



RESEARCH ARTICLE

Assessment of targeted yield equations integrating conventional and nano di-ammonium phosphate (DAP) fertilizers for maize productivity in *alfisols* of the Southern Transition Zone, Shivamogga, Karnataka

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Received: 19 September 2025; Accepted: 05 December 2025; Available online: Version 1.0: 24 December 2025

Cite this article: Annappa NN, Krishna MR, Thimmegowda MN, Saralakumari J, Veeranagappa P, Bhavya N. Assessment of targeted yield equations integrating conventional and nano di-ammonium phosphate (DAP) fertilizers for maize productivity in *alfisols* of the Southern Transition Zone, Shivamogga, Karnataka. *Plant Science Today*. 2025;12(sp4):01–12. <https://doi.org/10.14719/pst.11859>

Abstract

Efficient nutrient management is essential to enhance maize productivity while conserving soil fertility. Soil test crop response (STCR)-based targeted yield equations enable soil- and yield-specific fertilizer recommendations; however, their validation across agroclimatic zones and with emerging inputs, such as nano di-ammonium phosphate (nano-DAP), remains limited. This study evaluated the transferability of STCR prescriptions using conventional fertilizers, nano-DAP and farmyard manure (FYM) in farmers' fields in the Southern Transition Zone (STZ) (Shivamogga), Karnataka. A rabi 2024 verification trial was conducted using the maize hybrid MAH 14-5 in a randomized complete block design (RCBD) with seven treatments: STCR targets (90 and 100 q ha⁻¹) ± FYM, general recommended dose (GRD), soil fertility rating (SFR) and control. STCR NPK + FYM (100 q ha⁻¹) recorded the highest kernel yield (97.82 q ha⁻¹) and stover yield (145.75 q ha⁻¹), along with maximum nitrogen (N), phosphorus (P) and potassium (K) uptake (302.72, 23.48 and 155.98 kg ha⁻¹, respectively). Integrated STCR + FYM treatments also achieved a superior response yardstick (24.00 kg kg⁻¹) and improved nutrient-use efficiency indices (AE-N: 40; RE-N: 0.70). All treatments recorded value cost ratio (VCR) > 2, confirming the economic feasibility of the integrated treatment. Nutrient balance analysis indicated positive K balance but consistent P depletion and variable N balances, highlighting the need for organic amendments. Soil test crop response-based nutrient management, particularly when combined with FYM and nano-DAP, improved yield, nutrient uptake and efficiency, demonstrating its applicability across zones and emphasizing the need for long-term P management strategies.

Keywords: maize; nano-fertilizers; nutrient-use efficiency; soil test crop response

Introduction

Maize (*Zea mays L.*) is one of the most widely cultivated cereal crops worldwide. It is valued not only as a staple food but also as a major source of livestock feed and as raw material for several industrial applications, including starch, oil and bioenergy production (1). In India, maize covers nearly 9.9 million hectares and accounts for about 31.51 million tonnes in production, ranking third after rice and wheat. Nutritionally, maize grains are rich in starch (80 %), protein (10 %), oil (4.5 %), fibre (3.5 %) and minerals (2 %), making them an important source of energy and nutrients (2). With growing demand for food, feed and industry, improving maize productivity has become increasingly important.

Nitrogen and P are two critical nutrients that directly

influence maize growth and yield. Nitrogen supports photosynthesis, protein synthesis and vegetative development, whereas P contributes to root growth, energy transfer and kernel formation. Lack of these nutrients results in reduced growth and poor grain development. However, maize productivity in India is often constrained by poor soil fertility, imbalanced fertilizer use and inefficient nutrient uptake (3). Continuous cropping and declining soil health further aggravate the problem.

In Karnataka, a large proportion of maize is grown on *Alfisols*, which cover around 30 % of the cultivable land. Although these soils are suitable for maize, they are generally low in organic matter (OM) and deficient in N, P and K (4). According to estimates by the Indian Council of Agricultural Research (ICAR), nearly two-thirds of Indian soils are deficient in one or more essential nutrients, leading to poor

nutrient use efficiency. In maize, N use efficiency rarely exceeds 30-40 %, while P use efficiency is usually less than 20 % due to soil fixation (5). These inefficiencies increase cultivation costs and cause environmental problems, such as groundwater contamination and greenhouse gas emissions (6). To address these challenges, STCR-based targeted yield equations have been developed. These equations are fertilizer prescription models that estimate a crop's nutrient requirements to achieve a desired yield, based on soil test values and crop nutrient uptake (7). They enable more precise fertilizer recommendations than general blanket doses, thereby improving productivity while avoiding excess application.

At the same time, advances in nanotechnology have introduced nano-fertilizers as an emerging solution to improve fertilizer use efficiency. Owing to their nanoscale size (1-100 nm), higher surface area and controlled-release properties, nano-fertilizers enhance nutrient availability and uptake compared to conventional fertilizers (8). Reports suggest that nano-fertilizers can increase N use efficiency by 50-70 % and P use efficiency by 30-50 %, often improving maize yield by 10-20 % while lowering fertilizer use by 20-30 % (9). Among them, nano-DAP has shown particular promise in improving P availability in maize. Yet, research on nano-fertilizers under farmer field conditions in *Alfisols* of Karnataka remains limited. Integrating targeted yield equations with nano-fertilizers could provide a sustainable solution to improve nutrient use efficiency, yield and profitability in maize. However, most previous studies have focused either on conventional fertilizers or on nano-fertilizers separately, with very few attempts to evaluate their combined role in nutrient management.

The present investigation was undertaken to evaluate the developed targeted yield equations for maize using both conventional fertilizers and nano-DAP under farmers field conditions of the STZ. Notably, this is the first study to test targeted yield equations developed in one agro-climatic zone for suitability in another. Such validation is essential to determine whether targeted yield models can be successfully extrapolated across environments, thereby enhancing their practical utility and enabling more sustainable maize production systems.

The central hypothesis of this research was that targeted yield equations developed for one agro-ecological zone would remain valid and perform efficiently when applied to a different zone, particularly when integrated with nano-fertilizers and organic amendments.

Based on this hypothesis, the specific objectives of the study were to: 1. Validate the performance of targeted yield equations for maize under farmers' field conditions in the STZ. 2. Assess the comparative efficiency of conventional fertilizers versus nano-DAP and FYM when applied through STCR-based prescriptions. 3. Evaluate treatment effects on maize yield, nutrient uptake, nutrient-use efficiency and economic feasibility. 4. Analyze post-harvest nutrient balance to understand long-term soil fertility implications under the tested nutrient management strategies.

Table 1. Meteorological data of the verification trial experimental site during Rabi 2024 at farmers field, STZ, Shivamogga

Month	Rainfall (mm)	Air temperature (°C)		Relative humidity (%)		Bright SSH (hr)	PET (mm)
		Minimum	Maximum	Minimum	Maximum		
October-24	127.00	20.00	27.70	66.00	88.00	6.40	4.20
November-24	38.00	18.20	28.10	60.00	85.00	7.20	4.00
December-24	8.00	17.00	28.80	55.00	83.00	8.10	3.70
January-25	3.40	15.20	27.40	53.00	86.00	5.70	4.00
February-25	2.00	18.30	32.20	45.00	80.00	9.20	4.80

Where, SSH: Sunshine hours, PET: Potential evapotranspiration

Materials and Methods

Experimental Site

To validate the fertilizer prescription equations, a verification trial was conducted with the maize hybrid MAH 14-5 during the Rabi season of 2024 under farmers' field conditions in the STZ of Shivamogga. The main objective of this trial was to test the accuracy and reliability of the targeted yield equations developed in the main experiment and to assess their suitability for practical adoption by farmers. Additionally, the study aimed to examine the combined effect of nano fertilizers with conventional fertilizers and to verify whether the applied treatments could achieve the targeted yield levels.

The farmers fields had a sandy loam texture with 68.40 % sand, 12.40 % silt and 19.20 % clay. Bulk density was 1.35 mg m⁻³, but water retention was higher (39.40 %) than in Bengaluru strips. The soil was slightly acidic (pH 6.01) with very low salinity (electrical conductivity (EC) 0.08 dS m⁻¹). Organic carbon (OC) (10.90 g kg⁻¹) and cation exchange capacity (CEC) (10.24 cmol (p⁺) kg⁻¹) were significantly higher. Nitrogen was abundant (489.55 kg ha⁻¹, medium), but P was critically low (27.83 kg ha⁻¹, high). Potassium (201.84 kg ha⁻¹, medium) and sulphur (24.70 mg kg⁻¹) were moderate. Exchangeable calcium (3.06 cmol (p⁺) kg⁻¹) was lower than in Bengaluru, while magnesium (2.30 cmol (p⁺) kg⁻¹) was higher. Micronutrients like iron (9.58 mg kg⁻¹) and manganese (13.70 mg kg⁻¹) were ample, but zinc was sufficient (0.85 mg kg⁻¹).

During the crop growth period in the Rabi 2024 season, a total of 178.4 mm of rainfall was recorded. The minimum temperature ranged from 15.2 °C to 20.0 °C, while the maximum temperature ranged from 27.4 °C to 32.2 °C. The minimum relative humidity ranged from 45 % to 66 %, whereas the maximum relative humidity ranged from 80 % to 88 %. The duration of bright sunshine hours fluctuated from 5.7 to 9.2 hr, while the potential evapotranspiration (PET) during the crop growth period varied between 3.7 mm and 4.8 mm. These agro-meteorological conditions (Table 1) were favourable for conducting the verification trial.

Design and layout of the experiment

The experiment was laid out in an RCBD with seven treatments and was replicated thrice. The layout plan for the verification trial is shown in Fig. 1. The field experiment was conducted during the Rabi 2024 season on farmers' fields in the STZ, using maize (variety MAH 14-5). The crop was sown at a spacing of 60 cm × 30 cm, with a seed rate of 15 kg per hectare. The experimental design employed was an RCBD with seven treatments and three replications, with a plot size of 4.5 m × 3.0 m per treatment. The recommended dose of fertilizers (RDF) applied was 150:75:37.5 kg N, phosphate (P₂O₅), potash (K₂O) per hectare, supplemented with FYM at 7.5 t ha⁻¹ and zinc sulphate at 10 kg ha⁻¹, to ensure adequate nutrient supply under field conditions in *Alfisols* typical of the region.

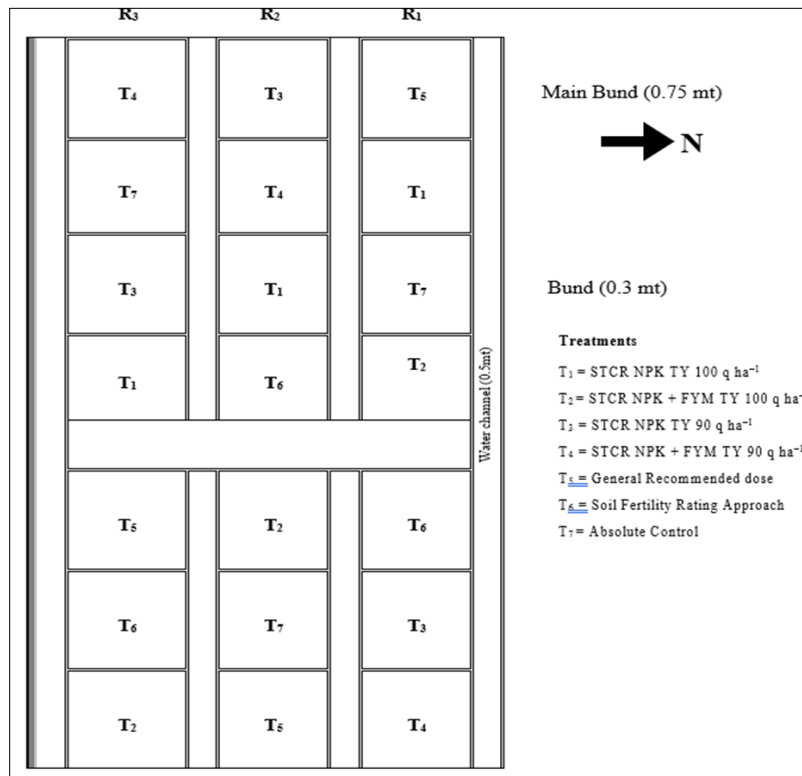


Fig. 1. Layout plan of the verification trial at the farmers' field in the STZ Shivamogga.

Fertilizer schedule

Nitrogen, P and K were applied as urea, SSP and MOP. 75 % of RDN were supplied through conventional fertilizers (50 % of 75 % RDN at sowing, 25 % of 75 % RDN at 45 DAS and the remaining 25 % of 75 % RDN at 75 DAS) and foliar application of Nano fertilizers at 30 DAS and 60 DAS through Nano DAP at the rate of 4 mL L⁻¹. 75 % of RDP was supplied through conventional fertilizers, with basal and foliar applications of Nano DAP at 30 DAS and 60 DAS, respectively, at 4 mL L⁻¹. 100 % of RDK was supplied through conventional fertilizers at basal.

Treatment details

The targeted yield was fixed considering the genetic potential of the maize variety MAH 14-5, at 83 q ha⁻¹. To achieve higher productivity through improved agronomic practices and nutrient management, the targeted yields were set at 90 q ha⁻¹ and 100 q ha⁻¹, representing a 10-15 % increase over the variety's genetic potential. This approach assumes that with optimized input use and favourable growing conditions, the crop can surpass its baseline genetic yield potential, thereby justifying the use of targeted nutrient management strategies such as the STCR approach. Fertilizer nutrients were applied according to the package of practices for the RDF method, whereas RDF was adjusted in the Low, Medium and High (LMH) or Soil Test Laboratory (STL) approach based on soil test values (Table 1a).

Table 2. Quantity of fertilizer nutrients and FYM applied per hectare through different approaches as per the treatments and soil test values during Rabi 2024 at farmers' fields in the STZ, Shivamogga

Treatments	Soil test values (kg ha ⁻¹)			FYM	Fertilizer nutrient (kg ha ⁻¹)		
	N	P	K	(t ha ⁻¹)	N	P	K
T ₁ : STCR TY 100 q ha ⁻¹ – NPK alone	521.55	29.89	216.50	0	125.39	41.07	54.79
T ₂ : STCR TY 100 q ha ⁻¹ – NPK + FYM	500.64	26.86	226.27	7.5	122.81	38.93	43.32
T ₃ : STCR TY 90 q ha ⁻¹ – NPK alone	506.61	25.92	239.63	0	111.98	34.63	42.30
T ₄ : STCR TY 90 q ha ⁻¹ – NPK + FYM	468.91	28.19	186.97	7.5	104.09	31.43	40.35
T ₅ : GRD (150:75:37.5 kg ha ⁻¹)	494.29	27.62	165.27	7.5	150.00	24.75	31.13
T ₆ : Soil fertility rating /LMH	456.59	26.86	188.90	7.5	150.00	18.56	31.13
T ₇ : Absolute control	478.24	29.51	189.37	0	0.00	0.00	0.00

Where, N: Nitrogen; P: Phosphorus; K: Potassium; FYM: Farmyard manure

Table 1a. Treatment details of verification trial experiment

T ₁	STCR NPK Targeted yield 100 q ha ⁻¹
T ₂	STCR NPK + FYM Targeted yield 100 q ha ⁻¹
T ₃	STCR NPK Targeted yield 90 q ha ⁻¹
T ₄	STCR NPK + FYM Targeted yield 90 q ha ⁻¹
T ₅	General recommended dose
T ₆	Soil fertility rating approach
T ₇	Absolute control

STCR fertilizer prescription targeted yield equations for maize

The soil test values for NPK fertilizer nutrients were applied to achieve specific yield targets in the STCR and SFR approaches. The amount of nutrients applied per hectare across different approaches, as per the treatments, is presented in Table 2.

Using the basic parameters, separate fertilizer prescription equations were developed for the NPK-only and NPK+FYM approaches (Table 3). Fertilizer response refers to the functional relationship between crop yield increase and the amount of nutrients supplied, which can be represented either graphically or mathematically. Thus, yield-target-based fertilizer recommendations are distinctive because they not only provide soil-test-based nutrient doses but also indicate the attainable yield potential when optimal agronomic practices are adopted.

Table 3. Targeted yield equations developed for maize

Fertilizer nutrients (kg ha ⁻¹)	NPK alone	NPK+FYM
FN	3.00 T - 0.28 STV (KMnO ₄ -N) - 89.95 NF	2.44 T - 0.18 STV (KMnO ₄ -N) - 68.50 NF - 0.73 OM
FP	0.77 T - 0.31 STV (Bray's-P) - 78.12 NF	0.71 T - 0.27 STV (Bray's-P) - 66.79 NF - 0.36 OM
FK	0.89 T - 0.16 STV (Am.Ace.K)	0.87 T - 0.15 STV (Am.Ace.K) - 1.41 OM

Source of OM: FYM

Where, FN, FP and FK are fertilizer N, P and K in kg ha⁻¹, respectively; T is the yield target in q ha⁻¹; STV (KMnO₄-N), STV (Bray's-P) and STV (Am.Ace.K) are available soil nutrients as KMnO₄-N, Bray's-P and NH₄OAc-K in kg ha⁻¹, respectively and OM is amount of FYM (organic manure) added in t ha⁻¹.

Derivation of fertilizer prescription equations for maize yield targets through the STCR approach under NPK alone and NPK + FYM treatments

From the basic parameters, fertilizer prescription equations were derived independently for the STCR approach with NPK alone and with NPK + FYM and are presented here.

STCR- NPK alone equations

Fertilizer nitrogen (FN) = 3.00 T - 0.28 STV (KMnO₄-N) - 89.95 NF
-(Eqn. 1)

Fertilizer phosphorus (FP) = 0.77 T - 0.31 STV (Bray's-P) - 78.12 NF
-(Eqn. 2)

Fertilizer potassium (FK) = 0.89 T - 0.16 STV (Am.Ace.K) (Eqn. 3)

STCR- NPK+FYM equations

Fertilizer nitrogen (FN) = 2.44 T - 0.18 STV (KMnO₄-N) - 68.50 NF - 0.73 OM
-(Eqn. 4)

Fertilizer phosphorus (FP) = 0.71 T - 0.27 STV (Bray's-P) - 66.79 NF - 0.36 OM
-(Eqn. 5)

Fertilizer potassium (FK) = 0.87 T - 0.15 STV (Am.Ace.K) - 1.41 OM
-(Eqn. 6)

Source of OM: FYM; NF: Amount of nitrogen supplied from organic manure

Where, FN, FP and FK are fertilizer N, P and K in kg ha⁻¹, respectively; T is the yield target in t ha⁻¹; soil test value (STV) (Potassium permanganate (KMnO₄-N), STV (Bray's-P) and STV (Am. Ace. K) are available soil nutrients as KMnO₄-N, Bray's-P and NH₄OAc-K in kg ha⁻¹, respectively and OM is amount of FYM (organic manure) added in t ha⁻¹.

Analysis of soil and plant samples

Analysis of soil samples

The soil samples collected from the experimental plot at 0-20 cm depth were air-dried under shade, pounded with a wooden mallet, sieved through a 2 mm sieve (0.2 mm for OC), labelled and stored in PVC boxes. Pre-sowing and post-harvest soil samples from the verification trial were analyzed for various physical, physico-chemical and chemical properties.

Analysis of plant samples

The five randomly selected and labelled plants used for recording growth and yield observations were sampled and analyzed for their nutrient content in kernels and stover. The samples were dried in an oven at 65 °C and powdered in a micro Willey mill. The samples were analyzed for different nutrient content by adopting standard chemical analytical methods

Nutrient uptake

The nutrient content of kernel and stover was estimated using standard chemical analytical methods and expressed as percentages. Nutrient uptake (kg ha⁻¹) by the crop was calculated for each treatment separately using the following formula.

Nutrient uptake (kg ha⁻¹) =

$$\frac{\text{Nutrient content (\%)} \times \text{Dry weight (kg ha}^{-1}\text{)}}{100} \quad (\text{Eqn. 7})$$

Nutrient use efficiency

Partial factor productivity (PFP): It is a simple expression of production efficiency, calculated in units of crop yield per unit of each nutrient applied.

$$\text{PFP (q kg}^{-1}\text{)} = \frac{\text{[Yield obtained in treated plot (q ha}^{-1}\text{)]}}{\text{Fertilizer nutrient applied (kg ha}^{-1}\text{)}} \quad (\text{Eqn. 8})$$

Apparent crop recovery efficiency (ARE): Apparent crop recovery efficiency was calculated by using the following formula and is expressed in kg's per kg. (kg's of nutrient uptake per kg of nutrient applied).

$$\text{ARE (kg kg}^{-1}\text{)} = \frac{\text{[Nutrient uptake in treated plot (kg ha}^{-1}\text{)} - \text{Nutrient uptake in control plot (kg ha}^{-1}\text{)]}}{\text{Fertilizer nutrient applied (kg ha}^{-1}\text{)}} \quad (\text{Eqn. 9})$$

Agronomic nutrient use efficiency (ANUE): Agronomic nutrient use efficiency was calculated by dividing the kernel yield obtained above the control by fertilizer nutrient applied + soil available nutrient and was expressed in kg's per kg. (kg's increase in seed yield per kg of nutrient applied).

$$\text{ANE (kg kg}^{-1}\text{)} = \frac{\text{[Kernel yield in treated plot (kg ha}^{-1}\text{)} - \text{Kernel yield in control plot (kg ha}^{-1}\text{)]}}{\text{Fertilizer nutrient applied (kg ha}^{-1}\text{)}} \quad (\text{Eqn. 10})$$

Reciprocal internal utilization efficiency (RIUE): Reciprocal internal utilization efficiency is the nutrient uptake relation to yield. RIUE was calculated using the following formula.

$$\text{RIUE (\%)} = \frac{\text{Nutrient uptake by kernel (kg ha}^{-1}\text{)}}{\text{Kernel yield (Mg ha}^{-1}\text{)}} \quad (\text{Eqn. 11})$$

Yield response (YR) and response yard stick (RYS): Yield response is the yield difference between treated plots and control plots. Response yard stick for each treatment was calculated using the following formula.

Yield response = Treated yield (q ha⁻¹) - Control yield (q ha⁻¹) (Eqn. 12)

$$\text{RYS} = \frac{\text{Yield response (kg ha}^{-1}\text{)}}{\text{Total nutrient applied (kg ha}^{-1}\text{)}} \quad (\text{Eqn. 13})$$

Per cent deviation: Per cent deviation from the fixed yield target was calculated using the following formula.

$$\text{Percent deviation} = \frac{[\text{Actual yield obtained (kg ha}^{-1}\text{)} - \text{Targeted yield (kg ha}^{-1}\text{)}]}{\text{Targeted yield (kg ha}^{-1}\text{)}} \times 100$$

(Eqn. 14)

Balance sheet of nitrogen, phosphorus and potassium

Balance sheets for N, P and K were prepared by considering the status of available N, P and K in the initial soil, the amount of N, P and K added through fertilizer and the crop's uptake of N, P and K. Expected balance of N, P and K were calculated by subtracting N, P and K uptake by the crop from total N, P and K. Net gain or loss of nutrient was worked out by subtracting actual balance from the expected balance of the nutrients.

Economic analysis

Value cost ratio

Since the cost of cultivation with respect to agronomic practices remains the same across all treatments, except for FYM and fertilizer doses, only the VCR was calculated, accounting for the costs of the applied manures and fertilisers. The VCR was calculated by using the following formula.

$$\text{VCR} = \frac{[\text{Yield in treated plot (q ha}^{-1}\text{)} - \text{Yield in control plot (q ha}^{-1}\text{)}]}{\text{Cost of fertilizers and FYM applied to treated plot}} \times \text{Cost q}^{-1} \text{ of kernel}$$

(Eqn. 15)

Statistical analysis of data

The experimental data generated in the verification trial were subjected to statistical analysis using Fisher's method of analysis of variance. The level of significance used in "F" and "t" tests was 5%. Critical difference (CD) values were calculated at 5 per cent level of significance whenever "F" test was found significant.

Results and Discussion

Kernel and Stover yield

In the STZ, the treatment T₂ [STCR NPK + FYM (100 q ha⁻¹)] recorded the highest kernel yield (97.82 q ha⁻¹) and stover yield (145.75 q ha⁻¹), which was significantly superior to T₅ [GRD] (82.95 and 122.06 q ha⁻¹), T₆ [SFR approach] (84.67 and 125.23 q ha⁻¹) and T₇ [absolute control] (48.58 and 74.01 q ha⁻¹). Other STCR-based treatments, including T₁

[STCR NPK for 100 q ha⁻¹] (95.77 and 142.26 q ha⁻¹), T₃ [STCR NPK (90 q ha⁻¹)] (86.15 and 129.90 q ha⁻¹) and T₄ [STCR NPK + FYM (90 q ha⁻¹)] (91.06 and 134.02 q ha⁻¹), were found to be statistically on par with T₂ [STCR NPK + FYM (100 q ha⁻¹)], though T₂ [STCR NPK + FYM (100 q ha⁻¹)] consistently recorded numerically higher yields. This result highlights the efficacy of the STCR approach, particularly when integrated with FYM (Table 4).

Response yardstick

The response yardstick indicates the yield obtained in kg per kg of NPK applied at that particular ratio for each treatment. The RYS values varied significantly across different fertility status, location and treatment conditions.

In the farmers' field, the highest RYS was recorded in STCR NPK + FYM, targeted yield 90 q ha⁻¹ (T₄), with 24.00 kg kg⁻¹, followed by STCR NPK + FYM, targeted yield 100 q ha⁻¹ (T₂), with 23.88 kg kg⁻¹. The STCR NPK targeted yield of 100 q ha⁻¹ (T₁) achieved 21.22 kg kg⁻¹, while the STCR NPK targeted yield of 90 q ha⁻¹ (T₃) recorded 19.75 kg kg⁻¹. The lower RYS values were observed in the SFR approach (T₆) at 17.89 kg kg⁻¹ and in the GRD (T₅) at 16.06 kg kg⁻¹. Across all locations, the STCR approaches with integrated nutrient management (NPK + FYM) consistently showed superior RYS values compared to NPK alone, with the 90 q ha⁻¹ target generally performing better than the 100 q ha⁻¹ target in terms of nutrient use efficiency (Fig. 2).

Per cent deviation

At farmers' field of STZ, Shivamogga, positive deviation was achieved in STCR NPK + FYM, with a targeted yield of 90 q ha⁻¹ (T₄) at 1.18%, surpassing the fixed target. The STCR NPK + FYM targeted yield 100 q ha⁻¹ (T₂) showed a negative deviation of -2.18% followed by STCR NPK targeted yield 100 q ha⁻¹ (T₁) with -4.23% and STCR NPK targeted yield 90 q ha⁻¹ (T₃) with -4.31%. The higher negative deviations were observed in the GRD (T₅) (-5.20%) and the SFR approach (T₆) (-3.23%). The absolute control (T₇) recorded the maximum negative deviation of -44.48%. Across all locations, the STCR integrated approach with NPK + FYM at a 90 q ha⁻¹ target consistently achieved positive deviations, indicating that the crop exceeded its genetic yield potential in these treatments. The absolute control treatment showed the highest negative deviations across all locations, demonstrating the critical importance of nutrient application for achieving target yields (Fig. 2).

Value cost ratio

The value-cost ratio indicates the economic viability of different nutrient management approaches by expressing the ratio of additional income generated to the additional cost incurred from fertilizer application (Fig. 2). At the farmers' field, the highest VCR was recorded in STCR NPK targeted yield 100 q ha⁻¹ (T₁) with 9.10,

Table 4. Influence of different approaches of fertilizer recommendation on yield, per cent deviation, yield response and VCR of maize in the STZ of Shivamogga, Karnataka

Treatment details	Kernel yield (q ha ⁻¹)	Stover yield (q ha ⁻¹)	RYS	Per cent deviation	VCR
T ₁ STCR NPK Targeted yield 100 q ha ⁻¹	95.77	142.26	21.22	-4.23	9.10
T ₂ STCR NPK + FYM Targeted yield 100 q ha ⁻¹	97.82	145.75	23.88	-2.18	4.44
T ₃ STCR NPK Targeted yield 90 q ha ⁻¹	86.15	129.9	19.75	-4.31	8.12
T ₄ STCR NPK + FYM Targeted yield 90 q ha ⁻¹	91.06	134.02	24.00	1.18	3.97
T ₅ GRD	82.95	122.06	16.06	-5.20	3.93
T ₆ Soil fertility rating approach	84.67	125.23	17.89	-3.23	4.32
T ₇ Absolute control	48.58	74.01		-44.48	-
S.Em. ±	4.10	6.10			
C.D. at 5 %	11.68	17.39			

Where, RYS: Response yard stick; VCR: Value cost ratio

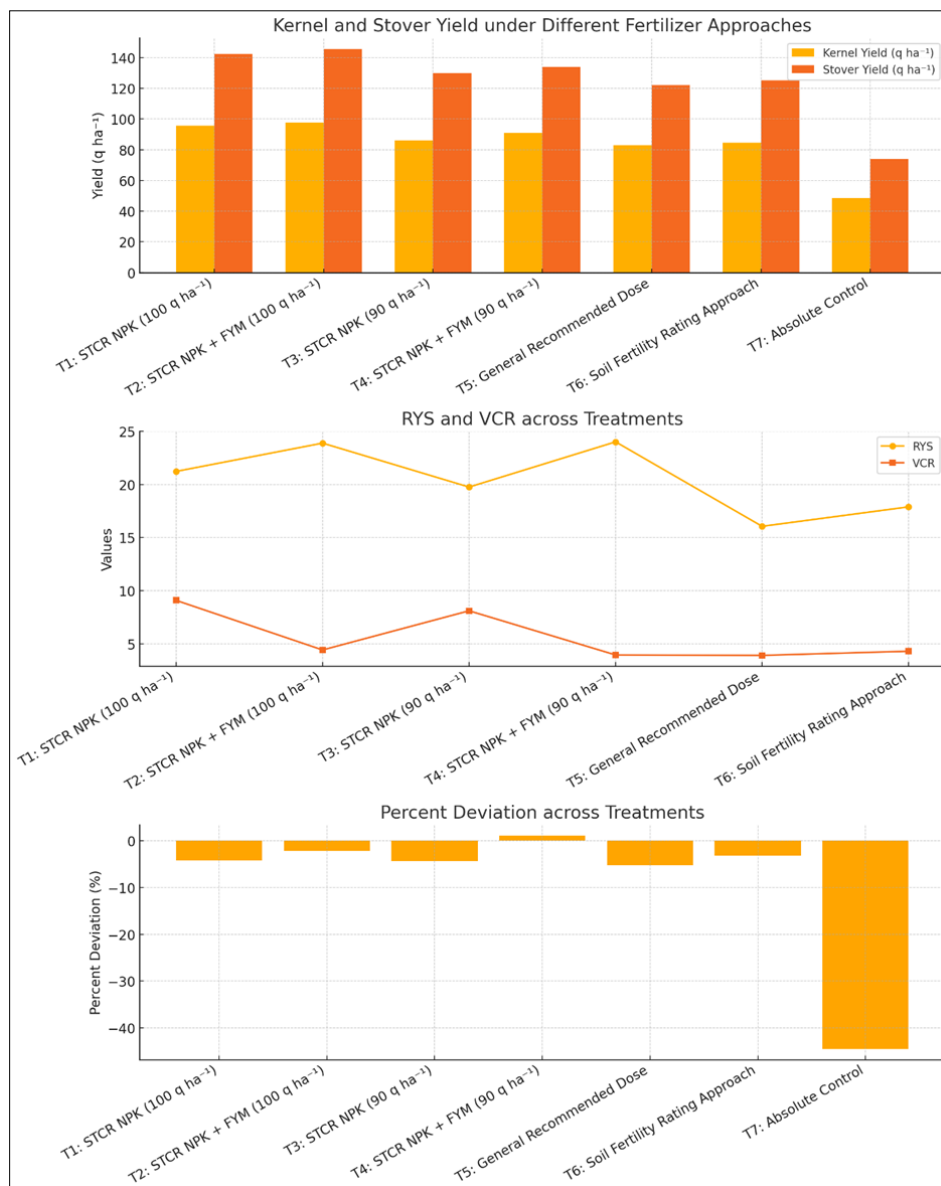


Fig. 2. Influence of different approaches of nutrient recommendation on per cent deviation (a), RYS & VCR (b) and kernel & stover yield (c) of maize in farmers' field of STZ of Shivamogga.

followed by STCR NPK targeted yield 90 q ha⁻¹ (T₃) with 8.12. The STCR NPK + FYM treatments showed T₂ (targeted yield 100 q ha⁻¹) with 4.44 and T₄ (targeted yield 90 q ha⁻¹) with 3.97. The conventional approaches recorded lower VCR values: the SFR approach (T₆) achieved 4.32 and the GRD (T₅) recorded 3.93.

Nitrogen uptake

The results on N uptake by maize kernels, stover and total uptake, as influenced by different nutrient management approaches, are presented in Table 5. At the farmers' fields, the STCR NPK + FYM treatment targeting 100 q ha⁻¹ yield (T₂) achieved the highest N uptake: 172.55 kg ha⁻¹ in kernels, 130.17 kg ha⁻¹ in stover and 302.72 kg ha⁻¹ total. T₂ significantly outperformed the GRD (T₅), SFR approach (T₆) and control (T₇), while remaining statistically comparable to T₁ (STCR NPK at 100 q ha⁻¹) and T₄ (STCR NPK + FYM at 90 q ha⁻¹) across all uptake parameters.

Phosphorus uptake

Table 6 presents the findings on P uptake by maize, detailing its absorption in the kernel, stover and total, as affected by various nutrient management strategies. At the Farmer field, the STCR NPK + FYM treatment targeting a 100 q ha⁻¹ yield [T₂] demonstrated superior kernel and stover P uptake performance at 14.09 kg ha⁻¹

and 9.39 kg ha⁻¹, respectively, significantly exceeding all other nutrient recommendation approaches, including absolute control [T₇]. Total P uptake was maximum under treatment T₂ [STCR NPK + FYM targeting 100 q ha⁻¹] at 23.48 kg ha⁻¹, representing a significant improvement over all other treatments.

Potassium uptake

The Table 7 presents the findings on K uptake by maize, detailing its absorption in the kernel, stover and the total, as affected by various nutrient management strategies (Fig. 3). At the Farmer field, higher uptake of K in kernel, stover and total was noticed in T₂ [STCR NPK + FYM targeted yield of 100 q ha⁻¹] (46.79, 109.19 and 155.98 kg ha⁻¹, respectively), significantly higher than all other treatments except T₁ [STCR NPK targeted yield of 100 q ha⁻¹] (44.87, 104.71 and 149.58 kg ha⁻¹, respectively) and T₄ [STCR NPK+FYM targeted yield of 90 q ha⁻¹] (41.99, 97.98 and 139.97 kg ha⁻¹, respectively), which showed statistically equivalent K uptake similar to T₂.

Nutrient use efficiency

The evaluation of nutrient use efficiency indices revealed distinct variations among treatments (Table 8). Nutrient-use efficiency indices varied considerably among treatments. For Agronomic Efficiency (AE), the highest N efficiency was recorded under T₄

Table 5. Influence of different approaches of nutrient recommendation on nitrogen uptake by maize in the farmers' field in the STZ of Shivamogga

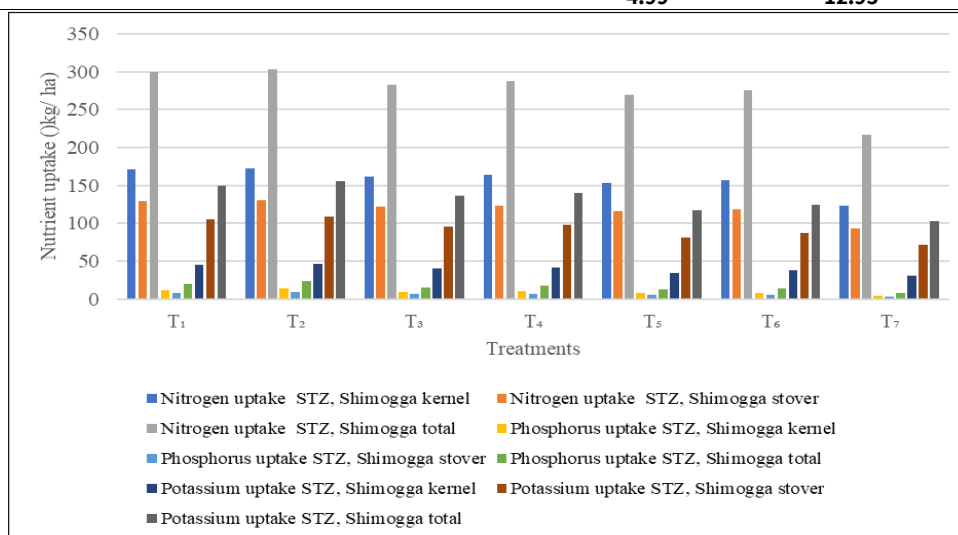
Treatment details		Nitrogen uptake		
		Kernel (kg ha ⁻¹)	Stover (kg ha ⁻¹)	Total (kg ha ⁻¹)
T ₁	STCR NPK Targeted yield 100 (q ha ⁻¹)	170.86	128.9	299.76
T ₂	STCR NPK + FYM Targeted yield 100 (q ha ⁻¹)	172.55	130.17	302.72
T ₃	STCR NPK Targeted yield 90 (q ha ⁻¹)	161.41	121.76	283.17
T ₄	STCR NPK + FYM Targeted yield 90 (q ha ⁻¹)	163.96	123.69	287.65
T ₅	GRD	153.79	116.02	269.81
T ₆	Soil fertility rating approach	157.01	118.45	275.46
T ₇	Absolute control	123.38	93.08	216.46
S.Em. ±		4.66	2.67	7.55
C.D. at 5 %		13.27	7.62	21.51

Table 6. Influence of different approaches of nutrient recommendation on phosphorus uptake by maize in the farmers' field in the STZ of Shivamogga

Treatment details		Phosphorus uptake		
		Kernel (kg ha ⁻¹)	Stover (kg ha ⁻¹)	Total (kg ha ⁻¹)
T ₁	STCR NPK Targeted yield 100 (q ha ⁻¹)	11.98	7.98	19.96
T ₂	STCR NPK + FYM Targeted yield 100 (q ha ⁻¹)	14.09	9.39	23.48
T ₃	STCR NPK Targeted yield 90 (q ha ⁻¹)	9.47	6.31	15.78
T ₄	STCR NPK + FYM Targeted yield 90 (q ha ⁻¹)	10.81	7.21	18.02
T ₅	GRD	7.67	5.11	12.78
T ₆	Soil fertility rating approach	8.19	5.46	13.65
T ₇	Absolute control	5.03	3.36	8.39
S.Em. ±		0.51	0.34	0.85
C.D. at 5 %		1.45	0.96	2.41

Table 7. Influence of different approaches of nutrient recommendation on potassium uptake by maize in the farmers' field in the STZ of Shivamogga

Treatment details		Potassium uptake		
		Kernel (kg ha ⁻¹)	Stover (kg ha ⁻¹)	Total (kg ha ⁻¹)
T ₁	STCR NPK Targeted yield 100 (q ha ⁻¹)	44.87	104.71	149.58
T ₂	STCR NPK + FYM Targeted yield 100 (q ha ⁻¹)	46.79	109.19	155.98
T ₃	STCR NPK Targeted yield 90 (q ha ⁻¹)	41.04	95.77	136.81
T ₄	STCR NPK + FYM Targeted yield 90 (q ha ⁻¹)	41.99	97.98	139.97
T ₅	GRD	35.05	81.78	116.83
T ₆	Soil fertility rating approach	37.51	87.52	125.03
T ₇	Absolute control	30.82	71.92	102.74
S.Em. ±		1.75	4.54	6.49
C.D. at 5 %		4.99	12.95	18.50

**Fig. 3.** Influence of different approaches of nutrient recommendation on nutrient uptake of maize in farmers' field of STZ of Shivamogga.**Table 8.** Influence of different approaches of nutrient recommendation on nutrient use efficiency of maize in the STZ of Shivamogga

Treatment details		AE			RE			RIUE			PFP		
		N	P	K	N	P	K	N	P	K	N	P	K
T ₁	STCR NPK Targeted yield 100 (q ha ⁻¹)	37.52	112.79	86.13	0.66	0.28	0.85	3.13	0.21	1.56	0.76	2.29	1.75
T ₂	STCR NPK + FYM Targeted yield 100 (q ha ⁻¹)	39.97	124.03	113.66	0.70	0.38	1.23	3.09	0.24	1.59	0.79	2.46	2.26
T ₃	STCR NPK Targeted yield 90 (q ha ⁻¹)	33.41	106.04	88.75	0.59	0.21	0.81	3.29	0.18	1.59	0.77	2.43	2.04
T ₄	STCR NPK + FYM Targeted yield 90 (q ha ⁻¹)	40.66	131.91	105.27	0.68	0.30	0.92	3.16	0.20	1.54	0.87	2.83	2.26
T ₅	GRD	22.91	104.95	109.98	0.36	0.13	0.45	3.25	0.15	1.41	0.55	2.53	2.65
T ₆	Soil fertility rating approach	24.06	176.34	115.49	0.39	0.26	0.71	3.25	0.16	1.48	0.56	4.14	2.71
T ₇	Absolute control	-	-	-	-	-	-	4.46	0.17	2.11	-	-	-

(40.66), followed by T₂ (39.97), while T₅ showed the lowest value (22.91). Phosphorus AE was highest under T₆ (176.34), followed by T₄ (131.91). For K, T₂ and T₆ performed best (113.66 and 115.49), whereas T₅ remained relatively lower. Recovery Efficiency (RE) showed similar trends, with T₂ recording the highest recovery for N (0.70), P (0.38) and K (1.23), while T₅ consistently recorded the lowest values. Reciprocal Internal Use Efficiency (RIUE) was highest in the absolute control (T₇) for all nutrients, indicating enhanced internal utilization under nutrient stress, while fertilized treatments showed relatively stable values. For PFP, T₄ recorded the highest N PFP (0.87), whereas T₅ showed the lowest (0.55). Phosphorus and K PFP were maximum under T₆ (4.14 and 2.71), with STCR + FYM treatments (T₂ and T₄) also performing well.

Nutrient balance

Nitrogen Balance in the soil

Nitrogen balance varied notably across nutrient management practices at the farmers' field (Table 9). The highest total nitrogen (TN) pool was recorded under T₁ (647.32 kg ha⁻¹), followed closely by T₅ (644.29 kg ha⁻¹), whereas the lowest TN was observed in T₇ (478.24 kg ha⁻¹). The addition of FYM in STCR treatments resulted in a slight reduction in TN, as reflected in T₂ (623.84 kg ha⁻¹) and T₄ (573.38 kg ha⁻¹). Crop nitrogen uptake (CU) was maximum under T₂ (302.72 kg ha⁻¹), followed by T₁ (299.76 kg ha⁻¹), demonstrating the benefit of integrating FYM with inorganic fertilizers. In contrast, the lowest CU occurred in T₇ (216.46 kg ha⁻¹). Expected balance (EB) and actual balance (AB) were highest under T₅ (374.48 and 468.73 kg ha⁻¹, respectively), while the lowest balance values were observed in T₄. Net gain/loss (G/L) trends further showed T₅ with the highest gain (94.25 kg ha⁻¹), followed by T₆ (90.28 kg ha⁻¹) and T₂ (85.60 kg ha⁻¹), whereas T₇ recorded the lowest gain (74.57 kg ha⁻¹), indicating gradual N depletion under unfertilized conditions.

Phosphorus balance in the soil

Phosphorus balance varied notably across nutrient management strategies (Table 10). The highest total phosphorus (TP) pool was

recorded under T₁ (71.73 kg ha⁻¹), followed by T₂ (66.56 kg ha⁻¹) and T₃ (61.32 kg ha⁻¹), while the lowest TP occurred in T₇ (29.51 kg ha⁻¹). Phosphorus uptake was maximum under T₂ (23.48 kg ha⁻¹), followed by T₁ (19.96 kg ha⁻¹) and T₄ (18.02 kg ha⁻¹), with the lowest uptake in T₇ (8.39 kg ha⁻¹). Expected and actual P balances were highest in T₁ and lowest in T₇ and T₄. Net G/L values were negative across all treatments, indicating overall P depletion. The smallest depletion occurred under T₇ (-2.20 kg ha⁻¹), followed by T₂ (-7.16 kg ha⁻¹), whereas the greatest loss was observed in T₅ (-17.47 kg ha⁻¹) and T₃ (-15.68 kg ha⁻¹). Overall, STCR-based nutrient management improved P availability and uptake. Yet, none of the treatments sustained a positive P balance, highlighting the risk of long-term P mining even under improved fertilization regimes.

Potassium Balance in Soil

Potassium balance differed clearly among the nutrient management strategies (Table 11). The highest total potassium (TK) pool was recorded under T₃ (281.93 kg ha⁻¹), followed by T₁ and T₂, whereas the lowest was observed under T₅ (196.52 kg ha⁻¹). Potassium uptake was maximum under T₂ (155.98 kg ha⁻¹), closely followed by T₁ and T₄, with the minimum recorded in T₇ (102.74 kg ha⁻¹). Expected and actual K balances were also highest under T₃ and lowest under T₅. All treatments exhibited a positive net K balance, with T₂ showing the greatest gain (35.24 kg ha⁻¹), followed by T₆ and T₁. Even the control (T₇) recorded a positive balance (21.23 kg ha⁻¹), indicating inherent soil K buffering. Overall, the results emphasize that STCR-based treatments, particularly when integrated with FYM and nano-DAP, improved K availability, uptake and soil retention compared to conventional fertilizer approaches.

Discussion

Target yield-based fertilizer recommendations are characterized by their unique ability to provide soil-test-calibrated nutrient dosages while simultaneously predicting achievable yield potential under optimized agronomic management practices (10). The superiority of the targeted yield approach over conventional fertilizer

Table 9. Nitrogen balance in soil as influenced by different approaches of nutrient application in the farmer's field, STZ, Shivamogga

Treatment details		IAN	FN	Nano N	TN	CU	EB	AB	G/L
		1	2		3(1+2)	4	5(3-4)	6	7(6-5)
T1	STCR NPK Targeted yield 100 q ha ⁻¹	521.55	125.78	0.384	647.32	299.76	347.56	423.30	75.74
T2	STCR NPK + FYM Targeted yield 100 q ha ⁻¹	500.64	123.20	0.384	623.84	302.72	321.12	406.72	85.60
T3	STCR NPK Targeted yield 90 q ha ⁻¹	506.61	112.36	0.384	618.97	283.17	335.80	418.70	82.90
T4	STCR NPK + FYM Targeted yield 90 q ha ⁻¹	468.91	104.47	0.384	573.38	287.65	285.73	366.97	81.24
T5	GRD	494.29	150.00	0.00	644.29	269.81	374.48	468.73	94.25
T6	Soil fertility rating approach	456.59	150.00	0.00	606.59	275.46	331.13	421.41	90.28
T7	Absolute control	478.24	0.00	0.00	478.24	216.46	261.78	336.35	74.57

Legend: IAN: Initial available nitrogen (kg ha⁻¹), FN: Fertilizer nitrogen (kg ha⁻¹), TN: Total nitrogen (kg ha⁻¹), CU: Crop uptake (kg N ha⁻¹), EB: Expected balance (kg ha⁻¹), AB: Actual balance (kg ha⁻¹), G/L: Net gain/ net loss (kg ha⁻¹)

Table 10. Phosphorus balance in soil as influenced by different approaches of nutrient application in the farmer's field, STZ, Shivamogga

Treatment details		IAP	FP	Nano P	TP	CU	EB	AB	G/L
		1	2		3(1+2)	4	5(3-4)	6	7(6-5)
T1	STCR NPK Targeted yield 100 q ha ⁻¹	29.89	41.84	0.768	71.73	19.96	51.77	40.01	-11.76
T2	STCR NPK + FYM Targeted yield 100 q ha ⁻¹	26.86	39.70	0.768	66.56	23.48	43.08	35.92	-7.16
T3	STCR NPK Targeted yield 90 q ha ⁻¹	25.92	35.40	0.768	61.32	15.78	45.54	29.86	-15.68
T4	STCR NPK + FYM Targeted yield 90 q ha ⁻¹	28.19	32.20	0.768	60.39	18.02	42.37	28.47	-13.90
T5	GRD	27.62	32.75	0.00	60.37	12.78	47.59	30.12	-17.47
T6	Soil fertility rating approach	26.86	20.47	0.00	47.33	13.65	33.68	25.46	-8.22
T7	Absolute control	29.51	0.00	0.00	29.51	8.39	21.12	18.92	-2.20

IAP: Initial available phosphorus (kg ha⁻¹), TP: Total phosphorus (kg ha⁻¹),

FP: Fertilizer phosphorus (kg P ha⁻¹)

CU: Crop uptake (kg P ha⁻¹), EB: Expected balance (kg ha⁻¹)

AB: Actual balance (kg ha⁻¹) G/L: Net gain/ net loss (kg ha⁻¹)

Table 11. Potassium balance in soil as influenced by different approaches of nutrient application in the farmers' field in the STZ, Shivamogga

Treatment details		IAK	FK	TK	CU	EB	AB	G/L
		1	2	3(1+2)	4	5(3-4)	6	7(6-5)
T1	STCR NPK Targeted yield 100 q ha ⁻¹	216.50	54.79	271.29	149.58	121.71	154.19	32.48
T2	STCR NPK + FYM Targeted yield 100 q ha ⁻¹	226.27	43.32	269.59	155.98	113.61	148.85	35.24
T3	STCR NPK Targeted yield 90 q ha ⁻¹	239.63	42.30	281.93	136.81	145.12	171.43	26.31
T4	STCR NPK + FYM Targeted yield 90 q ha ⁻¹	186.97	40.35	227.32	139.97	87.35	109.82	22.47
T5	GRD	165.27	31.25	196.52	116.83	79.69	110.46	30.77
T6	Soil fertility rating approach	188.90	31.25	220.15	125.03	95.12	128.74	33.62
T7	Absolute control	189.37	0.00	189.37	102.74	86.63	107.86	21.23

Legend: **IAK:** Initial available potassium (kg ha⁻¹), **TK:** Total potassium (kg ha⁻¹) **FK:** Fertilizer potassium (kg K ha⁻¹)

CU: Crop uptake (kg K ha⁻¹), **EB:** Expected balance (kg ha⁻¹)

AB: Actual balance (kg ha⁻¹) **G/L:** Net gain/ net loss (kg ha⁻¹)

recommendation methods in eggplant cultivation, reporting enhanced yields, increased net returns and improved economic profitability (11).

The study highlights that site-specific nutrient management through the STCR approach, particularly when integrated with organic sources such as FYM and emerging inputs such as nano-fertilizers (Nano DAP), markedly enhanced maize yield and yield components across different fertility gradients. The higher productivity observed under STCR treatments may be attributed to the targeted yield strategy, which ensures efficient nutrient supply to the crop. Nitrogen application during the initial growth stages stimulates vegetative development, thereby favourably influencing yield potential through its key roles in chlorophyll formation and protein synthesis (12). Phosphorus was equally important, supporting energy transfer, metabolic processes and seed development, thereby contributing to increased yield. Potassium application improved both quantitative and qualitative aspects of maize performance. The significantly higher kernel and stover yields obtained under the STCR NPK+FYM treatment for the 100 q ha⁻¹ target could be ascribed to the balanced nutrient supply adjusted to crop demand and soil fertility status. Moreover, the incorporation of FYM improved soil structure, organic matter and microbial activity, leading to enhanced nutrient release and uptake (13). The superiority of STCR-based recommendations over conventional fertilizer doses and fertility rating approaches. STCR-guided nutrient management enhances nutrient use efficiency while sustaining crop productivity (14).

The higher yields achieved under the NPK + FYM approach at elevated yield targets, compared to NPK alone, can be attributed to the addition of FYM, which enhanced microbial activity and supplied sufficient carbon, thereby improving nutrient availability and contributing to greater crop growth and productivity (15). Although lower amounts of P fertilizer were applied in the STCR-based treatments compared with GRD and SFR, yields were significantly higher in the STCR plots. This highlights the efficient utilization of native soil P, suggesting that P fertilizer costs can be minimized when soils possess adequate available P.

The superior nutrient uptake and higher nutrient use efficiency achieved through the STCR approach, as compared to SFR and GRD, had a favorable impact on growth and yield attributes, thereby contributing to increased maize yield. In addition, the synergistic effect of combining organic and inorganic sources under the STCR NPK+FYM treatment likely improved soil chemical, physical and biological properties, thereby supporting higher productivity (16). The enhanced yield attributes of soybean under the STCR approach, relative to SFR, GRD and farmer's practice, were due to the balanced nutrient application based on soil test values

and the crop's nutrient requirement for achieving a predetermined yield target (17). Moreover, recent research supports the incorporation of nanofertilizers, such as nano-DAP, which offer controlled nutrient release, reduced nutrient losses and improved crop response at lower application rates (18).

The positive percent deviation recorded under the STCR NPK+FYM approach for both yield targets suggests that this method not only achieves but often surpasses the expected yield goals. This highlights the reliability and precision of STCR calculation in predicting and realizing targeted productivity. The consistency observed across different yield levels further demonstrates the robustness of the STCR methodology. Similar trends of lower percent deviation with the STCR approach have been documented in several crops, including groundnut (19), chickpea (20) and greengram (21). This cross-crop validation indicates that STCR principles are universally applicable and effective across different leguminous crops with varying nutrient requirements.

The superior performance of the STCR NPK+FYM approach over NPK alone highlights the synergistic effects of combining chemical fertilizers with organic sources. Such integration not only enhances nutrient availability but also contributes to better soil health, increased microbial activity and long-term sustainability of the cropping system. In contrast, the lower RYS values observed under the SFR approach may be due to its soil-focused strategy, which overlooks the crop's specific nutrient requirements. This approach merely adjusts recommended fertilizer doses based on soil test values, without accounting for the crop's actual nutrient demand to achieve specific yield targets, leading to either under- or over-fertilization.

The fact that even negative deviations in the STCR approach remained within $\pm 10\%$ tolerance limit validates the accuracy of the STCR equations. The equations with deviations within $\pm 10\%$ are considered reliable and do not require modification, confirming the suitability of the developed STCR equations for practical field application. Elevated RYS values under STCR treatments reflect superior nutrient use efficiency, which in turn leads to higher economic returns for farmers. This approach reduces fertilizer waste while maximizing yield potential, leading to enhanced profitability and sustainable farming practices. The balanced nutrient application through the STCR approach minimizes environmental risks associated with excessive fertilizer use, such as nutrient leaching, groundwater contamination and eutrophication. This contributes to sustainable agricultural practices while maintaining productivity (22).

The VCR values above 2.0 across all treatments indicate the economic viability of the nutrient management practices, with STCR approaches showing substantially higher profitability than

conventional fertilizer application methods. In the present study, STCR NPK+FYM treatments showed lower VCR compared to NPK alone. The higher VCR observed in NPK-only treatments may be attributed to reduced fertilizer application rates, which, together, were associated with relatively higher yields. Although STCR NPK+FYM treatments produced superior yield, their VCR remained lower, largely due to the high cost of phosphatic fertilizers and FYM used in these treatments. The STCR inorganic treatments for a 30 t ha⁻¹ yield target achieved higher VCR, while integrated treatments involving FYM recorded lower VCR owing to the additional cost of organic inputs (22).

STCR based nutrient management, especially STCR + FYM at the 100 q ha⁻¹ target (T₂), consistently increased N, P and K accumulation in both kernel and stover compared with GRD, SFR and the control, reflecting improved nutrient availability and uptake under balanced, soil-test-based applications (22). The addition of Nano DAP under STCR treatments further enhanced N and P concentrations and nutrient-use efficiency, likely due to better foliar delivery and greater surface-area effects of nanoscale formulations (23). FYM increased nutrient availability by improving soil OM, structure and microbial activity, thereby aiding P solubilization and K retention and supporting greater root proliferation and nutrient absorption (12). Observed increases in N uptake under STCR and split-application practices align with earlier findings that soil-test guidance and split N dressings minimize losses (denitrification, leaching) and enhance plant recovery (24). Overall, the combined use of STCR prescriptions, FYM and Nano DAP in the farmers' field produced a more synchronized supply-demand of nutrients, improving nutrient-use efficiency and resulting in higher uptake and yields compared with conventional recommendations (25).

The nutrient balance analysis revealed distinct trends in N, P and K across different nutrient management approaches. For N, STCR-based treatments, particularly STCR NPK + FYM at 100 q ha⁻¹ (T₂), showed higher uptake and more favorable balances than GRD and SFR. The higher uptake in T₂ (302.72 kg ha⁻¹) supports earlier findings that integration of organic manures with inorganic fertilizers enhances N availability and plant absorption by improving soil physical environment and microbial activity (12). However, the GRD (T₃) fell short of the maximum residual N, indicating inefficient uptake and a potential risk of nutrient losses, consistent with the low N use efficiency reported in Indian maize systems (5). For P, none of the treatments maintained a positive balance; all showed net losses. This reflects the inherent low P use efficiency of Indian soils due to fixation processes (26). Although STCR-based approaches (T₁ and T₂) improved P uptake compared to GRD and SFR, the overall depletion underscores the importance of integrated FYM use, which supplies organic acids and stimulates phosphatase activity, thereby releasing bound P (11). The relatively smaller depletion in the absolute control (-2.20 kg ha⁻¹) indicates that high-yield targeted fertilization accelerates soil P mining if not balanced with organic sources. In the case of K, all treatments recorded positive balances, suggesting that K mining was less critical than N and P under the experimental conditions. The highest uptake was again observed under T₂ (155.98 kg ha⁻¹), supported by balanced nutrient application and improved CEC resulting from FYM addition (25). Overall, the results emphasize that STCR-based nutrient management, integrated with FYM and Nano DAP, provided a more sustainable balance by improving nutrient uptake efficiency and maintaining higher residual nutrient levels than conventional recommendations. However, the

continued depletion of soil P indicates the need for sustained OM addition and careful monitoring to avoid long-term nutrient mining.

The successful cross-zonal validation of the targeted yield equations represents one of the most critical outcomes of this study. Demonstrating that fertilizer prescription models developed in one agro-ecological zone can perform effectively under a different soil and climatic condition confirms the robustness and adaptability of the STCR approach. This finding is significant because it suggests that such models are not confined to the location of development but can be transferred, calibrated and scaled across broader production landscapes.

From a practical perspective, this opens the door to regional or state-level deployment of soil-test-based fertilizer recommendation frameworks, reducing the need for repeated full-scale calibration experiments in every new location. Instead, future efforts may focus on fine-tuning through minor adjustments, such as integrating organic amendments, including nano-fertilizers, or stratifying soil fertility. Therefore, the success of this cross-zonal validation strengthens the feasibility of scaling STCR-based prescriptions and integrating them into precision nutrient management programs, ultimately supporting wider adoption, improved nutrient efficiency and sustainable maize production systems across diverse agro-climatic regions.

Conclusion

This investigation demonstrated that Soil Test Crop Response-based nutrient management is superior to conventional approaches, such as the GRD and SFR, in improving maize yield, nutrient uptake and use efficiency under farmers' field conditions in the STZ. Among treatments, STCR NPK + FYM at 100 q ha⁻¹ (T₂) consistently produced the highest kernel and stover yields, along with the highest N, P and K uptake. The balanced nutrient application based on soil test values, complemented by FYM, improved soil health and nutrient availability. Nutrient use efficiency indices confirmed the advantage of STCR-based practices, while the addition of Nano DAP further enhanced N and P uptake. Nutrient balance studies showed positive K balances but N and P depletion, highlighting the need for organics to sustain fertility. Overall, STCR equations proved robust and transferable across zones, offering a reliable, profitable and sustainable strategy for maize production.

Acknowledgements

We gratefully acknowledge the financial support provided by the Karnataka Science and Technology Promotion Society (KSTePS), Department of Science and Technology (DST), Government of Karnataka.

Authors' contributions

ANN conceptualized and designed the study, conducted the experiments, analyzed the data, interpreted the results and prepared the manuscript. He served as the corresponding author and coordinated all research activities. KMR provided critical guidance on experimental design, contributed to data interpretation and reviewed the manuscript. He supervised the implementation of balanced NPK fertilization techniques. TMN offered insights on agrometeorological factors affecting nutrient uptake and soil

sustainability and assisted in data analysis and interpretation related to environmental sustainability. SJ provided technical expertise in soil science and agricultural chemistry, refined the research methodology and critically reviewed and improved the manuscript. VP contributed to field-level implementation and data collection, assisted in soil and plant sample analysis and participated in manuscript review. BN assisted in editing and supervision during manuscript preparation. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

- Murdia LK, Wadhvani R, Wadhawan N, Bajpai P, Shekhawat S. Maize utilization in India: an overview. *Am J Food Nutr.* 2016;4(6):169-76.
- Devi V, Sethi M, Kaur C, Singh V, Kumar R, Chaudhary DP. Temporal profile of amino acids and protein fractions in the developing kernel of maize germplasm. *Sci Rep.* 2024;14(1):27161. <https://doi.org/10.1038/s41598-024-65514-2>
- Wang LQ, Ma DL, Liu HY, Hu SP, Yu XF, Gao JL. Soil fertility differences due to tillage methods modulate maize yield formation at different planting densities. *Sci Rep.* 2025;15(1):2437. <https://doi.org/10.1038/s41598-025-85924-0>
- Kiran SK, Prakash SS, Chamegowda TC, Krishnamurthy R, Yogananda SB, Asha NN. Root and yield parameters of maize as influenced by application of different biostimulants in Alfisols of Karnataka. *Int J Chem Stud.* 2020;8(6):829-33. <https://doi.org/10.22271/chemi.2020.v8.i6l.10873>
- Govindasamy P, Muthusamy SK, Bagavathiannan M, Mowrer J, Jagannadham PT, Maity A, et al. Nitrogen use efficiency-a key to enhance crop productivity under a changing climate. *Front Plant Sci.* 2023;14:1121073. <https://doi.org/10.3389/fpls.2023.1121073>
- Khan N, Ahmed ZI, Ahmed M, Jilani G, Ahmad S. Soil health and crop yield assessment for different cropping systems and nutrient management to determine sustainable management practices in a semi-arid region. *J Soil Sci Plant Nutr.* 2025;25(3):7420-38. <https://doi.org/10.1007/s42729-025-02604-8>
- Reddy KJ, Chandrashekhara CP, Biradar DP, Rajakumar GR, Kanannavar PS. Effect of soil test crop response and STCR-integrated plant nutrition system based fertilizer prescription equations on maize productivity, economics and soil fertility status in Vertisols of Northern Karnataka. *Int J Plant Soil Sci.* 2022;34(24):1-12. <https://doi.org/10.9734/ijpss/2022/v34i242607>
- Sary DH, Abd El-Aziz ME. Synthesis and characterization of nano-micronutrient fertilizer and its effect on nutrient availability and maize (*Zea mays* L.) productivity in calcareous soils. *Sci Rep.* 2025;15(1):25838. <https://doi.org/10.1038/s41598-025-11273-7>
- Asha KK, Jayadeva HM, Gangana Gowdra VM, Pruthviraj N, Kotresh DJ, Devika AR. Nutrient and energy conservation through nano-fertilizers in maize. *Plant Sci Today.* 2024;11(4).
- Basavaraja PK, Reddy PNN, Rajesh NL, Apoorva KB. Development of fertilizer prescription targeted yield equation for carrot crop based on soil test values. *J Horti Sci.* 2011;6(1):33-6. <https://doi.org/10.24154/jhs.v6i1.438>
- Rangaiah K, Bhavya N, Kasturappa G, Nanjundappa S, Uday SN, Srivastava S, et al. Assessment of fertilizer prescription equations, crop and soil performance with different nutrient management practices for green gram (*Vigna radiata*) in Southern India's Alfisols. *Sci Rep.* 2025;15:1-10. <https://doi.org/10.1038/s41598-025-04738-2>
- Isha, Gautam P, Chandra R. Soil test crop response-based site-specific integrated nutrient management in mungbean. *J Plant Nutr.* 2024;47(5):690-704. <https://doi.org/10.1080/01904167.2023.2280158>
- Aher SB, Lakaria BL, Kaleshananda S, Singh AB. Yield, nutrient uptake and economics of soybean-wheat cropping system under organic nutrient management in Central India. *J Plant Nutr.* 2022;45(6):904-19. <https://doi.org/10.1080/01904167.2021.1994600>
- Singh VK, Gautam P, Sen S. Soil test crop response-based fertilizer application improves soil fertility and wheat (*Triticum aestivum*) productivity grown after direct-seeded rice in Mollisols of northern India. *Commun Soil Sci Plant Anal.* 2025;1-23. <https://doi.org/10.1080/00103624.2025.2473630>
- Abhirami P, Maragatham S, Rajeswari R, Balachandar D, Vanitha K. Effect of integrated nutrient management practices on soil quality indicators and plant growth in greengram on Alfisol. *Int J Plant Sci.* 2023;35(18):1526-35. <https://doi.org/10.9734/ijpss/2023/v35i183422>
- Dhaliwal SS, Sharma V, Verma V, Kaur M, Singh P, Gaber A, et al. Impact of manures and fertilizers on yield and soil properties in a rice-wheat cropping system. *PLoS One.* 2023;18(11):e0292602. <https://doi.org/10.1371/journal.pone.0292602>
- Raghav RS, Singh YV, Kumar M, Dey P, Dubey S. Soil test crop response-based nutrient management in soybean (*Glycine max*) for higher productivity and profitability. *Indian J Agric Sci.* 2019;89(10):1660-63. <https://doi.org/10.56093/ijas.v89i10.94603>
- Subramanian KS, Manikandan A, Thirunavukkarasu M, Rahale CS. Nanofertilizers: synergistic nanotechnology tools for sustainable agriculture. *J Soil Sci Plant Nutr.* 2021;21(2):1047-60.
- Chari MS, Madhavi A, Sriyaya T, Dey P. Validation of soil test and yield target-based fertilizer prescription equations developed for groundnut in Alfisols. *Int J Chem Stud.* 2020;8(6):1252-56. <https://doi.org/10.22271/chemi.2020.v8.i6r.10934>
- Singh YV, Dey P, Meena R, Varma SK. Effect of soil test-based fertilizer application on yield and economics of chickpea in Inceptisol. *Ann Plant Sci.* 2016;18(4):409-12.
- Abhirami P, Maragatham S, Rajeswari R, Balachandar D, Vanitha K. Validation of soil test and yield target-based fertilizer prescription model developed for greengram on Alfisol. *Acta Sci Agric.* 2024;8(4):3-8.
- Krishna Murthy R, Bhavya N, Govinda K, Uday Kumar SN, Basavaraja PK, et al. Influence of different approaches and forms of fertilizer application on yield and nutrient uptake of hybrid maize. *Theor Biol Forum.* 2023;12(2):252-59. <https://doi.org/10.61739/TBF.2023.12.2.252>
- Raliya R, Saharan V, Dimkpa C, Biswas P. Nanofertilizer for precision and sustainable agriculture: current state and future perspectives. *J Agric Food Chem.* 2018;66(26):6487-503. <https://doi.org/10.1021/acs.jafc.7b02178>
- Krishna Murthy R, Bhavya N, Govinda K, Annappa NN, Basavaraja PK, Uday Kumar SN, et al. Inductive cum targeted yield model-based integrated fertilizer prescription for sweet corn (*Zea mays saccharata*) on Alfisols of southern India. *PLoS One.* 2024;19(8):e0307168. <https://doi.org/10.1371/journal.pone.0307168>
- Tiwari R, Upadhyay AK, Rai HK, Dey P. Impact of fertilizers and manure on growth, yield, nutrient uptake by rice and soil properties in Vertisol under soil test crop response approach. *Int Arch Appl Sci Technol.* 2020;11(2):57-65.
- Van de Wiel CC, van der Linden CG, Scholten OE. Improving phosphorus use efficiency in agriculture: opportunities for breeding. *Euphytica.* 2016;207:1-22. <https://doi.org/10.1007/s10681-015-1572-3>

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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