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PHENOTYPIC VARIATION IN MAIZE GROWTH AND YIELD ATTRIBUTES UNDER SOIL TEST-BASED NUTRIENT MANAGEMENT IN TROPICAL ALFISOLS

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ABSTRACT
Maize growth and yield attributes are measurable phenotypic traits that may respond to nutrient availability in heterogeneous tropical Alfisols. This study assessed phenotypic responses and productivity under farmers' practice (FP), soil test-based nutrient management (STB) and the recommended fertilizer dose (RDF) in seven farmer fields during each of *Kharif* 2020 and *Rabi* 2020-21. Plant height, kernel weight per cob, grains per cob and 100-grain weight were evaluated alongside grain yield, nutrient uptake and economic returns. Available soil nitrogen was generally low, while phosphorus, potassium and zinc varied among fields. STB recorded the highest plant height (167.4 and 173.3 cm), kernel weight per cob (120.8 and 123.0 g), and 100-grain weight (29.2 and 29.4 g) in Kharif and Rabi, respectively. Differences in grains per cob were non-significant. Grain yields under STB were 6,856 and 8,570 kg ha^{-1}, approximately 22.2% and 22.3% higher than FP, respectively. The first two principal components of four standardized traits accounted for 84.6% of variation in *Kharif* and 88.8% in *Rabi*. These observations describe management-associated phenotypic responses, not genetic variation. Because fertilizer nitrogen rates differed among treatments, the effect of soil testing cannot be isolated from the complete fertilizer package.

KEYWORDS: Alfisols; farm profitability; maize; nutrient uptake; soil testing; yield gap

INTRODUCTION
Maize (*Zea mays* L.) exhibits measurable phenotypic responses in growth and yield-related traits under contrasting nutrient environments. Plant height, kernel weight per cob, grains per cob and 100-grain weight provide agronomically relevant indicators of crop performance, although differences among management treatments should not be interpreted as genetic variation. Uniform fertilizer recommendations may not reflect field-to-field variation in available nitrogen, phosphorus, potassium and micronutrients in Alfisols. Indian maize studies have evaluated precision nutrient management for yield and profitability (Singh et al., 2020; Shyam et al., 2021). Soil test crop response research for hybrid maize on Alfisols has developed targeted-yield fertilizer prescriptions (Coumaravel et al., 2013); the present study instead evaluates a categorical soil-test-based fertilizer package.

Soil test-based nutrient management adjusts fertilizer inputs to the diagnosed nutrient status of individual fields. Indian maize research on precision nutrient management reports context-dependent improvements in productivity and profitability (Singh et al., 2020; Shyam et al., 2021). STCR targeted-yield equations provide a more quantitative alternative to categorical adjustments and should not be treated as equivalent to the 130%, 100% and 70% of recommended dose rule evaluated here (Coumaravel et al., 2013). The central comparison in this experiment is the complete fertilizer prescription package, including its higher nitrogen rate, rather than the isolated contribution of soil testing.

Long-term soil-quality changes should be distinguished from short-term fertilizer responses. Work in Alfisol cropping systems has evaluated soil quality and carbon-related indicators (Shruthi et al., 2026), but such studies do not directly establish the effectiveness of the present maize prescription. The present analysis therefore focuses on observed seasonal crop responses and does not infer sustained improvement in soil carbon from these demonstrations.

Yield-gap analysis provides a practical basis for evaluating nutrient-management interventions. On-farm maize research in Southeast Asia reported that site-specific nutrient management increased grain yield and profitability relative to farmers' fertilizer practice (Pasuquin et al., 2014). Such comparisons quantify a management-recoverable gap under observed conditions; they do not measure the difference between farmer yields and biophysical yield potential. The size and causes of a management gap remain contingent on soil, climate, fertilizer rates and farmer practices.

Despite growing evidence on precision nutrient delivery, there is limited direct farmer-field evidence linking measured nutrient heterogeneity, corresponding fertilizer prescriptions, maize nutrient uptake and economic outcomes in the red sandy loam Alfisols of Telangana. This gap matters for extension recommendations because blanket nutrient rates may be

inappropriate for both deficient and sufficiently supplied fields. The practical question is whether an affordable pre-sowing soil test can guide a better fertilizer decision within the same farm, not whether a particular fertilizer dose is universally superior.

The specific contribution of this study is the paired evaluation, within farmer-managed environments, of baseline soil nutrient variability, field-wise fertilizer prescriptions, crop nutrient uptake and observed returns. Unlike trials focused on fertilizer placement, irrigation technology or long-term soil quality, the present comparison evaluates an operational soil-testing decision package; individual nutrient effects and genetic components of variation cannot be separated.

This study compared farmers' practice (T_1), soil test-based nutrient management (T_2) and the blanket recommended fertilizer dose (T_3) in seven farms per season during *Kharif* 2020 and *Rabi* 2020-21. It aimed to (i) characterize field-to-field soil-fertility variation, (ii) quantify treatment effects on maize growth, grain yield, nutrient uptake, residual fertility and economic return, and (iii) estimate the management-recoverable yield advantage over farmers' practice. We hypothesized that the implemented soil-test-based fertilizer package would be associated with improved maize phenotypic performance under the studied Alfisol conditions.

MATERIALS AND METHODS

Experimental sites, design and grain yield estimation

Frontline on-farm demonstrations were conducted during *Kharif* 2020 and *Rabi* 2020-21 in farmers' fields at Tornala, Irkode, Ibrahimpur, Bussapur and Venkatapur villages of Siddipet district, Telangana, India (Figure 1), under the supervision of the Agricultural Research Station, Tornala. The experimental sites comprised irrigated maize fields on red sandy loam Alfisols. The experiment was laid out in a randomized block design comprising three nutrient-management treatments and seven farmers' fields serving as replications in each season. Each treatment was allocated a gross plot area of approximately one acre (4,046.86 m²). Maize was planted at a spacing of 60 × 20 cm, corresponding to a theoretical plant population of 83,333 plants ha^{-1}. At physiological maturity, two border rows were excluded, resulting in a net harvested area of approximately 3,970.5 m² per treatment plot. The actual plant population was approximately 82,000 plants ha^{-1}, with approximately 81,500 harvested cobs ha^{-1}. Harvested cobs were shelled separately for each treatment plot, and grain weight was adjusted to 14% moisture content. Grain yield was expressed in kg ha^{-1} based on the net harvested area.

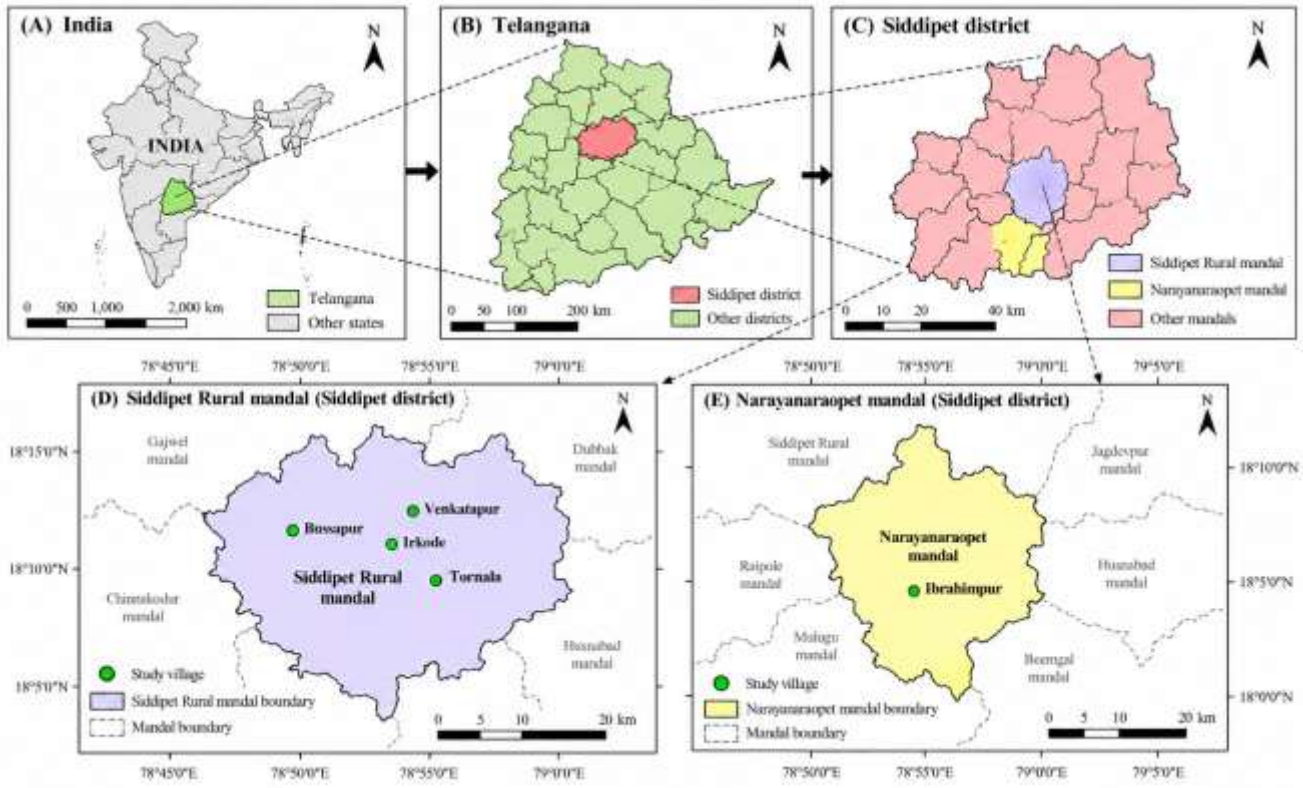


Figure 1. Location map of study area showing India (A), Telangana (B), Siddipet district (C) and study of villages in Siddipet rural (D) and Narayanraopet mandals (E).

Fertilizer prescription and application

Pre-sowing soil samples were collected and analyzed separately from seven farmers' fields during each cropping season (Tables 1 and 2). Three nutrient-management treatments were evaluated: farmers' practice (T_1), soil test-based nutrient

management (STB; T_2) and the recommended dose of fertilizer (RDF; T_3). The seasonal RDF was 200-60-50 kg N-P_2O_5-K_2O ha^{-1} during *Kharif* 2020 and 240-80-80 kg ha^{-1} during *Rabi* 2020-21.

For soil test-based nutrient management, soil available N, P_2O_5 and K_2O were classified into low, medium and high fertility categories. The low fertility category included available N below 280 kg ha^{-1}, P_2O_5 below 25 kg ha^{-1} and K_2O below 110 kg ha^{-1}. The medium category comprised N of 280-560 kg ha^{-1}, P_2O_5 of 25-60 kg ha^{-1} and K_2O of 110-280 kg ha^{-1}, whereas the high category included N above 560 kg ha^{-1}, P_2O_5 above 60 kg ha^{-1} and K_2O above 280 kg ha^{-1}. The initial fertilizer prescriptions were calculated independently for each nutrient at 130%, 100% and 70% of the corresponding seasonal RDF for low, medium and high fertility categories, respectively.

However, the fertilizer rates recorded as applied in six field–nutrient combinations differed from those calculated using the categorical prescription rule. In these instances, the recorded application rates corresponded to the respective seasonal RDF for the nutrients concerned. The field-specific fertilizer application rates presented in Tables 3 and 4 represent the reported actual applications rather than the theoretical prescriptions. Consequently, the effects of T_2 were interpreted as responses to the implemented soil test-based nutrient-management package rather than strict adherence to the categorical prescription rule. The specific reasons for these deviations could not be established from the available field records. Additionally, zinc sulphate ($ZnSO_4$) was applied at 50 kg ha^{-1} under T_2 in *Kharif* fields F3, F4 and F6, where the initial DTPA-extractable Zn concentrations were below the critical threshold of 0.6 mg kg^{-1}. The field-specific fertilizer application rates under farmers' practice (T_1), soil test-based nutrient management (T_2) and RDF (T_3) are presented in Tables 3 and 4.

Soil, plant sample analysis and management

Surface soil (0-15 cm) was sampled before sowing and at the designated crop stages. Soil pH and electrical conductivity were determined in 1:2.5 soil:water suspensions using a glass-electrode pH meter and conductivity meter, respectively (Jackson, 1973). Soil organic carbon was estimated by Walkley-Black wet oxidation (Walkley et al., 1934). Available N was measured by alkaline potassium permanganate distillation (Subbiah and Asija, 1956); available P by Olsen sodium bicarbonate extraction (Olsen et al., 1954); and available K by neutral 1 N ammonium acetate extraction followed by flame photometry (Jackson, 1973). DTPA-extractable Zn was measured following Lindsay and Norvell (Lindsay et al., 1978). Plant N concentration was determined by micro-Kjeldahl digestion and distillation using a Kelplus apparatus; P was determined colorimetrically by the vanadomolybdate yellow-colour method following digestion; and K was determined by flame photometry after wet digestion (Jackson, 1973).

Application timing and crop management. One-third of prescribed N, all P_2O_5 and half of prescribed K_2O were applied at sowing; the remaining N was split equally between knee-height and tasselling, and the remaining K_2O was applied at tasselling. The stated fertilizer sources were urea, DAP and/or SSP and MOP. Source-wise kilograms cannot be derived uniquely without the DAP/SSP mix and a fertilizer application ledger, since DAP supplies both N and P_2O_5. *Kharif* crops received supplemental irrigation during dry spells; *Rabi* crops generally received 6-8 irrigations at 10-15-day intervals.

Table 1. Initial soil fertility of maize demonstration fields, *Kharif* 2020.

Parameter	F1	F2	F3	F4	F5	F6	F7
pH	7.41	7.55	6.81	7.80	6.70	6.82	7.48
EC (dS m^{-1})	0.18	0.16	0.20	0.25	0.20	0.16	0.15
Organic carbon (%)	0.54	0.51	0.45	0.48	0.51	0.45	0.48
Available N (kg ha^{-1})	125	148	275	165	145	165	138
Available P_2O_5 (kg ha^{-1})	24	44	23	67	41	45	68
Available K_2O (kg ha^{-1})	265	275	390	435	300	435	356
DTPA extractable Zn (mg kg^{-1})	1.12	0.90	0.20	0.50	0.75	0.50	0.70

Kharif field locations: F1-F4 = Tornala, F5-F6 = Irkode, F7 = Ibrahimpur villages farmers

Table 2. Initial soil fertility of maize demonstration fields, *Rabi* 2020-21.

Parameter	F1	F2	F3	F4	F5	F6	F7
pH	7.32	7.59	6.29	7.67	7.32	6.38	7.50
EC (dS m^{-1})	0.15	0.19	0.12	0.15	0.14	0.17	0.11
Organic carbon (%)	0.51	0.54	0.48	0.51	0.58	0.54	0.48
Available N (kg ha^{-1})	175	187	196	188	184	195	189
Available P_2O_5 (kg ha^{-1})	29	26	32	42	52	35	28
Available K_2O (kg ha^{-1})	294	273	292	235	310	235	246
DTPA extractable Zn (mg kg^{-1})	1.21	0.94	0.97	0.69	0.75	1.83	1.72

Rabi field locations: F1-F4 = Bussapur; F5-F6 = Venkatapur; F7 = Ibrahimpur villages farmers

Table 3. Field-specific fertilizer rates (kg N-P_2O_5-K_2O ha^{-1}), *Kharif* 2020.

No.	Field/location	FP (T_1)	STB (T_2)	RDF (T_3)
1	F1 Tornala	250-60-00	260-60-50	200-60-50
2	F2 Tornala	250-50-00	260-60-50	200-60-50
3	F3 Tornala	280-50-80	260-60-35 + $ZnSO_4$	200-60-50
4	F4 Tornala	300-60-50	260-42-35 + $ZnSO_4$	200-60-50
5	F5 Irkode	200-80-00	260-60-50	200-60-50
6	F6 Irkode	200-60-50	260-60-35 + $ZnSO_4$	200-60-50
7	F7 Ibrahimpur	200-80-00	260-42-35	200-60-50

Farmers' practice: FP (T_1); soil test-based nutrient management: STB (T_2); recommended dose of fertilizer: RDF (T_3).

Table 4. Field-specific fertilizer rates (kg N-P_2O_5-K_2O ha^{-1}), *Rabi* 2020-21.

No.	Field/location	FP (T_1)	STB (T_2)	RDF (T_3)
1	F1 Bussapur	270-90-80	312-80-80	240-80-80
2	F2 Bussapur	240-80-00	312-80-80	240-80-80
3	F3 Bussapur	270-90-80	312-80-80	240-80-80
4	F4 Bussapur	270-90-00	312-80-80	240-80-80
5	F5 Venkatapur	240-80-00	312-80-80	240-80-80
6	F6 Venkatapur	270-90-80	312-80-80	240-80-80
7	F7 Ibrahimpur	270-90-00	312-80-80	240-80-80

Farmers' practice: FP (T_1); soil test-based nutrient management: STB (T_2); recommended dose of fertilizer: RDF (T_3).

Statistical analysis

Experimental data were subjected to separate seasonal analyses of variance (ANOVA) appropriate for a randomized block design using OPSTAT statistical software, following Gomez and Gomez (Gomez and Gomez, 1984). Each farmer's field constituted a block containing one randomly allocated plot of each of the three treatments; the treatment plot was the experimental unit (three treatments × seven blocks = 21 observations per season). Degrees of freedom were 2 for treatment, 6 for blocks, 12 for error and 20 for total. Where the overall treatment F-test was significant, treatment means were compared using the critical difference (CD) at $P \leq 0.05$; otherwise, differences were reported as non-significant (NS).

RESULTS AND DISCUSSION

Baseline soil fertility and nutrient prescription

Initial soil testing revealed a consistent N constraint together with marked field-to-field heterogeneity in P, K and Zn (Tables 1 and 2). Available N ranged from 125 to 275 kg ha^{-1} in *Kharif* and 175 to 196 kg ha^{-1} in *Rabi*. Available P_2O_5 and K_2O varied more widely among *Kharif* fields, and DTPA extractable Zn was below 0.6 mg kg^{-1} in F3, F4 and F6. *Kharif* CVs were 30.3% for N, 40.5% for P_2O_5, 20.6% for K_2O and 45.0% for DTPA extractable Zn; corresponding *Rabi* values were 3.8, 26.5, 11.4 and 39.2%, respectively (Figure 2). Farmers applied relatively high N but omitted K in several fields, whereas Zn deficiency was localized. Consequently, a single fertilizer schedule could not reflect all initial soil conditions. T_2 adjusted nutrient rates and supplied $ZnSO_4$ only to diagnosed Zn-deficient *Kharif* fields. This approach is consistent with the site-specific nutrient-management rationale evaluated in earlier on-farm maize work (Pasuquin et al., 2014), although the present prescription also involved different N rates.

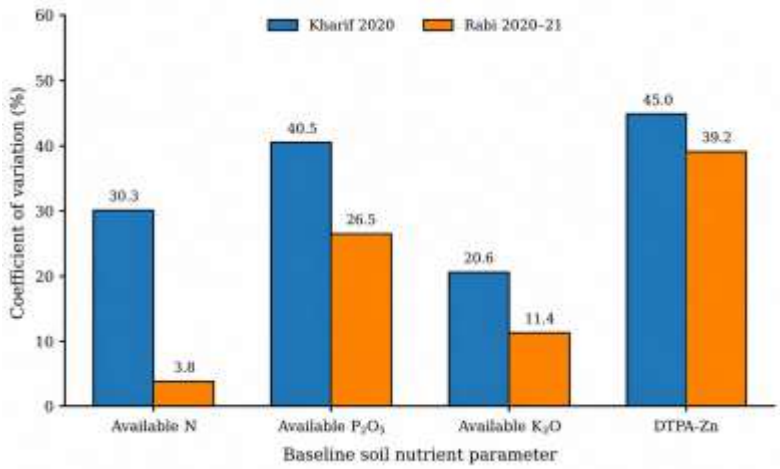


Figure 2. Field-to-field variability (coefficient of variation, %) in pre-sowing soil available N, P_2O_5, K_2O and DTPA extractable Zn across seven maize demonstration fields during *Kharif* 2020 and *Rabi* 2020-21 (n = 7 per season).

Crop growth, yield attributes and productivity

The evaluated nutrient-management packages were associated with differences in maize phenotypic growth and yield attributes (Table 5). STB (T_2) recorded the highest plant height (167.4 and 173.3 cm), kernel weight per cob (120.8 and 123.0 g), grains per cob (413.8 and 418.5) and 100-grain weight (29.2 and 29.4 g) in *Kharif* and *Rabi*, respectively. Treatment effects were significant for plant height, kernel weight per cob and 100-grain weight, but non-significant for grains per cob. Grain yields under STB were 6,856 and 8,570 kg ha^{-1}, increases of 22.2% and 22.3% over FP and 33.4% and 33.5% over RDF in *Kharif* and *Rabi*, respectively (Figure 4; Table 6). Stover dry matter yields were also highest under STB (11,585 and 14,482 kg ha^{-1}; Figure 3). These phenotypic and productivity responses may reflect differences in nutrient availability under the complete management packages. Similar agronomic responses have been reported in maize nutrient-management studies (Singh et al., 2020; Shyam et al., 2021; Coumaravel et al., 2013). Because STB included higher nitrogen application than RDF, the observed responses cannot be attributed to soil testing alone and do not demonstrate genetic differences.

Table 5. Growth and yield attributes of maize as influenced by nutrient-management practices at harvest stage

Treatments	Plant height (cm)		Kernel weight (g cob^{-1})		Grains cob^{-1}		100-grain weight (g)	
	Kharif 2020	*Rabi* 2020-21	*Kharif* 2020	*Rabi* 2020-21	*Kharif* 2020	*Rabi* 2020-21	*Kharif* 2020	*Rabi* 2020-21
FP (T_1)	160.3^c	166.2^c	117.4^b	119.2^b	410.5	413.8	28.6^b	28.8^b
STB (T_2)	167.4^a	173.3^a	120.8^a	123.0^a	413.8	418.5	29.2^a	29.4^a
RDF (T_3)	163.0^b	168.8^b	116.5^b	117.3^b	408.8	408.7	28.5^b	28.7^b
SE(m) ±	0.45	0.45	1.00	1.07	2.47	2.95	0.118	0.118

Farmers' practice: FP (T_1); soil test-based nutrient management: STB (T_2); recommended dose of fertilizer: RDF (T_3). NS = non-significant. Different superscript letters within the same column indicate significant differences at $P \leq 0.05$; no letters are assigned where treatment effects were non-significant

Table 6. Seasonal maize grain yield and management yield gaps under nutrient-management practices

Season	Yield advantage of soil test-nutrient management			
	$T_2 - T_1$ (kg ha^{-1})	T_2 over T_1 (%)	$T_2 - T_3$ (kg ha^{-1})	T_2 over T_3 (%)
Kharif, 2020	1,245	22.2	1,718	33.4
Rabi, 2020-21	1,559	22.3	2,151	33.5

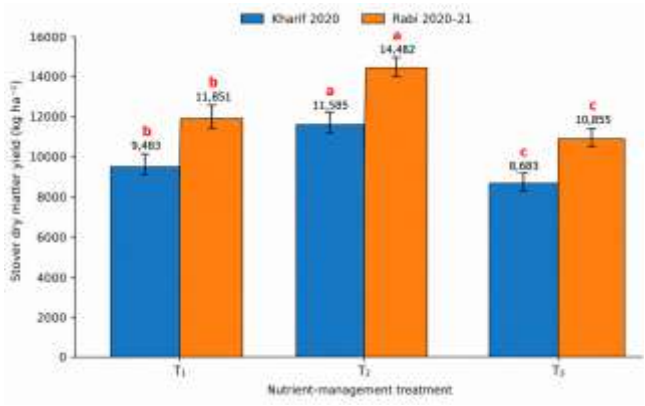


Fig. 3. Seasonal maize stover dry matter yield under farmers' practice (T_1), soil test-based nutrient management (T_2) and recommended dose of fertilizer (T_3). Error bars represent SE(m) (±196 and ±249 kg ha^{-1} for *Kharif* 2020 and *Rabi* 2020-21, respectively). Within each season, bars bearing different lowercase letters differ significantly at $P \leq 0.05$. CD ($P = 0.05$) = 604 and 768 kg ha^{-1} for *Kharif* 2020 and *Rabi* 2020-21, respectively.

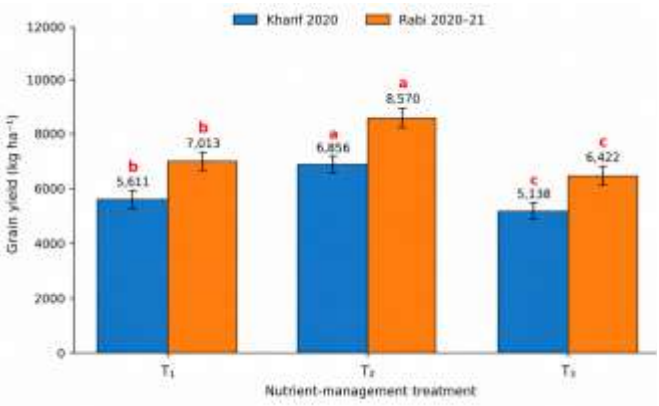


Fig. 4. Seasonal maize grain yield under farmers' practice (T_1), soil test-based nutrient management (T_2) and recommended dose of fertilizer (T_3). Error bars represent SE(m) (±117.51 and ±146.89 kg ha^{-1} for *Kharif* 2020 and *Rabi* 2020-21, respectively). Within each season, bars bearing different lowercase letters differ significantly at $P \leq 0.05$. CD ($P = 0.05$) = 362.08 and 452.61 kg ha^{-1} for *Kharif* 2020 and *Rabi* 2020-21, respectively.

Economics

Soil test-based nutrient management (STB) recorded the highest economic returns during both *Kharif* 2020 and *Rabi* 2020-21 (Table 7). STB registered gross returns of ₹1,26,831 and ₹1,58,538 ha^{-1} and net returns of ₹70,716 and ₹98,971 ha^{-1} during *Kharif* and *Rabi*, respectively. The corresponding benefit:cost (B:C) ratios were 2.27 and 2.66, compared with 1.90 and 2.27

under farmers' practice and 1.72 and 2.01 under the recommended fertilizer dose (RDF) (Fig. 5). Despite slightly higher cultivation costs, STB increased net returns over farmers' practice by 43.8% in *Kharif* and 36.7% in *Rabi*, primarily due to greater grain productivity. These findings agree with Pasuquin et al. (Pasuquin et al., 2014), who reported improved maize profitability through site-specific nutrient management, and Coumaravel et al. (Coumaravel et al., 2013), who demonstrated the relevance of soil test-based fertilizer prescriptions for hybrid maize in Alfisols. However, the economic advantage reflects the combined fertilizer prescription package, including higher nitrogen application, rather than the independent effect of soil testing.

Table 7. Economic performance of maize under different nutrient-management practices

Treatments	Cost of cultivation (₹/ha)		Gross returns (₹/ha)		Net returns (₹/ha)	
	***Kharif* 2020**	***Rabi* 2020-21**	***Kharif* 2020**	***Rabi* 2020-21**	***Kharif* 2020**	***Rabi* 2020-21**
FP (T_1)	54628	57362	103798	129748	49170	72386
STB (T_2)	56115	59568	126831	158538	70716	98971
RDF (T_3)	55341	59257	95050	118813	39709	59556

Farmers' practice: FP (T_1); soil test-based nutrient management: STB (T_2); recommended dose of fertilizer: RDF (T_3). Gross returns were calculated using a maize grain price of ₹18.50 kg^{-1}. Net returns = gross returns - cost of cultivation.

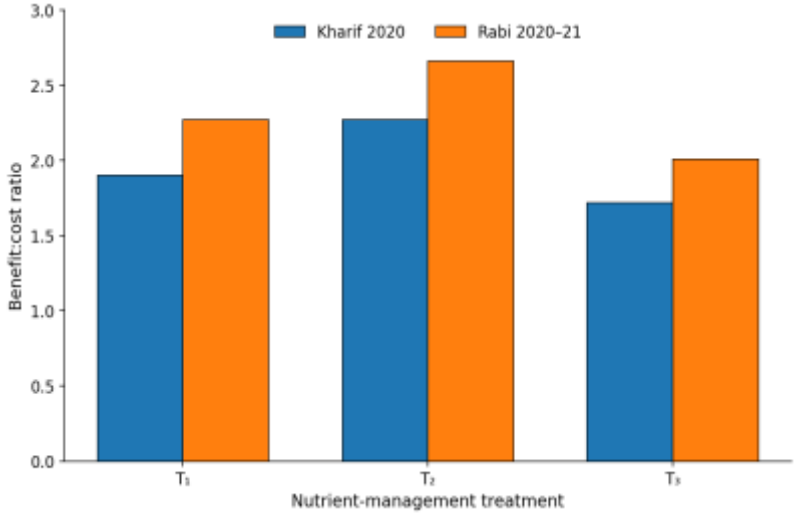


Fig. 5. Seasonal benefit:cost ratio of maize under farmers' practice (T_1), soil test-based nutrient management (T_2) and recommended dose of fertilizer (T_3).

Post-harvest soil fertility

Treatment effects on post-harvest soil pH, EC and organic carbon were non-significant in both seasons (Table 8). Available N and P_2O_5 differed significantly among treatments in *Kharif* and *Rabi*. The field-level analysis indicated a significant *Rabi* DTPA extractable Zn treatment effect, with T_2 greater than T_1 and T_3. Long-term Alfisol evidence has documented soil-quality responses to integrated nutrient inputs (Shruthi et al., 2026), while studies of residue management in a Telangana Alfisol demonstrate that soil biological indicators can respond to management practices not evaluated here (Prasad et al., 2025). Longer-term evidence also differs in experimental design and management: Raghuwanshi et al. (Raghuwanshi et al., 2025) evaluated carbon and nitrogen dynamics after 14 cropping cycles under conservation-agriculture systems in Vertisols. Thus, the non-significant organic-carbon response in this two-season Alfisol evaluation should be interpreted as an unresolved long-term outcome, not as evidence for or against sustained soil-carbon improvement under the present prescriptions.

Table 8. Post-harvest soil properties as influenced by nutrient-management practices

Treatment	pH		EC (dS m^{-1})		Organic carbon (%)		Available N (kg ha^{-1})		Available P_2O_5 (kg ha^{-1})		Available K_2O (kg ha^{-1})		DTPA extractable Zn (mg kg^{-1})	
	Kharif 2020	*Rabi* 2020-21	*Kharif* 2020	*Rabi* 2020-21	*Kharif* 2020	*Rabi* 2020-21	*Kharif* 2020	*Rabi* 2020-21	*Kharif* 2020	*Rabi* 2020-21	*Kharif* 2020	*Rabi* 2020-21	*Kharif* 2020	*Rabi* 2020-21
FP (T_1)	7.25	7.24	0.14	0.15	0.56	0.57	171.45	189.84	44.82	39.63	341.50	271.05	0.62	1.18[b]

STB (T_2)	7.20	7.27	0.15	0.15	0.56	0.57	176.76	191.70	43.21	41.74	347.26	274.91	0.73	1.23[a]
RDF (T_3)	7.22	7.26	0.14	0.16	0.53	0.54	170.25	188.43	43.61	40.98	356.61	272.94	0.64	1.20[b]
SE(m) ±	0.024	0.009	0.004	0.005	0.022	0.024	1.22	0.33	0.28	0.36	1.70	0.46	0.054	0.011

Farmers' practice: FP (T_1); soil test-based nutrient management: STB (T_2); recommended dose of fertilizer: RDF (T_3). NS = non-significant. Different superscript letters within the same column indicate significant differences at $P \leq 0.05$; no letters are assigned where treatment effects were non-significant

Plant nutrient concentration and nutrient uptake

Soil test-based nutrient management (T_2) recorded the highest calculated total N, P and K uptake in both seasons (Table 9). Based on seven farmer-field blocks per season, T_2 total N uptake was 250 and 266 kg ha^{-1} during *Kharif* and *Rabi*, respectively, compared with 196 and 210 kg ha^{-1} under farmers' practice (T_1). Total N, P and K uptake differed significantly among nutrient-management treatments in both seasons. Grain N, P and K concentrations did not differ significantly among treatments; Kharif stover N concentration was significant. Higher N accumulation was consistent with increased grain production, but differences in fertilizer N application rates prevent attribution of the response solely to soil testing or demonstration of improved N-use efficiency. Nutrient placement and precise water fertilizer delivery have been investigated as approaches to improving nutrient capture (Glotra et al., 2024; Srikanth et al., 2025); these mechanisms were not directly evaluated in the present study.

Table 9. Stover dry matter and grain nutrient concentrations and calculated nutrient accumulation indices of maize as influenced by nutrient-management practices

Nutrient	Treatment	*Kharif*, 2020			*Rabi*, 2020-21		
		Stover dry matter concentration (%)	Grain concentration (%)	Total uptake (kg ha^{-1})	Stover dry matter concentration (%)	Grain concentration (%)	Total uptake (kg ha^{-1})
N	FP (T_1)	1.27[b]	1.33	196[b]	0.90	1.45	210[b]
	STB (T_2)	1.32[a]	1.40	250[a]	0.94	1.50	266[a]
	RDF (T_3)	1.26[b]	1.31	177[c]	0.89	1.43	189[c]
	SE(m) ±	0.016	0.035	5.67	0.023	0.037	7.27
P	FP (T_1)	0.24	0.44	48[b]	0.26	0.45	63[b]
	STB (T_2)	0.25	0.45	59[a]	0.27	0.46	78[a]
	RDF (T_3)	0.24	0.43	43[b]	0.27	0.44	57[c]
	SE(m) ±	0.0085	0.0156	1.87	0.0097	0.0156	1.53
K	FP (T_1)	0.71	1.41	147[b]	0.75	1.44	190[b]
	STB (T_2)	0.72	1.45	184[a]	0.77	1.47	238[a]
	RDF (T_3)	0.74	1.42	139[b]	0.76	1.44	174[b]
	SE(m) ±	0.055	0.077	10.02	0.054	0.066	8.72

Farmers' practice: FP (T_1); soil test-based nutrient management: STB (T_2); recommended dose of fertilizer: RDF (T_3). NS = non-significant. Different superscript letters within the same column indicate significant differences at $P \leq 0.05$; no letters are assigned where treatment effects were non-significant

Multivariate analysis of maize growth and yield attributes

Principal component analysis (PCA) summarized multivariate patterns among four standardized maize phenotypic traits: plant height, kernel weight per cob, grains per cob and 100-grain weight. Separate seasonal analyses used seven field-level observations per treatment (n = 21 per season). The first two components explained 84.6% of measured trait variation in *Kharif* (PC1: 60.0%; PC2: 24.6%) and 88.8% in *Rabi* (PC1: 62.0%; PC2: 26.8%) (Figure 6). The biplots illustrate associations and overlap among observed trait profiles under nutrient-management treatments; they do not identify genetic variation, causal mechanisms or genotype-specific responses.

The observed phenotypic responses are limited to seven farmer fields per season across two cropping seasons. The higher nitrogen rates under STB relative to RDF prevent separation of soil-testing effects from fertilizer-rate effects. Neither genetic variation nor molecular mechanisms were measured. Nutrient-use efficiency, environmental impacts and long-term soil-fertility changes were also not directly assessed. Accordingly, the results support only the observed performance of the implemented nutrient-management package under these conditions. Multi-year and multi-location trials with comparable nitrogen rates are needed to test the reproducibility of these phenotypic responses.

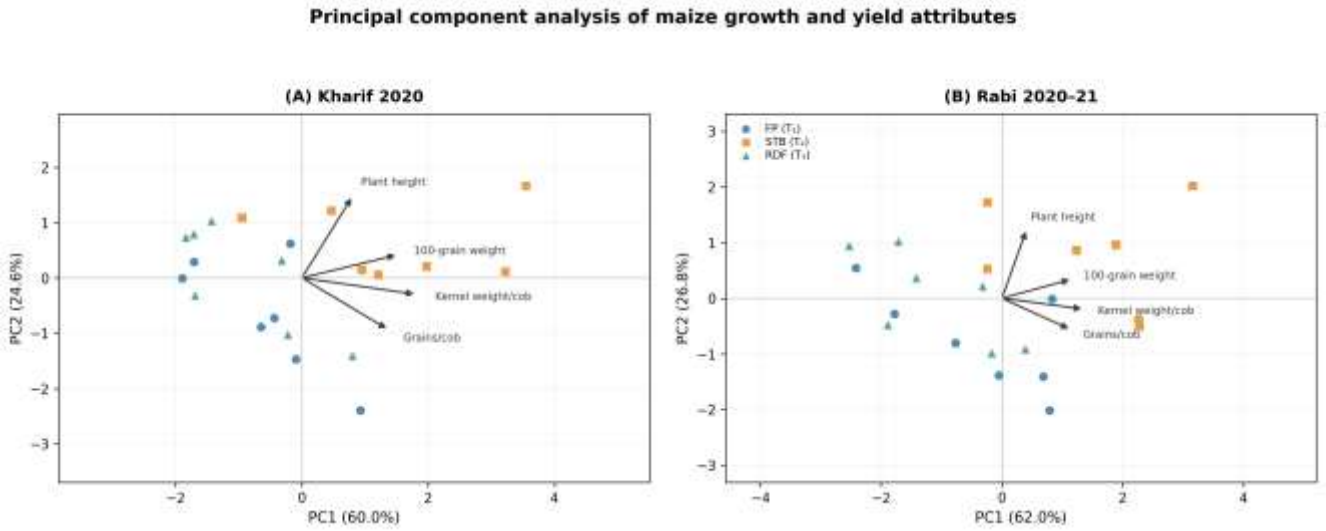


Fig. 6. Principal component analysis biplots of four standardized maize variables (plant height, kernel weight per cob, grains per cob and 100-grain weight) in (A) *Kharif* 2020 and (B) *Rabi* 2020-21 (n = 21 field-by-treatment observations per season). PC1 and PC2 explain 60.0% and 24.6% in *Kharif*, and 62.0% and 26.8% in *Rabi*.

CONCLUSION

Under the studied tropical Alfisol conditions, the implemented soil test-based nutrient-management package was associated with greater maize plant height, kernel weight per cob, 100-grain weight and grain yield than the comparison practices, while differences in grains per cob were non-significant. PCA summarized associations among these measured phenotypic traits across treatments and seasons. These management-associated differences should not be interpreted as genetic variation or as the isolated effect of soil testing, because nitrogen application rates differed among treatments. Harvest, laboratory and expenditure records require verification before definitive recommendations can be made; additional controlled multi-location experiments are warranted.

Acknowledgements

The authors sincerely acknowledge Professor Jayashankar Telangana Agricultural University (PJTAU), Hyderabad, for research facilities and support, and the staff of Agricultural Research Station, Tornala, for assistance in farmers field experimentation, observations and laboratory analyses.

Conflict of interest

The authors declare no conflict of interest.

Authors' contributions

S.N.: Conceptualization, methodology, investigation, formal analysis and writing - original draft; A.V.R and S.S.: writing - review, editing, supervision, project administration and critical review.

Ethics and field permissions

The study involved on-farm agronomic demonstrations conducted during *Kharif* 2020 and *Rabi* 2020-21 in farmers' fields in Siddipet district, Telangana, India, under the supervision of the Agricultural Research Station, Tornala. The experiments did not involve human participants or animals as research subjects. Permission to conduct the field demonstrations was obtained from the participating farmers before the initiation of the experiments. The study was conducted in accordance with applicable institutional guidelines for on-farm agricultural research.

Data availability statement

The field-level experimental data supporting the findings of this study, including crop growth, yield attributes, grain yield, nutrient uptake, post-harvest soil properties and economic observations, are provided in the supplementary material accompanying this article. Additional information regarding the experimental methods and data analysis may be obtained from the corresponding author upon reasonable request.

References

1. Coumaravel K, Santhi R, Maragatham S. Soil test crop response correlation studies under integrated plant nutrition system for hybrid maize on an Alfisol. Madras Agric J (2013). 100:660-664. https://doi.org/10.29321/MAJ.10.001378

2. Glotra A, Jat SL, Singh AK, Parihar CM, Pooniya V, Kumar S, et al. Influence of tillage, residue and nitrogen placement on maize growth and yield under conservation agriculture. Plant Sci Today (2024). 11(sp2):1-7. https://doi.org/10.14719/pst.3662
3. Gomez KA, Gomez AA. Statistical procedures for agricultural research. 2nd ed. New York: John Wiley & Sons (1984).
4. Hasanain M, Singh VK, Rathore SS, Meena VS, Meena SK, Shekhawat K, et al. Crop establishment and nutrient management options: Optimizing productivity, profitability and mitigating adverse climatic conditions in the maize-based production system of Northwest India. Field Crops Res (2024). 318: 109606. https://doi.org/10.1016/j.fcr.2024.109606
5. Jackson ML. Soil chemical analysis. New Delhi: Prentice Hall of India (1973).
6. Lindsay WL, Norvell WA. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci Soc Am J (1978). 42:421-428. https://doi.org/10.2136/sssaj1978.03615995004200030009x
7. Marschner P, editor. Marschner's mineral nutrition of higher plants. 3rd ed. Academic Press (2012).
8. Mohandas S, Dhanushkodi V, Karunakaran V, Nageswari R, Venkatalakshmi K, Parameswari K, et al. Effect of soil breeding and soil amendments on soil physical properties, rice yield and economics in crusted Alfisol. Plant Sci Today (2025). 12(2):1-6. https://doi.org/10.14719/pst.6179
9. Nagula S, Ramanjaneyulu AV, Sravanthi D, Swetha D. Comparative evaluation of nutrient management strategies for enhancing productivity, nutrient uptake, soil fertility and profitability of maize (Zea mays L.) in Alfisols. J Adv Biol Biotechnol (2026). 29(8):514-523. https://doi.org/10.9734/jabb/2026/v29i84200
10. Olsen SR, Cole CV, Watanabe FS, Dean LA. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Washington (DC): US Department of Agriculture (1954). Circular No. 939
11. Pasuquin JM, Pampolino MF, Witt C, Dobermann A, Oberthür T, Fisher MJ, Inubushi K. Closing yield gaps in maize production in Southeast Asia through site-specific nutrient management. Field Crops Res (2014). 156:219–230. https://doi.org/10.1016/j.fcr.2013.11.016
12. Prasad V, Sridevi S, Jayasree G, Triveni S, Venkata Ramana M. Effect of rice residue management options on soil microbial dynamics and enzyme activity under Rabi sunflower cultivation in an Alfisol. Plant Sci Today (2025). 12(sp1):1-11. https://doi.org/10.14719/pst.8699
13. Raghuwanshi S, Chaudhary RS, Sinha NK, Somasundaram J, Trivedi SK. Vertical distribution of carbon and nitrogen dynamics in black soil of central India under long-term zero-tillage with different cropping systems. Appl Biol Res (2025). 27(3):321-329. https://doi.org/10.48165/abr.2025.27.01.31
14. Shruthi GS, Kadalli GG, Jayanthi T, Sidharam P, Krishnamurthy R, Hanumanthappa DC. Soil quality and carbon sequestration potential in response to long term nutrient management practices under finger millet-maize cropping system in an Alfisol. Plant Sci Today (2026). 13(sp5):1-15. https://doi.org/10.14719/pst.13056
15. Shyam CS, Rathore SS, Shekhawat K, Singh RK, Padhan SR, Singh VK. Precision nutrient management in maize (Zea mays) for higher productivity and profitability. Indian J Agric Sci (2021). 91(6):933-935. https://doi.org/10.56093/ijas.v91i6.114303
16. Singh AK, Jat SL, Parihar CM, Kumar M, Singh CS, Hallikeri SS, et al. Precision nutrient management for enhanced yield and profitability of maize (Zea mays). Indian J Agric Sci (2020). 90(5):952-956. https://doi.org/10.56093/ijas.v90i5.104369
17. Srikanth Reddy K, Parihar CM, Panneerselvam P, Patra K, Sarkar A, Kumar S, et al. Impact of drip fertigation on maize growth and productivity under conservation agriculture practices in the eastern Indo-Gangetic plains of India. Plant Sci Today (2025). 12(2):1-8. https://doi.org/10.14719/pst.7001
18. Subbiah BV, Asija GL. A rapid procedure for the estimation of available nitrogen in soils. Curr Sci (1956). 25: 259-260
19. Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci (1934). 37(1):29-38