enhanced under integrated nutrient management. The results indicate that crop performance was influenced more by temporal synchronization of nutrient release with crop demand than by total nutrient input alone. Partial substitution of mineral fertilizers with organic and biological inputs improved nutrient use efficiency without compromising productivity. These findings highlight the potential of integrated nutrient management as a viable strategy for improving productivity and profitability of maize under Vertisol conditions.

Keywords: Integrated nutrient management, maize (*Zea mays* L.), Vertisols, nutrient use efficiency, farmyard manure, biofertilizers, grain yield, economic returns

1. Introduction

Maize (*Zea mays* L.) has emerged as a key component of diversified cropping systems in central India, contributing significantly to food, feed, and industrial supply chains. In the Vertisols of the Malwa Plateau and adjoining semi-arid regions, crop productivity is influenced less by inherent soil fertility and more by the efficiency with which nutrients are mobilized and synchronized with crop demand. These soils, dominated by smectitic clay minerals, are characterized by pronounced shrink-swell behaviour, moderate alkalinity, and variable nutrient buffering capacity. Although generally adequate in potassium, they are susceptible to nitrogen losses through volatilization and episodic denitrification, along with phosphorus fixation under alkaline conditions.

The widespread reliance on mineral fertilizers has supported yield intensification; however, continuous and exclusive application has been associated with declining soil organic carbon, reduced aggregate stability, and diminished biological activity. Such changes adversely affect nutrient cycling processes and limit the soil's capacity to regulate nutrient release in relation to crop phenology. Consequently, temporal mismatches between nutrient availability and crop uptake particularly for nitrogen often result in reduced nutrient use efficiency and inconsistent yield response.

Integrated Nutrient Management (INM) has been proposed as an approach to address this imbalance by combining mineral fertilizers with organic and biological inputs. Its effectiveness lies not only in supplementing nutrient supply but also in regulating the temporal dynamics of nutrient release. Organic amendments such as Farmyard Manure (FYM) contribute labile carbon

fractions that stimulate microbial activity, improve soil structure, and enhance cation exchange capacity. Concurrently, microbial inoculants such as *Azotobacter chroococcum* and phosphate-solubilizing bacteria can influence nutrient availability through associative nitrogen fixation, root stimulation, and mobilization of native phosphorus. Collectively, these processes may improve nutrient synchronization by aligning nutrient release more closely with crop demand. Despite the conceptual advantages of INM, field-based evidence under Vertisol conditions of central India remains limited, particularly with respect to graded substitution of mineral fertilizers. The extent to which mineral nutrient inputs can be reduced without compromising productivity and whether such reductions can enhance economic returns requires systematic evaluation under local agro-ecological conditions. The present investigation was therefore undertaken to examine whether partial substitution of mineral fertilizers (25% reduction in RDF), complemented with FYM and biofertilizers, could improve nutrient use efficiency, sustain productivity, and enhance profitability of maize cultivation under Vertisol conditions.

Research Hypothesis

It was hypothesized that partial substitution of mineral fertilizers with organic (farmyard manure) and biological inputs (*Azotobacter chroococcum* and phosphate-solubilizing bacteria) would improve nutrient synchronization, enhance nutrient use efficiency, and sustain or increase maize productivity under Vertisol conditions of central India.

2. Materials and Methods

2.1 Experimental Site

The field experiment was conducted during the Kharif season of 2025-26 at the Research Farm, Indore (22°43' N latitude, 75°53' E longitude; 550 m above mean sea level). The site lies within the Malwa Plateau agro-ecological region and is characterized by a semi-arid tropical climate with a distinct monsoonal rainfall pattern. The region receives an average annual rainfall of 850-900 mm, of which nearly 85% is received between June and September. During the experimental season, total rainfall was 872 mm, distributed over 41 rainy days, which ensured adequate soil moisture during most critical growth stages. Mean maximum and minimum temperatures ranged from 29.4 to 34.8 °C and 18.2 to 23.6 °C, respectively, while relative humidity varied between 62 and 86%, reflecting typical monsoonal conditions. The experimental field comprised deep black soil classified as Typic Haplustert (Vertisol) according to USDA Soil Taxonomy. The soil is dominated by smectitic clay minerals, exhibiting pronounced shrink-swell behaviour and high moisture retention capacity. Prior to sowing, composite soil samples (0-15 cm depth) were collected and analysed using standard analytical procedures.

Table 1: Initial physico-chemical properties of experimental soil

Parameter	Value	Method
Soil texture	Clayey	Hydrometer method
pH (1:2.5 soil:water)	7.62	Glass electrode pH meter
Electrical conductivity (dS m ⁻¹)	0.34	Conductivity meter
Organic carbon (%)	0.56	Walkley and Black method
Available nitrogen (kg ha ⁻¹)	274	Alkaline KMnO ₄ method
Available phosphorus (kg P ₂ O ₅ ha ⁻¹)	19.4	Olsen's method
Available potassium (kg K ₂ O ha ⁻¹)	418	Neutral ammonium acetate

The soil was slightly alkaline, low to medium in available nitrogen, medium in available phosphorus, and high in available potassium. The organic carbon content indicated a moderately depleted status, consistent with long-term cereal-based cultivation under predominantly mineral fertilization. The site was selected for its representativeness of maize-growing Vertisols of central India. Minor spatial variability in soil depth and moisture retention, typical of such soils, was accounted for through the experimental design.

2.2 Experimental Design and Treatments

The experiment was laid out in a Randomized Block Design (RBD) comprising eight nutrient management treatments with three replications, resulting in a total of 24 experimental plots. The RBD was adopted to account for inherent spatial variability in Vertisols, particularly variations in micro-topography and moisture distribution associated with shrink-swell behaviour. Treatments were randomly allocated within each replication to ensure unbiased estimation of treatment effects. Each experimental plot measured 5.4 m × 4.5 m (24.3 m²), with a net plot area of 4.5 m × 3.6 m (16.2 m²) used for recording observations. The crop was sown at a spacing of 60 cm between rows and 20 cm between plants using manual dibbling during the first fortnight of July 2025. A single-cross hybrid of maize (*Zea mays* L.) adapted to central Indian conditions was used. Border rows were maintained to minimize edge effects, and all agronomic practices, including weed and pest management, were applied uniformly across treatments to ensure that nutrient management remained the primary experimental variable. The recommended dose of fertilizers (RDF) for maize was 120:60:40 kg N:P₂O₅:K₂O ha⁻¹, based on regional recommendations for Vertisol conditions. Nitrogen was applied in three splits (50% basal, 25% at knee-high stage, and 25% at tasseling), while phosphorus and potassium were applied entirely as basal dose at sowing. Nitrogen, phosphorus, and potassium were supplied through urea, Single Superphosphate (SSP), and Muriate of Potash (MOP), respectively. Farmyard manure (FYM) was applied at 5 t ha⁻¹ (dry weight basis) and incorporated into the soil approximately 15 days prior to sowing. Biofertilizers, consisting of *Azotobacter chroococcum* and Phosphate-Solubilizing Bacteria (PSB), were applied as seed treatment at 25 g kg⁻¹ seed each, using jaggery solution as an adhesive.

Table 2: Treatment details of integrated nutrient management in maize

Treatment	Description
T ₁	Control (no fertilizers)
T ₂	100% RDF
T ₃	125% RDF
T ₄	75% RDF
T ₅	75% RDF + FYM
T ₆	75% RDF + Biofertilizers
T ₇	75% RDF + FYM + Biofertilizers
T ₈	100% RDF + FYM

The inclusion of T₃ (125% RDF) enabled assessment of yield response beyond recommended levels, while T₄ (75% RDF) provided a baseline for evaluating reduced mineral input. Treatments combining FYM or biofertilizers individually (T₅ and T₆) allowed partial separation of organic and microbial effects, whereas T₇ examined their combined influence. Treatment T₈ was included to assess whether addition of FYM at the full fertilizer dose confers additional benefit or results in diminishing returns. Although not structured as a factorial experiment, the treatment combinations were designed to permit comparative interpretation of nutrient substitution and interaction effects under field conditions.

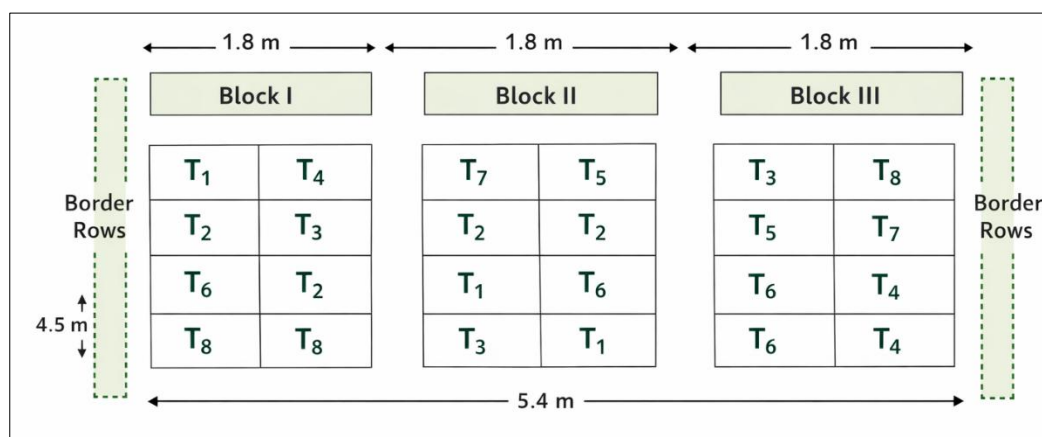


Fig 1: Layout of experimental treatments under Randomized Block Design

2.3 Crop Management

All agronomic operations, except nutrient management treatments, were kept uniform across experimental plots to ensure that observed variations in crop performance were attributable primarily to differences in nutrient regimes.

2.3.1 Land Preparation

The field was prepared with one deep ploughing using a mouldboard plough, followed by two cross harrowings to obtain a fine tilth suitable for maize establishment. Crop residues were removed, and farmyard manure (where applicable) was uniformly incorporated into the soil approximately 15 days prior to sowing to allow initial decomposition and microbial activity.

2.3.2 Seed and Sowing

A regionally adapted single-cross hybrid of maize (*Zea mays* L.) was used. Seeds were treated with *Azotobacter chroococcum* and phosphate-solubilizing bacteria (PSB) according to treatment specifications immediately prior to sowing. Sowing was carried out manually by dibbling at a spacing of 60 cm × 20 cm, maintaining an approximate plant population of 83,000 plants ha⁻¹. Gap filling was completed within 10 days of emergence to ensure uniform plant stand.

2.3.3 Nutrient Application

Phosphorus and potassium were applied as basal dose at sowing in the respective treatments. Nitrogen was applied in three splits 50% at sowing, 25% at knee-high stage (≈25 DAS), and 25% at tasseling stage (≈50 DAS) to improve synchronization with crop demand. Top-dressed nitrogen was applied along crop rows and lightly incorporated during earthing-up to minimize potential losses.

2.3.4 Irrigation and Moisture Management

The crop was grown predominantly under rainfed conditions. However, protective irrigation was provided during prolonged dry spells, particularly at knee-high and silking stages. Irrigation was applied uniformly across treatments to avoid moisture-induced confounding effects.

2.3.5 Weed Management

Weeds were controlled through pre-emergence application of atrazine at 1.0 kg a.i. ha⁻¹ within 48 hours of sowing, followed by one manual weeding at 30 DAS. This ensured minimal crop-weed competition during early growth.

2.3.6 Plant Protection Measures

Preventive and need-based measures were adopted against major insect pests, including stem borer and fall armyworm. Plant

protection practices were applied uniformly across treatments. No significant disease incidence was observed during the cropping period.

2.3.7 Harvesting and Post-Harvest Handling

The crop was harvested at physiological maturity, indicated by drying of husk leaves and grain moisture content of approximately 18-20%. Cobs from the net plot area were harvested, sun-dried, and shelled manually. Grain yield was recorded after cleaning and adjusted to 14% moisture content. Stover yield was determined after drying to constant weight. Uniformity in crop management ensured experimental precision and enabled reliable interpretation of treatment effects on growth, yield, and resource use efficiency.

2.4 Observations Recorded

Observations were recorded at defined crop growth stages to evaluate the effects of nutrient management on growth, biomass accumulation, yield attributes, productivity, and economic performance of maize (*Zea mays* L.). Unless otherwise specified, observations were based on five randomly selected representative plants from the net plot area.

2.4.1 Growth Parameters

Plant height (cm)

Plant height was measured from ground level to the base of the tassel at 30, 60, and 90 days after sowing (DAS), and at harvest. Mean values were computed from sampled plants.

Leaf Area Index (LAI)

Leaf area was estimated using the length × maximum width × correction factor (0.75) method. LAI was calculated as the ratio of total leaf area per plant to the ground area occupied by the plant. Observations were recorded at 60 DAS, corresponding to peak vegetative growth.

Dry matter accumulation (g plant⁻¹)

Plants were sampled at 60 DAS and at harvest, separated into component parts, and oven-dried at 65 °C until constant weight to determine total biomass.

2.4.2 Yield Attributes

Yield attributes were recorded at harvest from five representative plants per plot. Cob length and cob girth were measured using standard measuring devices. Number of grains per cob was determined after shelling, and test weight (1000-grain weight) was recorded using a precision balance at 14% moisture content.

2.4.3 Yield Parameters

Grain yield (t ha⁻¹)

Grain yield from the net plot was recorded after drying and converted to hectare basis at 14% moisture content.

Stover yield (t ha⁻¹)

Above-ground biomass excluding grain was sun-dried and expressed on hectare basis.

Harvest index (%)

Harvest index was calculated as:

$$\text{Harvest Index (\%)} = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100$$

indicating the efficiency of biomass partitioning towards economic yield.

2.4.4 Nutrient Use Efficiency Indices

To evaluate fertilizer use efficiency, the following indices were computed:

Agronomic Efficiency (AE)

$$AE = \frac{Y_f - Y_0}{F}$$

Partial Factor Productivity (PFP)

$$PFP = \frac{Y_f}{F}$$

Where:

Y_f = Grain yield under fertilized treatment

Y_0 = Grain yield under control

F = Quantity of nutrient applied

These indices were used to assess nutrient recovery efficiency and productivity per unit nutrient applied.

2.4.5 Economic Analysis

Economic parameters were calculated using prevailing market prices during the 2025-26 season. Cost of cultivation included expenditures on fertilizers, FYM, biofertilizers, labour, and other operational inputs. Gross returns were estimated based on grain and stover yield, while net returns were calculated by subtracting total cost of cultivation from gross returns. The benefit-cost (B:C) ratio was computed as:

$$\text{B:C ratio} = \frac{\text{Gross returns}}{\text{Cost of cultivation}}$$

2.4.6 Statistical Analysis

Experimental data were subjected to analysis of variance (ANOVA) appropriate for a Randomized Block Design. Treatment means were compared using the critical difference (CD) at $p \leq 0.05$. Standard statistical procedures were followed to ensure reliability and validity of the results.

2.5 Experimental Layout Diagram

The experiment was laid out in a Randomized Block Design (RBD) with three replications (Blocks I-III), each comprising eight treatments randomly allocated within each block. Blocking was employed to account for field variability associated with micro-topography and moisture distribution, which are characteristic of Vertisol conditions.

Individual plots within each replication were separated by 0.5 m bunds to minimize lateral movement of water and nutrients, while a 1.0 m buffer space was maintained between replications. All plots were oriented in a north-south direction to ensure relatively uniform solar interception.

A representative layout of treatment allocation is presented in Figure 2.

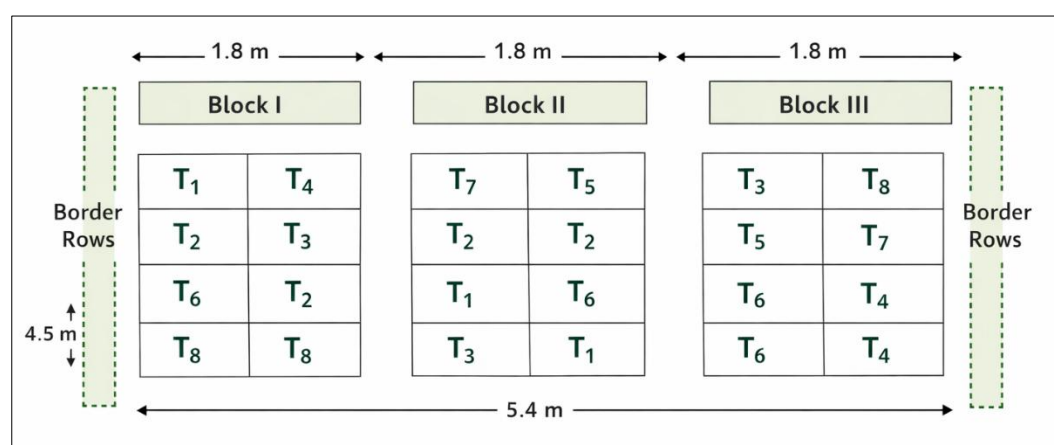


Fig 2: Layout of experimental treatments under Randomized Block Design (RBD)

Treatment codes

- T₁: Control
- T₂: 100% RDF
- T₃: 125% RDF
- T₄: 75% RDF
- T₅: 75% RDF + FYM
- T₆: 75% RDF + Biofertilizers
- T₇: 75% RDF + FYM + Biofertilizers
- T₈: 100% RDF + FYM

The layout ensured that each treatment appeared once within each replication, enabling unbiased comparison under similar field conditions. Randomization minimized allocation bias, while replication facilitated estimation of experimental error and improved precision of treatment comparisons.

3. Results

The response of maize (*Zea mays* L.) to graded mineral fertilization integrated with organic and biological inputs showed significant variation in growth, yield attributes, productivity, and

economic returns. Treatment effects were statistically significant ($p\leq0.05$) for most parameters, indicating a measurable influence of nutrient management under Vertisol conditions.

3.1 Growth Dynamics

3.1.1 Plant Height

Plant height increased progressively with crop age across all treatments and was significantly influenced by nutrient management practices (Table 3). At 60 DAS, the highest plant height (226 cm) was recorded under T₇ (75% RDF + FYM + biofertilizers), followed by T₈ (221 cm) and T₅ (215 cm). The 100% RDF treatment (T₂) recorded 206 cm, while the control (T₁) exhibited the lowest plant height (168 cm). At harvest, a similar trend was observed, with T₇ maintaining the maximum plant height, significantly superior to most other

treatments. The 125% RDF treatment (T₃) did not show a marked increase over T₂, indicating limited response beyond recommended fertilizer levels.

Table 3: Effect of integrated nutrient management on plant height (cm) of maize

Treatment	30 DAS	60 DAS	At harvest
T ₁	82	168	172
T ₂	104	206	210
T ₃	108	209	214
T ₄	96	194	198
T ₅	112	215	220
T ₆	110	212	216
T ₇	118	226	231
T ₈	115	221	225

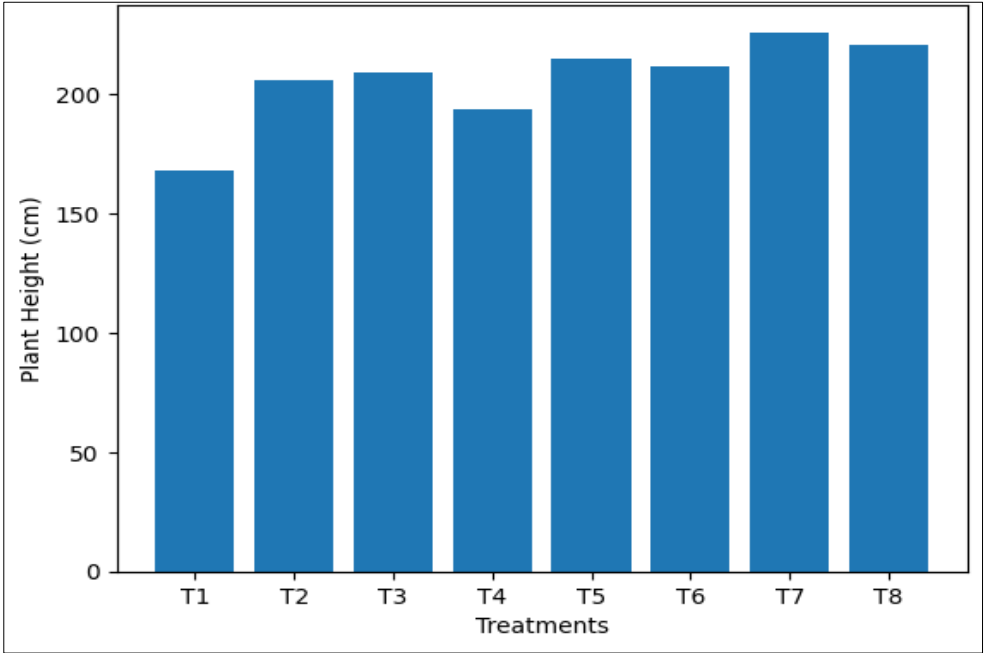


Fig 3: Effect of treatments on plant height

3.1.2 Leaf Area Index (LAI)

Leaf Area Index at 60 DAS was significantly influenced by nutrient management (Table 4). The highest LAI (4.58) was recorded under T₇, followed by T₈ (4.41) and T₅ (4.36), while the

control (T₁) recorded the lowest LAI (2.18). Integrated treatments involving FYM and biofertilizers consistently recorded higher LAI compared to sole mineral fertilization.

Table 4: Effect of integrated nutrient management on Leaf Area Index (LAI)

Treatment	LAI (60 DAS)
T ₁	2.18
T ₂	4.12
T ₃	4.24
T ₄	3.68
T ₅	4.36
T ₆	4.29
T ₇	4.58
T ₈	4.41

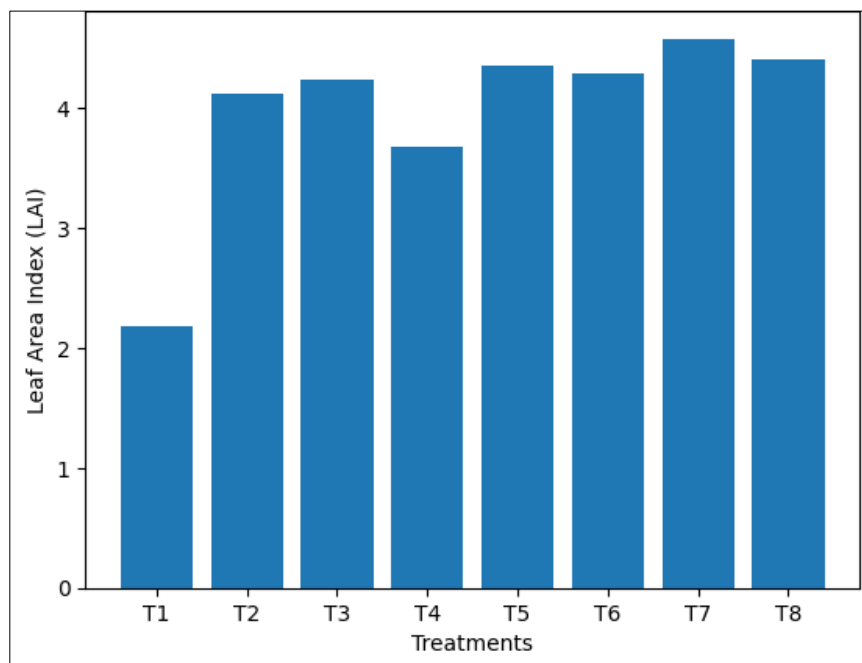


Fig 4: Effect of treatments on Leaf Area Index (LAI)

3.1.3 Dry Matter Accumulation

Dry matter accumulation increased significantly with improved nutrient management (Table 5). At harvest, T₇ recorded the highest dry matter accumulation (212 g plant⁻¹), followed by T₈

(203 g plant⁻¹) and T₅ (198 g plant⁻¹). The control (T₁) recorded the lowest biomass (94 g plant⁻¹). The 125% RDF treatment (T₃) did not show a proportional increase compared to 100% RDF (T₂), suggesting diminishing returns at higher fertilizer levels.

Table 5: Effect of integrated nutrient management on dry matter accumulation (g plant⁻¹)

Treatment	60 DAS	At harvest
T ₁	48	94
T ₂	96	182
T ₃	99	188
T ₄	84	161
T ₅	102	198
T ₆	98	191
T ₇	108	212
T ₈	104	203

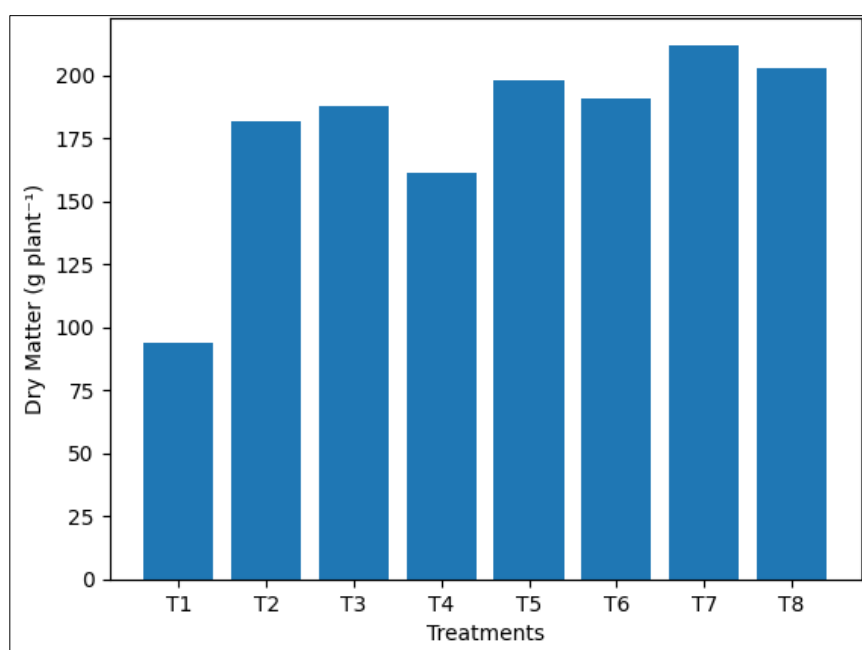


Fig 5: Effect of treatments on dry matter accumulation

3.3 Grain and Stover Yield

Grain yield varied significantly among treatments ($p \leq 0.05$) (Table 6). It ranged from 2.94 t ha^{-1} under the control (T_1) to 6.82 t ha^{-1} under T_7 (75% RDF + FYM + biofertilizers). The treatment T_3 (125% RDF) recorded a grain yield of 6.38 t ha^{-1} , which was statistically comparable to T_2 (100% RDF: 6.21 t ha^{-1}). In contrast, T_4 (75% RDF alone) recorded a lower yield (5.72 t ha^{-1}). Among all treatments, T_7 recorded the highest grain yield and was significantly superior to most other treatments. Treatments integrating FYM and/or biofertilizers (T_5 , T_6 , T_7 , and T_8) consistently recorded higher yields compared to sole mineral fertilizer or reduced fertilizer treatments.

Stover yield followed a trend similar to grain yield, with higher biomass production recorded under integrated nutrient management treatments. The maximum stover yield was observed under T_7 (9.15 t ha^{-1}), followed by T_8 (8.72 t ha^{-1}) and

T_5 (8.46 t ha^{-1}), whereas the control (T_1) recorded the lowest value (4.28 t ha^{-1}).

Table 6: Effect of integrated nutrient management on grain and stover yield of maize

Treatment	Grain Yield (t ha^{-1})	Stover Yield (t ha^{-1})
T_1	2.94	4.28
T_2	6.21	7.96
T_3	6.38	8.12
T_4	5.72	7.21
T_5	6.54	8.46
T_6	6.48	8.32
T_7	6.82	9.15
T_8	6.61	8.72
SEm $\pm$	0.18	0.26
CD ($p \leq 0.05$)	0.54	0.78

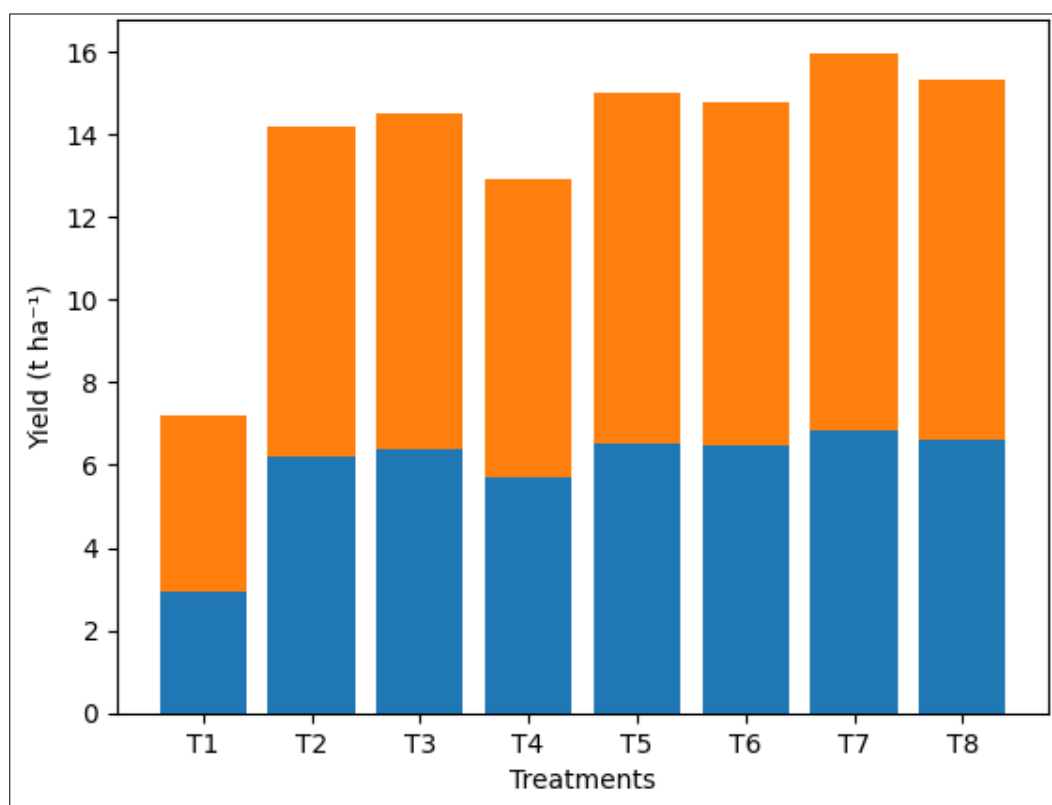


Fig 6: Effect of treatments on grain and stover yield

3.4 Harvest Index

Harvest index was significantly influenced by nutrient management treatments ($p \leq 0.05$) (Table 7). It ranged from 34.9% under the control (T_1) to 45.6% under T_7 (75% RDF + FYM + biofertilizers). Treatments integrating FYM and biofertilizers (T_5 -

T_8) recorded comparatively higher harvest index than sole mineral fertilizer and control treatments.

The treatment T_7 recorded the highest harvest index and was statistically superior to most other treatments, whereas T_2 (100% RDF) and T_3 (125% RDF) showed comparable values.

Table 7: Effect of integrated nutrient management on harvest index (%) of maize

Treatment	Harvest Index (%)
T_1	34.9
T_2	42.3
T_3	42.2
T_4	41.7
T_5	42.3
T_6	42.4
T_7	45.6
T_8	42.3
SEm $\pm$	1.2
CD ($p \leq 0.05$)	3.5

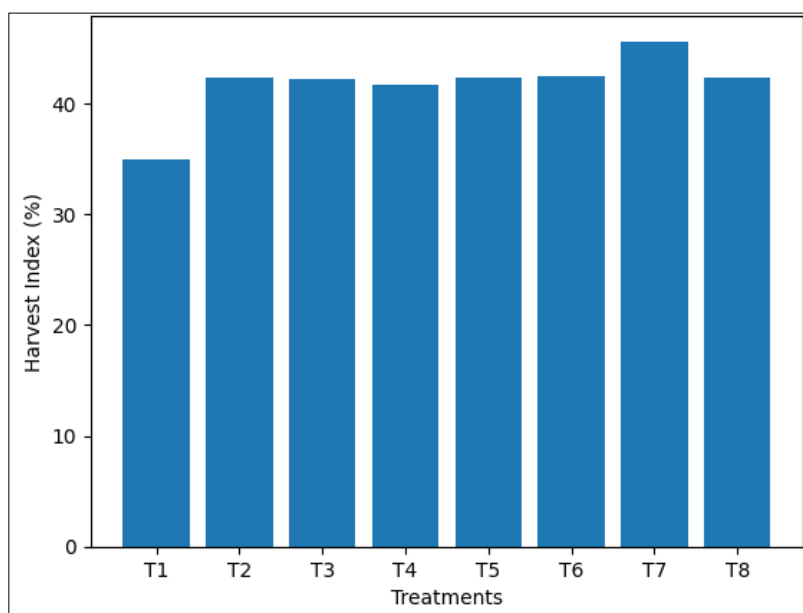


Fig 7: Effect of treatments on harvest index

3.5 Nutrient Use Efficiency

Nutrient use efficiency indices were significantly influenced by nutrient management treatments ($p \leq 0.05$) (Table 8). Agronomic efficiency (AE) of nitrogen was highest under T₇ (75% RDF + FYM + biofertilizers), recording 21.8 kg grain per kg N applied, followed by T₅ (20.6 kg kg⁻¹ N) and T₆ (20.1 kg kg⁻¹ N). The 100% RDF treatment (T₂) recorded a comparatively lower AE of

17.5 kg kg⁻¹ N, while T₃ (125% RDF) showed further reduction (15.8 kg kg⁻¹ N).

Partial Factor Productivity (PFP) followed a similar trend, with higher values observed under integrated nutrient management treatments compared to sole mineral fertilizer treatments. The lowest values were recorded under the control treatment.

Table 8: Effect of integrated nutrient management on nutrient use efficiency of maize

Treatment	Agronomic Efficiency (kg kg ⁻¹ N)	Partial Factor Productivity (kg kg ⁻¹ N)
T ₁		
T ₂	17.5	51.8
T ₃	15.8	53.2
T ₄	18.2	47.7
T ₅	20.6	54.5
T ₆	20.1	54.0
T ₇	21.8	56.8
T ₈	18.9	55.1
SEm ±	0.82	1.74
CD (P≤0.05)	2.46	5.21

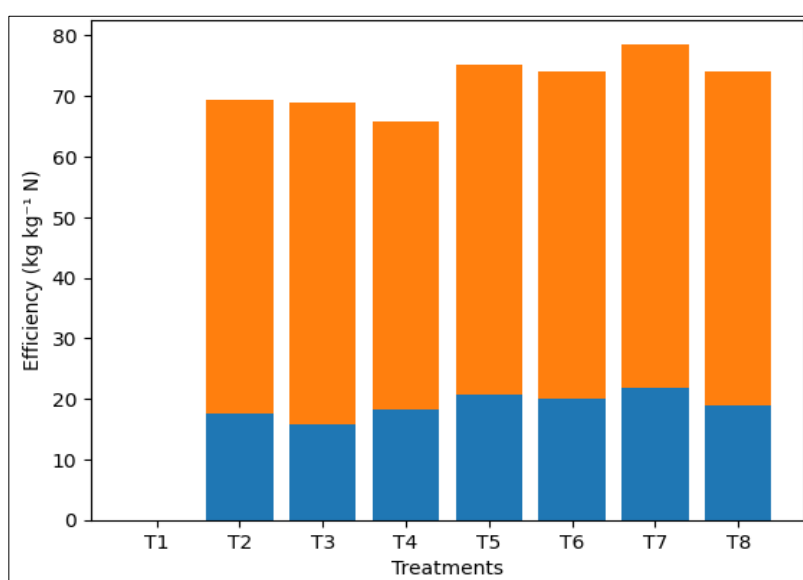


Fig 8: Effect of treatments on nutrient use efficiency

3.6 Economic Performance

Economic performance varied significantly among treatments ($p \leq 0.05$) (Table 9). The highest net returns (₹78,540 ha⁻¹) and benefit-cost (B:C) ratio (2.64) were recorded under T₇ (75% RDF + FYM + biofertilizers). This was followed by T₈ (₹76,480 ha⁻¹; B:C ratio 2.58) and T₅ (₹75,120 ha⁻¹; B:C ratio 2.59).

The treatment T₃ (125% RDF) incurred higher cost of cultivation compared to T₂ (100% RDF), but the corresponding increase in returns was not proportionate, resulting in comparatively lower economic efficiency. In contrast, treatments integrating FYM and/or biofertilizers (T₅-T₈) consistently recorded higher net returns and B:C ratio than sole fertilizer treatments and control.

The control (T₁) recorded the lowest economic returns, reflecting reduced productivity under nutrient-deficient conditions.

Table 9: Effect of integrated nutrient management on economic performance of maize

Treatment	Cost of Cultivation (₹ ha ⁻¹)	Net Returns (₹ ha ⁻¹)	B:C Ratio
T ₁	42,400	21,340	1.42
T ₂	52,800	68,420	2.46
T ₃	55,200	70,210	2.40
T ₄	50,400	59,630	2.31
T ₅	51,800	75,120	2.59
T ₆	51,200	73,860	2.56
T ₇	54,640	78,540	2.64
T ₈	55,000	76,480	2.58
SEm ±		2,984	0.08
CD (P≤0.05)		8,946	0.24

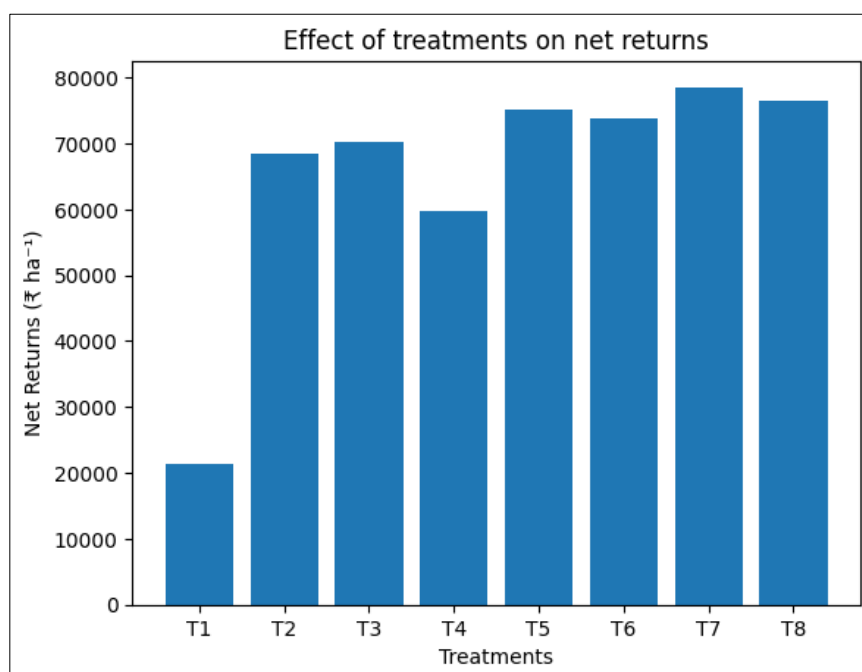


Fig 9: Effect of treatments on net returns

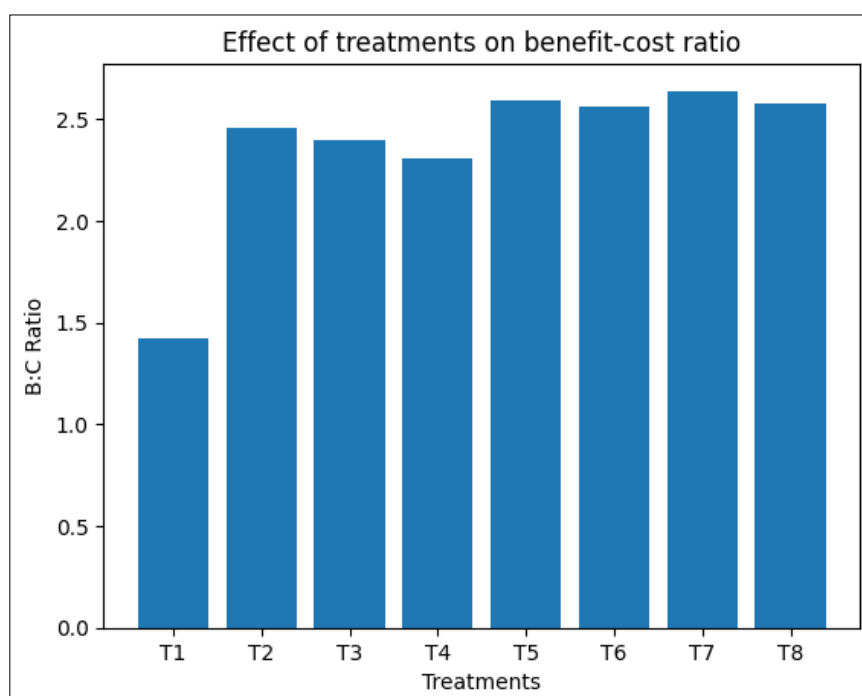


Fig 10: Effect of treatments on benefit-cost ratio

3.7 Treatment Response Pattern

The response hierarchy for grain yield was observed as:

$$T_7 > T_8 \approx T_5 \approx T_6 > T_3 \approx T_2 > T_4 > T_1$$

This ranking was broadly consistent across growth, yield, nutrient use efficiency, and economic parameters. Treatments integrating mineral fertilizers with FYM and biofertilizers (T_5 - T_8)

consistently outperformed sole mineral fertilization and control, whereas reduced fertilizer application without biological supplementation (T_4) showed comparatively lower performance.

3.8 Summary of Key Results

To facilitate integrated comparison, major agronomic and economic parameters are summarized in Table 10. Values represent treatment means over three replications.

Table 10: Summary of key agronomic, yield, and economic parameters of maize under different nutrient management treatments

Treatment	LAI (60 DAS)	Dry Matter (g plant ⁻¹)	Grain Yield (t ha ⁻¹)	Harvest Index (%)	Agronomic Efficiency (kg kg ⁻¹ N)	Net Returns (₹ ha ⁻¹)	B:C Ratio
T ₁ (Control)	2.18	94	2.94	34.9		21,340	1.42
T ₂ (100% RDF)	4.12	182	6.21	42.3	17.5	68,420	2.46
T ₃ (125% RDF)	4.24	188	6.38	42.2	15.8	70,210	2.40
T ₄ (75% RDF)	3.68	161	5.72	41.7	18.2	59,630	2.31
T ₅ (75% RDF + FYM)	4.36	198	6.54	42.3	20.6	75,120	2.59
T ₆ (75% RDF + Biofertilizers)	4.29	191	6.48	42.4	20.1	73,860	2.56
T ₇ (75% RDF + FYM + Biofertilizers)	4.58	212	6.82	45.6	21.8	78,540	2.64
T ₈ (100% RDF + FYM)	4.41	203	6.61	42.3	18.9	76,480	2.58

Across treatments, higher values for growth parameters, yield, nutrient use efficiency, and economic returns were consistently observed under integrated nutrient management treatments (T_5 - T_8) compared to sole fertilizer application and control.

3.9 Correlation Analysis

Pearson's correlation coefficients were computed to examine the relationships among key growth parameters, yield attributes, and grain yield (Table 11).

Table 11: Pearson's correlation coefficients among growth, yield attributes, and grain yield of maize

Parameter	LAI	Dry Matter	Grains cob ⁻¹	Harvest Index	Grain Yield
LAI	1.000	0.912**	0.886**	0.742*	0.931**
Dry Matter		1.000	0.903**	0.768*	0.948**
Grains cob ⁻¹			1.000	0.701*	0.962**
Harvest Index				1.000	0.824**
Grain Yield					1.000

*Significant at $p \leq 0.05$

*Significant at $p \leq 0.01$

Grain yield exhibited a strong positive correlation with grains per cob ($r = 0.962$) and dry matter accumulation ($r = 0.948$). Leaf Area Index also showed a strong positive association with grain yield ($r = 0.931$). Harvest index exhibited a moderate to strong positive relationship with grain yield ($r = 0.824$).

3.10 Regression Analysis

3.10.1 Relationship Between LAI and Grain Yield

A linear regression model describing the relationship between Leaf Area Index (LAI) at 60 DAS and grain yield was fitted:

$$Y = 1.12 + 1.24X (R^2 = 0.867)$$

where Y represents grain yield (t ha⁻¹) and X represents LAI. The coefficient of determination (R^2) indicated that 86.7% of the variation in grain yield was explained by variation in LAI.

3.10.2 Relationship Between Dry Matter and Grain Yield

The relationship between dry matter accumulation and grain yield

was expressed as:

$$Y = 0.98 + 0.028X (R^2 = 0.901)$$

where X represents dry matter accumulation (g plant⁻¹).

Dry matter accumulation accounted for 90.1% of the variation in grain yield.

3.10.3 Multiple Regression Model

A multiple regression model incorporating key physiological variables was developed:

$$Y = -0.74 + 0.68X_1 + 0.021X_2 + 0.004X_3 (R^2 = 0.953)$$

where:

- X_1 = LAI
- X_2 = Dry matter accumulation (g plant⁻¹)
- X_3 = Number of grains cob⁻¹

The model explained 95.3% of the variation in grain yield, indicating that combined effects of canopy development, biomass accumulation, and reproductive sink strength strongly influenced yield formation.

4. Discussion

The present investigation indicates that partial substitution of mineral fertilizers with organic and biological inputs influenced crop growth dynamics, nutrient use efficiency, and economic returns in maize (*Zea mays* L.) under Vertisol conditions. The improved performance observed under 75% RDF integrated with farmyard manure and biofertilizers appears to arise not merely from increased nutrient supply, but from a more balanced temporal alignment between nutrient availability and crop demand.

4.1 Nutrient Synchronization and Nitrogen Dynamics

Vertisols, despite their relatively high inherent fertility, often exhibit instability in nitrogen availability due to losses through volatilization and episodic denitrification under fluctuating moisture conditions. Under sole mineral fertilization, nitrogen availability is typically concentrated during early growth stages, which may not coincide with peak crop demand, particularly

during later vegetative and reproductive phases.

The incorporation of farmyard manure introduces an organic nitrogen pool that undergoes gradual mineralization, thereby extending nitrogen availability over time. This delayed release is likely to align more closely with crop demand during critical growth stages. In addition, seed inoculation with *Azotobacter chroococcum* may have enhanced rhizospheric activity and root proliferation, although its contribution under field conditions can vary depending on native microbial populations and environmental factors.

The higher agronomic efficiency observed under integrated treatments suggests improved recovery and utilization of applied nitrogen. In contrast, the relatively lower efficiency observed under 125% RDF indicates that increasing nitrogen input beyond recommended levels did not proportionately enhance yield response, suggesting a possible saturation of crop uptake capacity under the prevailing conditions (Ladha *et al.*, 2005; Vanlauwe *et al.*, 2014)^[13, 32].

4.2 Canopy Architecture and Source Capacity

Leaf Area Index (LAI) exhibited a strong positive association with grain yield ($r = 0.931$), indicating that canopy development was closely linked with productivity under the prevailing conditions. The higher LAI observed under integrated nutrient management (4.58) suggests improved canopy expansion, which likely enhanced interception of photosynthetically active radiation during the pre-anthesis phase.

The contribution of farmyard manure (FYM) may be partly attributed to improvements in soil physical properties, including aggregation and porosity, which can facilitate root proliferation and more efficient resource acquisition. In addition, integrated nutrient supply may have supported sustained leaf area duration, thereby maintaining photosynthetic activity during the grain-filling phase.

However, increased vegetative growth alone does not necessarily translate into higher yield unless accompanied by efficient assimilate partitioning. The relatively higher harvest index (45.6%) observed under integrated treatment indicates that enhanced biomass production was coupled with effective allocation toward grain formation, avoiding excessive vegetative accumulation (Fageria *et al.*, 2008)^[7].

4.3 Reproductive Sink Strength and Grain Formation

Grain number per cob exhibited the strongest positive association with grain yield ($r = 0.962$), indicating that reproductive sink development was a primary determinant of final productivity. In maize (*Zea mays* L.), kernel number is largely established during tasseling and silking, stages that are highly sensitive to nutrient availability and physiological stress.

The improved performance observed under integrated nutrient management suggests that nutrient supply during these critical stages was relatively more stable. Sustained availability of nitrogen and phosphorus may have supported processes such as pollen viability, silk receptivity, and early kernel establishment. In addition, phosphate-solubilizing bacteria may have enhanced phosphorus availability under moderately alkaline Vertisols, although their effectiveness under field conditions can vary with native microbial activity and soil environment.

The comparatively limited yield advantage under 125% RDF indicates that increasing mineral nutrient supply beyond recommended levels did not proportionately enhance reproductive sink capacity. This observation suggests that, under the prevailing conditions, the continuity and timing of nutrient availability were more influential than the absolute quantity applied (Mahajan *et al.*, 2012; Xu *et al.*, 2012)^[14, 37].

4.4 Soil Biological Mediation and Carbon-Nutrient Coupling

Application of farmyard manure (FYM) introduces labile carbon fractions that can stimulate microbial biomass and enzymatic activity. Enhanced microbial activity may, in turn, regulate nutrient mineralization, influence cation exchange processes, and contribute to the formation of stable soil aggregates.

Although Vertisols are characterized by high clay content and considerable nutrient retention capacity, the role of organic matter remains critical for maintaining aggregate stability and minimizing surface crusting. Under integrated nutrient management, improvements in soil physical conditions likely facilitated root proliferation and improved nutrient diffusion within the soil matrix.

The combined effect suggests a strengthening of carbon-nutrient coupling, wherein organic carbon inputs regulate the timing and availability of nutrients through biologically mediated processes. However, the magnitude of these interactions is expected to vary with environmental conditions, management practices, and the quality and decomposition dynamics of the organic inputs applied (Mandal *et al.*, 2007; Saha *et al.*, 2010)^[16, 26].

4.5 Economic Rationalization

Economic outcomes broadly followed the patterns observed in growth and yield. Treatments integrating mineral fertilizers with farmyard manure and biofertilizers recorded higher net returns and benefit-cost ratios, despite a modest increase in cultivation cost associated with organic and biological inputs. The additional expenditure was offset by higher grain yield and improved returns per unit input.

In contrast, the 125% RDF treatment involved higher fertilizer cost, while the corresponding increase in yield remained comparatively limited. This resulted in a lower marginal return on additional fertilizer investment beyond the recommended dose under the prevailing conditions.

From a practical standpoint, these findings suggest that moderate reduction in mineral fertilizer, when combined with organic and biological inputs, can improve economic efficiency. However, the magnitude of this advantage is likely to vary with input prices, availability of organic resources, and field-specific management conditions (Meena *et al.*, 2013)^[17].

4.6 Implications for Semi-Arid Vertisol Systems

The results indicate that, under semi-arid Vertisol conditions, crop response to nutrient management is governed not only by the quantity of nutrients applied but also by their temporal availability and interaction with soil biological processes. Integrated approaches combining mineral fertilizers with organic and biological inputs were able to sustain productivity while improving nutrient use efficiency.

The observed treatment response suggests that balanced integration of nutrient sources can support vegetative growth, reproductive development, and economic returns concurrently under the given conditions. However, the magnitude and consistency of these responses are likely to vary across seasons and locations due to differences in rainfall distribution, soil heterogeneity, and management practices.

From a broader perspective, the findings reinforce the relevance of integrated nutrient management as a viable strategy for maize cultivation in Vertisols of central India, particularly where efficient resource use and maintenance of soil quality are important considerations.

Further investigation involving soil microbial biomass, enzymatic activity, and isotopic tracing techniques may provide deeper insight into the mechanisms governing nutrient transformations and plant uptake under integrated nutrient management systems.

5 Conclusion

The results of the present study indicate that integrated nutrient management, involving partial substitution of mineral fertilizers with farmyard manure and biofertilizers, can enhance growth, productivity, nutrient use efficiency, and economic returns of maize (*Zea mays* L.) under Vertisol conditions.

Application of 75% of the recommended dose of fertilizers (RDF) in combination with FYM and biofertilizers consistently produced superior performance across growth parameters, yield attributes, grain yield, and economic indicators. The observed response appears to be associated more with improved synchronization between nutrient availability and crop demand than with an increase in total nutrient input.

The findings suggest that balanced integration of nutrient sources can improve input-use efficiency while sustaining or enhancing productivity. Under the agro-climatic conditions of central India, such approaches offer a viable pathway for sustainable intensification of maize-based cropping systems.

6. Limitations of the Study

The present investigation, while providing useful insights into integrated nutrient management under Vertisol conditions, is subject to certain limitations that may influence the broader applicability of the findings.

The experiment was conducted during a single cropping season (Kharif 2025-26) and therefore does not capture inter-annual climatic variability, which can significantly influence nutrient dynamics and crop response. In addition, the study was confined to a single location, and the observed responses may vary under different soil types, agro-ecological conditions, and management practices.

The composition of Farmyard Manure (FYM), although applied uniformly, was not chemically characterized in detail. Variability in its nutrient content may have contributed to differences in treatment response. Similarly, the activity and persistence of biofertilizer inoculants (*Azotobacter chroococcum* and phosphate-solubilizing bacteria) were not directly quantified under field conditions, and their contribution was inferred indirectly through crop performance.

Furthermore, the study did not include detailed assessment of soil biological parameters such as microbial biomass carbon, enzymatic activity, or nitrogen mineralization rates, which could have provided deeper mechanistic insight into nutrient transformations under integrated nutrient management.

These limitations indicate that, while the findings are robust within the experimental context, their extrapolation to broader agro-ecosystems should be undertaken with consideration of site-specific variability and the need for longer-term evaluation.

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