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RESEARCH ARTICLE

Assessment of combined influence of soil test crop response-based fertilizer recommendations and nano-fertilizers on post-harvest soil fertility in Alfisols of Karnataka

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Abstract

Maize (*Zea mays* L.) productivity in Alfisols is constrained by low organic matter, nutrient deficiencies and nutrient losses, requiring precision nutrient management. This study evaluated whether Soil test crop response-based (STCR) fertilizer prescriptions integrated with farmyard manure (FYM) and foliar nano-diammonium phosphate (nano-DAP) could improve post-harvest soil fertility across low, medium and high fertility strips at Zonal Agricultural Research Station (ZARS), Gandhi Krishi Vigyana Kendra (GKVK) (Bengaluru) and farmer fields in the Southern Transition Zone (Shivamogga) during *Rabi* 2024. A randomized complete block design with seven treatments (T_1–T_7: STCR nitrogen, phosphorus, potassium (NPK) at 90 and 100 q ha^{-1}, STCR NPK+FYM, General recommended dose, Soil fertility rating and absolute control) was used; soil physical, chemical and nutrient parameters were measured pre-sowing and at harvest. STCR combined with FYM (T_2, T_4) improved soil buffering, in the low fertility strip final pH in T_2 was 5.98 compared to 5.70 in STCR alone (T_1), a rise of 0.28 pH units and produced modest increases in soil organic carbon (T_2: 0.46 → 0.49 %, Δ = +0.03 %). Electrical conductivity increased marginally under fertilizer treatments but remained well below salinity risk (maximum observed ~0.095 dS m^{-1}). Residual nutrients varied by approach: blanket approaches (GRD, SFR) left higher post-harvest N and P (In the medium fertility strip available N in T_6 = 309 kg ha^{-1} vs T_2 = 226 kg ha^{-1}, Δ = +83 kg ha^{-1}; available P in T_6 = 441.6 kg ha^{-1} vs T_2 = 315.1 kg ha^{-1}, Δ = +126.5 kg ha^{-1}). Potassium depletion was minimized where FYM and STCR were combined. Overall, STCR integrated with FYM and targeted nano-DAP foliar applications enhanced post-harvest soil quality indicators and promoted more efficient nutrient management in Alfisols. These results support adoption of STCR-based integrated nutrient management for sustainable maize production in nutrient-deficient Alfisols of Karnataka.

Keywords: FYM; Maize; Nano-fertilizers; STCR

Introduction

Maize (*Zea mays* L.) is a major cereal crop and an important source of food, feed and industrial raw material (1). Its cultivation in Alfisols is particularly important due to their wide distribution in the semi-arid tropics of southern India (2). However, Alfisols are inherently low in organic matter, nutrient-deficient and prone to leaching, often resulting in nitrogen (N), phosphorus (P) and potassium (K) limitations for maize production (3). Therefore, efficient and balanced nutrient management is essential to sustain productivity. Site-specific fertilizer recommendations, especially those derived from the Soil test crop response approach, have shown promise in improving maize performance in such soils (4). In addition, integrating organic sources and nano-fertilizers can further enhance soil fertility and nutrient availability (5). Strengthening maize productivity in Alfisols not only promotes soil health but also improves farmer livelihoods and contributes to food and nutritional security in these regions (6). Despite this, the widespread use of conventional fertilizers in maize cultivation frequently results in low nutrient use efficiency, as substantial quantities of applied nutrients are lost through leaching, volatilization or fixation (7). Such inefficiencies increase production costs and contribute to soil degradation, nutrient imbalance and environmental concerns, especially in fragile Alfisols (8).

STCR equations provide a scientific basis for precision nutrient management by integrating soil test values with crop nutrient requirements and targeted yield levels (9). This approach ensures balanced nutrient supply, enhances nitrogen use efficiency (NUE) and helps maintain soil fertility, ultimately promoting sustainable maize production in Alfisols (10).

Nano-fertilizers such as nano-DAP have emerged as innovative inputs to enhance nutrient use efficiency by providing sustained nutrient release and reducing losses compared to conventional fertilizers (11). In the present study, the use of foliar nano-DAP in the STCR treatments contributed to lower post-harvest residual nitrogen and phosphorus compared to GRD and SFR approaches. Their ability to enhance nutrient uptake and crop performance is particularly relevant for nutrient-poor Alfisols (12). However, while both STCR and nano-fertilizers are individually promising technologies, their combined influence, especially on post-harvest soil fertility-remains insufficiently documented. Most existing studies have evaluated nano-fertilizers as supplements to blanket fertilizer doses, with limited research on their integration into STCR-based, soil test–guided nutrient prescriptions. We hypothesize that integrating STCR-based nutrient prescriptions with farmyard manure and foliar nano-DAP applications will enhance nutrient use efficiency, maintain or improve post-harvest soil fertility indicators (pH, EC, organic carbon and available NPK) and reduce residual nutrient accumulation compared to conventional fertilizer recommendation approaches. Given this knowledge gap, the present study was undertaken to assess the combined effect of STCR-based fertilizer recommendations and nano-DAP application on post-harvest soil fertility in Alfisols of Karnataka.

Materials and Methods

Experimental site

The verification trials with maize (Phase III) were conducted during *Rabi 2024* in Low Fertility Strips (LFS), Medium Fertility Strips (MFS) and High Fertility Strips (HFS) under the AICRP on STCR at the ZARS, University of Agricultural Sciences, GKVK Bengaluru and in farmers fields of the Southern Transition Zone, Shivamogga. The experimental site at GKVK lies in the Eastern Dry Zone (Zone 5) of Karnataka, geographically situated at 13 ° 04' 55.2'' N latitude and 77 ° 34' 10.0'' E longitude, with an altitude of 930 m above Mean Sea Level. The farmers field in Shivamogga is located at 14 ° 03' 06.9'' N latitude and 75 ° 14' 54.7'' E longitude, with an altitude of 654 m above Mean Sea Level.

Low fertility strip– ZARS, GKVK, Bengaluru

The soil texture in the LFS was sandy loam, with a composition of 68.50 % sand, 13.40 % silt and 18.10 % clay. The bulk density was 1.35 Mg m^{-3} and the maximum water holding capacity was 35.80 %. The soil was slightly acidic (pH 6.29) with low salinity (EC 0.22 dS m^{-1}) and moderate organic carbon (4.70 g kg^{-1}). The cation exchange capacity (CEC) was 9.80 cmol (p^+) kg^{-1}, indicating moderate nutrient retention. The available nitrogen was 195.57 kg ha^{-1} (low), phosphorus 215.01 kg ha^{-1} (high) (Bray's and Kurtz extractant method) and potassium 147.64 kg ha^{-1} (medium). Secondary nutrients included 28.53 mg kg^{-1} sulphur, 4.57 cmol (p^+) kg^{-1} calcium and 1.51 cmol (p^+) kg^{-1} magnesium. Micronutrient levels were moderate, with 6.21 mg kg^{-1} iron, 6.92 mg kg^{-1} manganese, 1.14 mg kg^{-1} copper and 4.12 mg kg^{-1} zinc.

Medium fertility strip– ZARS, GKVK, Bengaluru

The Medium Fertility Strip also had a sandy loam texture, with 67.95 % sand, 13.55 % silt and 18.50 % clay. The bulk density was slightly lower (1.33 Mg m^{-3}) than LFS, while water retention improved (36.47 %). The soil pH (6.25) and EC (0.25 dS m^{-1}) remained near-neutral. Organic carbon was marginally higher (4.72 g kg^{-1}) and CEC increased to 10.21 cmol (p^+) kg^{-1}. Nutrient availability showed improvement: nitrogen (237.87 kg ha^{-1}, low), phosphorus (372.66 kg ha^{-1}, high) (Brays and kurtz extractant method) and potassium (239.04 kg ha^{-1}, medium). Sulphur (31.93 mg kg^{-1}), calcium (4.83 cmol (p^+) kg^{-1}) and magnesium (1.74 cmol (p^+) kg^{-1}) were slightly higher than in LFS. Micronutrients exhibited minor increases: 6.62 mg kg^{-1}iron, 7.35 mg kg^{-1} manganese, 1.18 mg kg^{-1} copper and 4.45 mg kg^{-1} zinc.

High fertility strip– ZARS, GKVK, Bengaluru

The High Fertility Strip maintained a sandy loam texture but with finer particles (67.90 % sand, 13.30 % silt, 18.80 % clay). Bulk density further decreased (1.31 Mg m^{-3}) and water holding capacity peaked at 37.10 %. Soil pH (6.21) and EC (0.31 dS m^{-1}) indicated stable conditions. Organic carbon (4.78 g kg^{-1}) and CEC (10.35 cmol (p^+) kg^{-1}) were the highest among the strips. Nitrogen availability increased to 305.97 kg ha^{-1} (medium), phosphorus to 447.03 kg ha^{-1} (high) (Brays and kurtz extractant method) and potassium to 315.86 kg ha^{-1} (medium). Secondary nutrients-sulphur (32.94 mg kg^{-1}), calcium (5.10 cmol (p^+) kg^{-1}) and magnesium (1.79 cmol (p^+) kg^{-1})-were optimal. Micronutrient levels were notably higher: 9.48 mg kg^{-1}iron, 7.79 mg kg^{-1} manganese, 1.22 mg kg^{-1} copper and 5.01 mg kg^{-1} zinc, suggesting better fertility.

Climate and weather

The experimental sites fall under a dry tropical savanna climate, characterized by moderately hot summers, cool winters and an average annual rainfall of about 916 mm. In Shivamogga, representing the Southern Transition Zone, the climate is tropical savanna with an annual rainfall of approximately 1,042 mm, mostly during the monsoon season. During the fertility gradient experiment at Bengaluru (July–September 2023), 335 mm rainfall was received, with temperatures ranging between 19.6 and 30.5 °C. The main test crop experiment conducted in *Rabi* 2023 at Bengaluru received 222.8 mm rainfall, with temperatures between 18.1 and 31.4 °C, providing favourable conditions for maize growth. In the *Rabi* 2024 verification trial at Bengaluru, the site received 724.6 mm rainfall, with temperatures ranging from 15.2 to 29.4 °C and high relative humidity (86-89 %). At Shivamogga during the same season, rainfall was 178.4 mm, with temperatures varying from 15.2 to 32.2 °C and bright sunshine hours extending between 5.7 and 9.2 hrs.

Design and layout of the experiment

The verification trial was conducted during *Rabi 2024* at the field unit of AICRP on STCR, ZARS, GKVK, Bengaluru and in farmers' fields of the Southern Transition Zone, Shivamogga. The experiment was laid out in a Randomized Complete Block Design with seven treatments replicated thrice and the layout plan is presented in Fig. 1. Maize variety MAH 14-5 was grown at a spacing

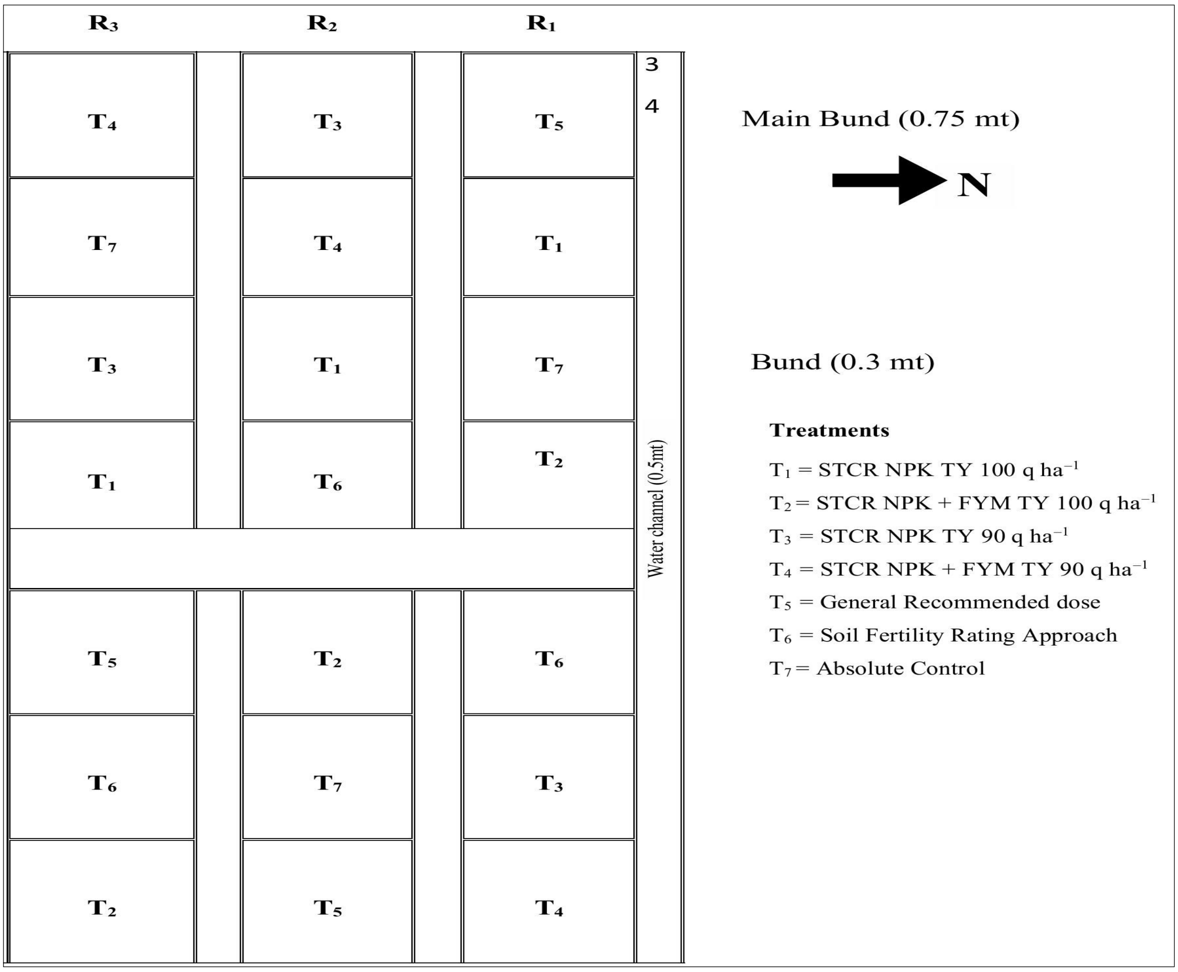

Fig. 1. Layout plan of the verification trial.

of 60 cm × 30 cm using a seed rate of 15 kg ha^{-1}. The plot size was maintained at 5.5 m × 2.2 m at ZARS, Bengaluru and 4.5 m x 3.0 m in the farmers' fields at Shivamogga. The Recommended Dose of Fertilizers consisted of 150:75:37.5 kg N, P_2O_5 and K_2O ha^{-1}, along with 7.5 t ha^{-1} of FYM and 10 kg ha^{-1} of zinc sulphate.

Fertilizer schedule

Nitrogen, phosphorus and potassium were applied through urea, Single superphosphate (SSP) and Muriate of potash (MOP). 75 % of Recommended dose of nitrogen (RDN) will be supplied through conventional fertilizers (50 % of 75 % RDN at sowing, 25 % of 75 % RDN at 45 Days after sowing (DAS) and remaining 25 % of 75 % RDN at 75 DAS) and foliar application of Nano fertilizers at 30 DAS and 60 DAS through Nano DAP @ 4mL L^{-1}. 75 % of Recommended dose of phosphorus (RDP) was supplied through conventional fertilizers at basal and foliar application of nano DAP at 30 DAS and 60 DAS @4 mL L^{-1}. 100 % of Recommended dose of potassium (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 to 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 based on the package of practices in the recommended dose of fertilizers (RDF) method, whereas RDF was adjusted in the low, medium and high (LMH) or soil test laboratory (STL) approach based on soil test values.

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 (SFR)

T_7: Absolute Control

STCR fertilizer prescription targeted yield equations for maize.

The soil test values NPK fertilizer nutrients were applied for specific yield targets in STCR and SFR approach. The amount of nutrients applied per hectare through different approaches as per the treatments are presented in Fig. 2, 3, 4 and 5 and the data was provided in supplementary table 1 to 4.

Using the basic parameters, separate fertilizer prescription equations were developed for the NPK-only and NPK+FYM approaches (Table 1). 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 yield potential attainable when optimal agronomic practices are adopted.

Table 1. Targeted yield equations developed for maize

Fertilizer nutrients (kg ha^{-1})	NPK alone	NPK+FYM
F.N.	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
F.P.	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
F.K.	0.89 T – 0.16 STV (Am.Ace.K)	0.87 T – 0.15 STV (NH$_4$OAc–K) – 1.41 OM

Source of OM: Farmyard manure

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 (KMnO$_4$-N), STV (Bray's-P) and STV (NH$_4$OAc–K) are available soil nutrients as KMnO$_4$-N, Bray's-P and NH$_4$OAc-K in kg ha^{-1}, respectively and OM is amount of farmyard manure (organic manure) added in t ha^{-1}.

Fig. 2. Quantity of fertilizer nutrients and farmyard manure applied per hectare through different approaches as per the treatments and soil test values during *rabi* 2024 for low fertility strips at ZARS GKVK, Bengaluru.

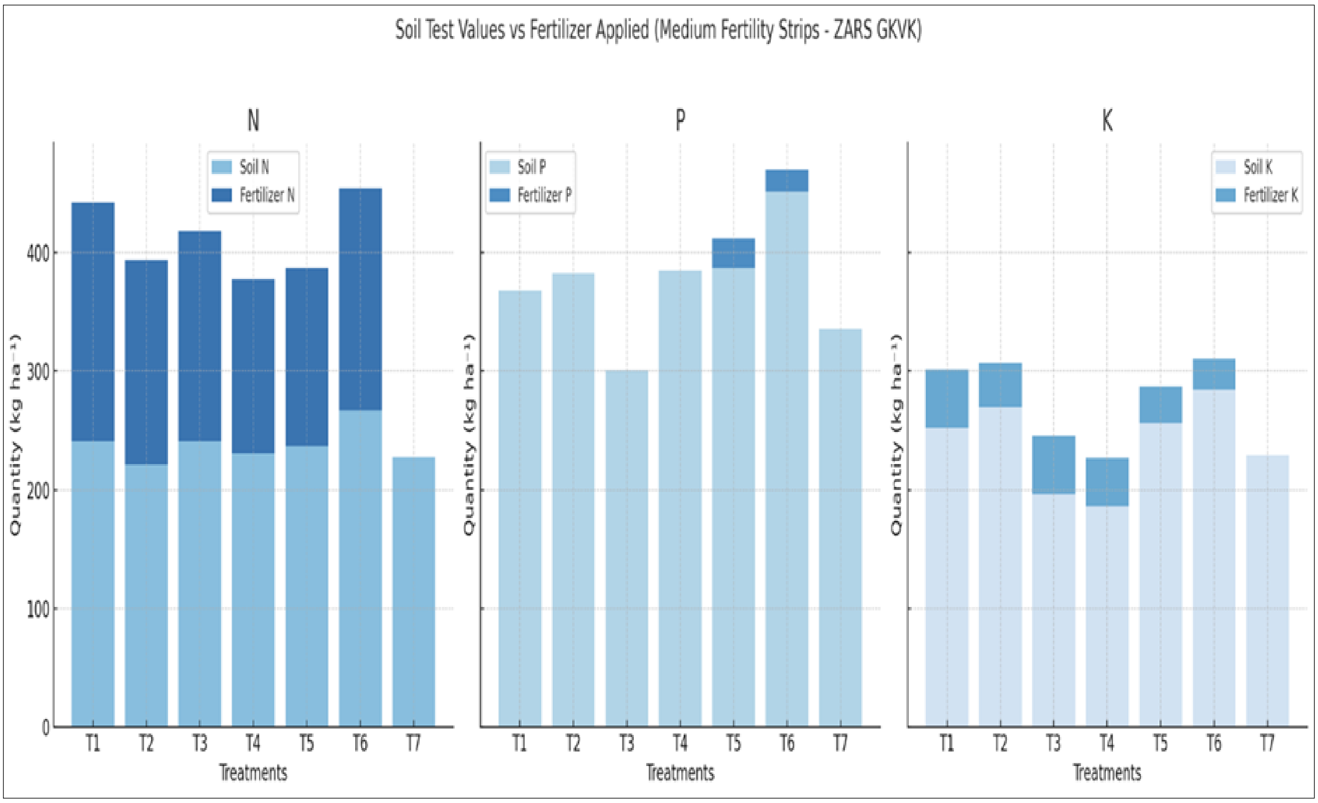

Fig. 3. Quantity of fertilizer nutrients and farmyard manure applied per hectare through different approaches as per the treatments and soil test values during *rabi* 2024 for medium fertility strips at ZARS GKVK, Bengaluru.

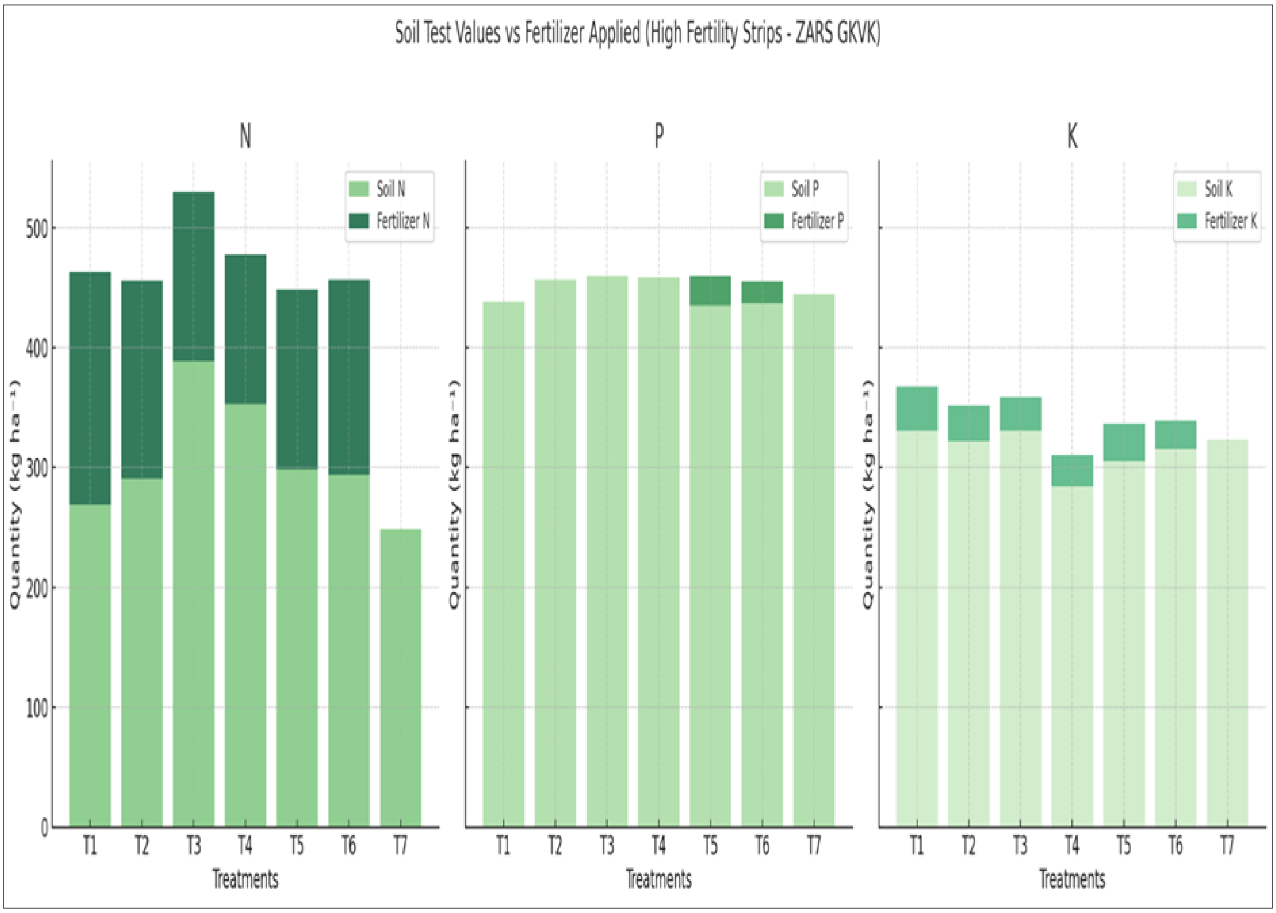

Fig. 4. Quantity of fertilizer nutrients and farmyard manure applied per hectare through different approaches as per the treatments and soil test values during *rabi* 2024 for high fertility strips at ZARS GKVK, Bengaluru.

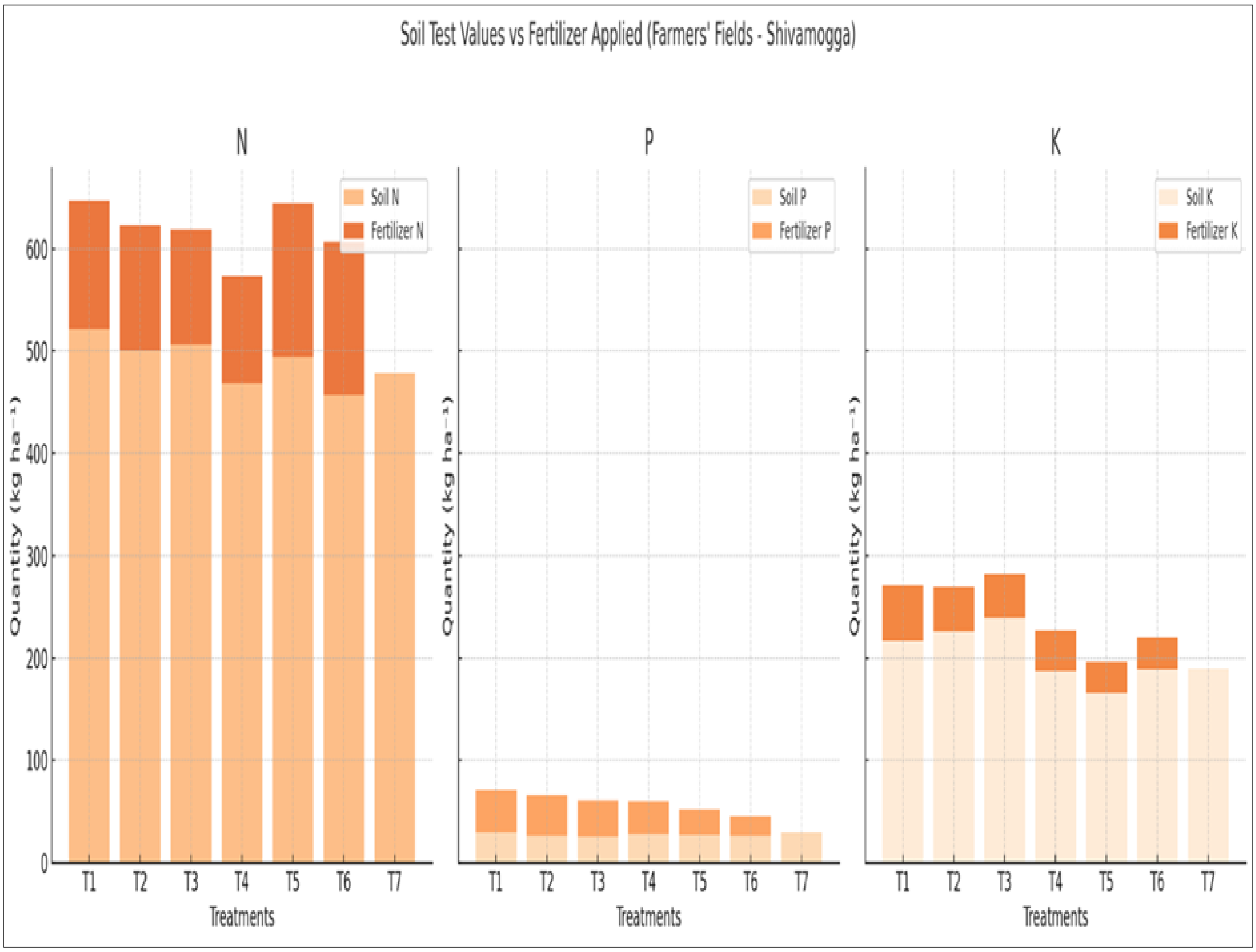

Fig. 5. Quantity of fertilizer nutrients and farmyard manure applied per hectare through different approaches as per the treatments and soil test values during *rabi* 2024 at farmers fields in the Southern Transition Zone, Shivamogga.

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 wooden mallet and sieved through 2 mm sieve (0.2 mm for organic carbon), labelled and stored in Polyvinyl chloride (PVC) boxes. Pre-sowing and post-harvest soil samples from verification trial were analyzed for various physical, physico-chemical and chemical properties. The details of analytical procedures followed in the analysis of soil samples are furnished in Table 2.

Statistical analysis of data

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

Results

Effect of various fertilizer recommendation approaches on post-harvest soil chemical properties

The Table 3 presents the post-harvest soil pH and electrical conductivity values under various nutrient application approaches.

Soil pH

Post-harvest soil pH showed variation across the fertility strips when compared to their respective initial values, suggesting an overall improvement in soil reaction as a result of crop cultivation and nutrient application.

In the low fertility strip, significantly lower soil pH (5.70) was recorded in T$_1$[STCR NPK (100 q ha^{-1})], whereas the highest pH (6.32) was observed in T$_7$[absolute control], where no fertilizers were applied. Treatments T$_2$ [STCR NPK + FYM (100 q ha^{-1})] and T$_4$ [STCR NPK + FYM (90 q ha^{-1})] showed improved pH levels (5.98 and 5.87, respectively) compared to T$_1$, suggesting the buffering capacity contributed by FYM addition. In the medium fertility strip, a similar trend was noted, where T$_1$ recorded a relatively lower pH (6.07), while T$_4$ (6.59), T$_2$ (6.49) and T$_5$ [general recommended dose] (6.65) exhibited higher post-harvest pH levels. However, the differences among treatments were statistically significant only in LFS and MFS. In the high fertility strip, though the differences were not statistically significant, the highest pH (6.51) was recorded in T$_6$ [soil fertility rating approach], followed closely by T$_5$ [general recommended dose] (6.49) and T$_2$ [STCR NPK + FYM (100 q ha^{-1})] (6.28), while T$_1$[STCR NPK (100 q ha^{-1})] registered a comparatively lower value (6.12). Similarly, in the farmers' field (Southern Transition Zone (STZ), Shivamogga), the soil pH varied from a minimum of 4.82 in T$_1$ to a maximum of 5.10 in T$_7$ [Absolute Control]. Among the fertilizer-treated plots, T$_2$ [STCR NPK + FYM (100 q ha^{-1})] (5.01) and T$_4$ [STCR NPK + FYM (90 q ha^{-1})] (4.97) showed a slight improvement in pH compared to T$_1$ [STCR NPK (100 q ha^{-1})] and T$_3$ [STCR NPK (90 q ha^{-1})] (4.89), highlighting the advantage of including FYM in nutrient management practices.

Soil electrical conductivity (EC)

The results showed an increase in electrical conductivity of post-harvest soil across all treatments when compared to their respective initial values, both in the fertility strips and in the farmer's field at STZ, Shivamogga (Table 3). Among the treatments, a slight increase in EC

Table 2. Methods adopted for soil analysis

Parameters	Methods	References
	Chemical properties	
pH (1:2.5)	Potentiometric method	(13)
EC (1:2.5)	Conductometric method	(13)
Organic carbon (g kg^{-1})	Wet oxidation method	(14)
Available nitrogen (kg N ha^{-1})	Alkaline potassium permanganate Method	(15)
Available phosphorous (kg P_2O_5 ha^{-1})	Bray's extractant using spectrophotometer	(13)
Available potassium (kg K_2O ha^{-1})	Ammonium acetate extractant using Flame photometer	(13)

Table 3. Influence of different approaches of nutrient application on soil pH and electrical conductivity (dS m^{-1}) of post-harvest soil of maize

Treatment details	Soil pH (1:2.5)								Electrical Conductivity (dS m^{-1})							
	LFS		MFS		HFS		Farmer field, STZ, Shivamogga		LFS		MFS		HFS		Farmer field, STZ, Shivamogga	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
T$_1$ STCR NPK Targeted Yield 100 q ha^{-1}	5.79	5.70	6.15	6.07	6.17	6.12	4.86	4.82	0.020	0.031	0.031	0.046	0.015	0.031	0.065	0.077
T$_2$ STCR NPK + FYM Targeted Yield 100 q ha^{-1}	5.94	5.98	6.45	6.49	6.20	6.28	4.99	5.01	0.019	0.035	0.020	0.035	0.016	0.035	0.063	0.069
T$_3$ STCR NPK Targeted Yield 90 q ha^{-1}	6.07	6.01	6.12	6.10	6.22	6.18	4.90	4.89	0.018	0.039	0.022	0.043	0.022	0.038	0.085	0.091
T$_4$ STCR NPK + FYM Targeted Yield 90 q ha^{-1}	5.79	5.87	6.56	6.59	6.13	6.19	4.94	4.97	0.017	0.045	0.027	0.031	0.023	0.040	0.079	0.087
T$_5$ General Recommended dose	6.05	6.09	6.62	6.65	6.45	6.49	4.91	4.96	0.015	0.029	0.019	0.027	0.026	0.031	0.066	0.070
T$_6$ Soil Fertility Rating Approach	6.15	6.20	5.99	6.00	6.47	6.51	4.97	4.99	0.017	0.047	0.020	0.023	0.023	0.035	0.091	0.095
T$_7$ Absolute control	6.29	6.32	6.25	6.29	6.43	6.47	5.08	5.10	0.019	0.029	0.022	0.031	0.028	0.030	0.074	0.081
SE	-	0.10	-	0.11	-	0.12	-	0.16		0.01	-	0.02	-	0.01	-	0.01
C.D. @ 5 %	-	0.29	-	0.30	-	NS	-	NS		NS	-	NS	-	NS	-	NS

NS: Non-Significant

was observed even in the control plot (T$_7$), where no fertilizers were applied, with values rising from 0.019 to 0.029 dS m^{-1} in LFS, from 0.022 to 0.031 dS m^{-1} in MFS, from 0.028 to 0.030 dS m^{-1} in HFS and from 0.074 to 0.081 dS m^{-1} in Farmer field, STZ, Shivamogga. Treatments receiving fertilizers in combination with FYM recorded higher EC values, particularly in T$_6$ [soil fertility rating approach] and T$_4$ [STCR NPK + FYM (90 q ha^{-1})]. In the LFS, the EC increased from 0.017 to 0.047 dS m^{-1} in T$_6$ and from 0.017 to 0.045 dS m^{-1} in T$_4$. Similarly, in MFS, EC values reached 0.043 dS m^{-1} in T$_3$ and 0.035 dS m^{-1} in T$_2$, compared to 0.027 dS m^{-1} in the general recommended dose (T$_5$). Although the differences in HFS were not significant statistically, numerically higher EC values (0.040 dS m^{-1}) were observed in T$_4$ and 0.038 dS m^{-1} in T$_3$, compared to 0.031 dS m^{-1} in T$_1$ and T$_5$. In the farmers' field at STZ, Shivamogga, high EC values were recorded in T$_6$ (0.095 dS m^{-1}) and 0.091 dS m^{-1} in T$_3$, as compared to 0.081 dS m^{-1} in absolute control (T$_7$). The lowest EC (0.069 dS m^{-1}) was found in T$_2$ [STCR NPK + FYM (100 q ha^{-1})], suggesting the regulatory effect of organic inputs on salt accumulation.

Soil organic carbon

The results showed an increase in organic carbon of post-harvest soil across all treatments relative to the initial values; however, the differences among treatments were not statistically significant (Table 4). In the low fertility strip, STCR NPK for the targeted yield of 100 q ha^{-1} (T$_1$) and STCR NPK + FYM for the targeted yield of 100 q ha^{-1} (T$_2$) resulted in a small but noticeable enhancement in organic carbon content from 0.42 % to 0.45 % and from 0.46 % to 0.49 %, respectively. Similarly, in the medium fertility strip, T$_1$ (0.43 % to 0.45 %) and T$_5$ [general recommended dose] (0.45 % to 0.49 %) showed moderate increases in organic carbon. In the high fertility strip, organic carbon values were slightly higher, with T$_1$ and T$_4$ recording 0.44 % to 0.46 % and 0.43 % to 0.46 %, respectively. T$_3$ (0.42 % to 0.45 %) and T$_5$ (0.44 % to 0.45 %) exhibited similar trends, showing small increases in organic carbon. In the Farmer field, STZ, Shivamogga, the absolute control (T$_7$) exhibited a moderate increase in organic carbon from 0.93 % to 0.96 %, while other treatments, such as T$_3$ [STCR NPK (90 q ha^{-1})] (1.20 % to 1.19 %) and T$_4$ [STCR NPK + FYM (90 q ha^{-1})] (1.17 % to 1.20 %) demonstrated a limited increase in organic carbon concentration compared to the control.

Available nitrogen

The available nitrogen content in post-harvest soil showed notable variation across the different fertilizer recommendation treatments and fertility strips, with the differences largely influenced by the initial soil nutrient levels and the quantity of fertilizer applied (Table 5).

n low fertility strip, significantly higher (238.84 kg ha^{-1}) available nitrogen was recorded in soil fertility rating approach (T$_6$) compared to absolute control (T$_7$) where the available nitrogen was 115.16 kg ha^{-1}, general recommended dose [T$_5$] (214.72 kg ha^{-1}), STCR NPK+FYM (90 q ha^{-1}) [T$_4$] (200.63 kg ha^{-1}), STCR NPK (90 q ha^{-1}) [T$_3$] (214.73 kg ha^{-1}) and STCR NPK+FYM (100 q ha^{-1}) [T$_2$] (205.72 kg ha^{-1}) but it was found to be on par with STCR NPK (100 q ha^{-1}) [T$_1$] (234.53 kg ha^{-1}). In medium fertility soils, the soil fertility rating approach (T$_6$) registered higher available nitrogen content of 309.00 kg ha^{-1}, significantly higher than all other treatments. The absolute control (T$_7$) recorded the lowest value at 153.64 kg ha^{-1}, while other treatments, STCR NPK + FYM (100 q ha^{-1}) [T$_2$] at 226.00 kg ha^{-1}, STCR NPK + FYM (90 q ha^{-1}) [T$_4$] at 219.00 kg ha^{-1}, STCR NPK (90 q ha^{-1}) [T$_3$] at 253.40 kg ha^{-1}, the general recommended dose [T$_5$] at 252.00 kg ha^{-1} and STCR NPK (100 q ha^{-1}) [T$_1$] at 275.98 kg ha^{-1}. In high fertility soils, STCR NPK (90 q ha^{-1}) [T$_3$] (370.67 kg ha^{-1}), which was significantly greater than all other treatments. The absolute control (T$_7$) showed the lowest nitrogen content (174.04 kg ha^{-1}), while remaining treatments exhibited varying levels: STCR NPK + FYM (100 q ha^{-1}) [T$_2$: 281.68 kg ha^{-1}), STCR NPK + FYM (90 q ha^{-1}) [T$_4$: 311.77 kg ha^{-1}), the soil fertility rating approach (T$_6$) recorded the available nitrogen content of 305.73 kg ha^{-1}, the general recommended dose [T$_5$: 298.87 kg ha^{-1}) and STCR NPK (100 q ha^{-1}) [T$_1$: 282.31 kg ha^{-1}). Notably, none of these treatments matched the performance of T$_3$, highlighting its effectiveness in improving soil nitrogen availability under high fertility conditions.

In the farmers field of the southern transition zone, Shivamogga, the significantly higher available nitrogen (468.73 kg ha^{-1}) was recorded under the general recommended dose [T$_5$]. This was substantially higher than the values observed in the absolute control (T$_7$) (336.35 kg ha^{-1}), STCR NPK + FYM (100 q ha^{-1}) [T$_2$: 406.72 kg ha^{-1}), STCR NPK+FYM (90 q ha^{-1}) [T$_4$: 366.97 kg ha^{-1}), STCR NPK (90 q ha^{-1}) [T$_3$: 418.70 kg ha^{-1}), STCR NPK (100 q ha^{-1}) [T$_1$: 423.30 kg ha^{-1}) and soil fertility rating approach (T$_6$: 421.41 kg ha^{-1}). Although treatments T$_1$, T$_3$ and T$_6$ recorded numerically comparable values, none were statistically on par with T$_5$.

Available phosphorus

The available phosphorus content in the soil showed significant variation under different fertilizer recommendation approaches (Table 5). In low fertility soils, significantly higher available phosphorus was recorded in the general recommended dose (T$_5$), which registered 251.50 kg ha^{-1} in relation to the other treatments. The STCR NPK + FYM for 100 q ha^{-1} (T$_2$) treatment resulted in 130.45 kg ha^{-1}, indicating the higher uptake of phosphorus. while the absolute control (T$_7$) recorded 191.44 kg ha^{-1}, indicating a decline from its initial value. In medium fertility soils, the highest available phosphorus was observed in the soil fertility rating approach (T$_6$), which recorded 441.59 kg ha^{-1}, significantly higher than all other treatments. This was followed by T$_5$ (general recommended dose) with 394.15 kg ha^{-1}and the NPK+FYM treatments T$_4$ and T$_2$, which recorded 321.79 and 315.12 kg ha^{-1}, respectively.

In high fertility soils, the general recommended dose (T$_5$) recorded significantly higher available phosphorus (427.89 kg ha^{-1})

Table 4. Influence of different approaches of nutrient application on organic carbon (%) of post-harvest soil of maize

Treatment details		organic carbon (%)							
		LFS		MFS		HFS		Farmer field, STZ, Shivamogga	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final
T$_1$	STCR NPK Targeted Yield 100 q ha^{-1}	0.42	0.45	0.43	0.45	0.44	0.46	1.08	1.10
T$_2$	STCR NPK + FYM Targeted Yield 100 q ha^{-1}	0.46	0.49	0.46	0.50	0.45	0.45	1.05	1.09
T$_3$	STCR NPK Targeted Yield 90 q ha^{-1}	0.40	0.42	0.41	0.44	0.42	0.45	1.20	1.19
T$_4$	STCR NPK + FYM Targeted Yield 90 q ha^{-1}	0.41	0.45	0.42	0.46	0.43	0.46	1.17	1.20
T$_5$	General Recommended dose	0.45	0.49	0.45	0.46	0.44	0.45	1.14	1.16
T$_6$	Soil Fertility Rating Approach	0.50	0.51	0.49	0.49	0.49	0.50	1.08	1.10
T$_7$	Absolute control	0.45	0.47	0.45	0.46	0.45	0.47	0.93	0.96
SE		-	0.09	-	0.08	-	0.09	-	0.09
C.D. @ 5 %		-	NS	-	NS	-	NS	-	NS

Table 5. Influence of different approaches of fertilizer recommendations on available nitrogen and available phosphorus status of post-harvest soil of maize

Treatment details		Available Nitrogen (kg ha^{-1})								Available Phosphorus (kg ha^{-1})							
		LFS		MFS		HFS		Farmer field, STZ, Shivamogga		LFS		MFS		HFS		Farmer field, STZ, Shivamogga	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
T_1	STCR NPK Targeted Yield 100 q ha^{-1}	191.16	234.53	241.17	275.98	269.17	282.31	521.55	423.30	218.08	158.39	367.63	301.12	438.24	371.50	29.89	40.01
T_2	STCR NPK + FYM Targeted Yield 100 q ha^{-1}	205.78	205.72	221.01	226.00	290.45	281.68	500.64	406.72	188.74	130.45	382.21	315.12	456.60	386.45	26.86	35.92
T_3	STCR NPK Targeted Yield 90 q ha^{-1}	184.41	214.73	241.17	253.40	388.64	370.67	506.61	418.70	211.48	153.66	300.62	239.87	459.63	388.38	25.92	29.86
T_4	STCR NPK + FYM Targeted Yield 90 q ha^{-1}	218.01	200.63	230.72	219.00	352.80	311.77	468.91	366.97	198.60	144.50	384.48	321.79	458.69	394.57	28.19	28.47
T_5	General Recommended dose	198.23	214.72	237.07	252.00	298.29	298.87	494.29	468.73	245.93	251.50	386.94	394.15	435.02	427.89	27.62	30.12
T_6	Soil Fertility Rating Approach	184.79	238.84	266.56	309.00	293.81	305.73	456.59	421.41	227.75	220.17	451.11	441.59	436.92	417.32	26.86	25.46
T_7	Absolute control	186.65	115.16	227.36	153.64	248.64	174.04	478.24	336.35	214.48	191.44	335.64	312.59	444.11	405.23	29.51	18.92
SE		-	6.20	-	7.41	-	9.08	-	11.54	-	7.44	-	15.05	-	16.54	-	1.56
C.D. @ 5 %		-	17.67	-	21.12	-	25.87	-	32.87	-	21.19	-	42.88	-	47.14	-	4.45

compared to STCR NPK for 100 q ha^{-1} targeted yield [T_1] (371.50 kg ha^{-1}). The soil fertility rating approach (T_6) (417.32 kg ha^{-1}), STCR NPK + FYM for 90 q ha^{-1} (T_4) (394.57 kg ha^{-1}) and all other treatments showed on par results of available phosphorus with T_5 (general recommended dose). In the Farmer field, STZ, Shivamogga (farmers field), the STCR NPK for targeted yield of 100 q ha^{-1} (T_1) resulted in the significantly higher available phosphorus content of 40.01 kg ha^{-1} compared to all other treatments except STCR NPK + FYM for targeted yield of 100 q ha^{-1} (T_2) with 35.92 kg ha^{-1}, which showed on par results with T_1.

Available potassium

The available potassium content in soil varied significantly across the different nutrient recommendation approaches (Table 6). At the end of the maize cropping season, the available potassium content in the post-harvest soil showed significant variation across treatments in all fertility strips. In low fertility soils, the higher available potassium was recorded in the general recommended dose treatment [T_5] with 160.47 kg ha^{-1}, which was significantly higher than the absolute control [T_7: 87.59 kg ha^{-1}) and all other treatments except STCR NPK (100 q ha^{-1}) (T_1: 151.20 kg ha^{-1}), which was on par with each other. In medium fertility soils, the highest available potassium was found in the soil fertility rating-based approach [T_6: 251.27 kg ha^{-1}), which recorded a significantly greater value than all other treatments, except general recommended dose [T_5: 241.28 kg ha^{-1}] and STCR NPK+ FYM for targeted yield of 100 q ha^{-1} [T_2: 235.85 kg ha^{-1}]. The lowest value was recorded in absolute control [T_7: 178.28 kg ha^{-1}]. In high fertility soils, the potassium content was significantly higher in STCR NPK (90 q ha^{-1}) [T_3] with 293.79 kg ha^{-1} compared to STCR NPK+FYM for the targeted yield of 90 q ha^{-1}[T_4] and all other treatments were on par with T_3 [STCR NPK (90 q ha^{-1})]. The absolute control [T_7] recorded the lowest value (269.83 kg ha^{-1}) among all treatments. Similarly, in the Farmer field, STZ farmers field, Shivamogga, the highest post-harvest potassium content was observed in STCR NPK (90 q ha^{-1}) [T_3] with 171.43 kg ha^{-1}, which was significantly higher than the absolute control [T_7: 107.86 kg ha^{-1}] and

Table 6. Influence of different approaches of fertilizer recommendations on available potassium status of post-harvest soil of maize

Treatment details		Available Potassium (kg ha^{-1})							
		LFS		MFS		HFS		Farmer field, STZ, Shivamogga	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final
T_1	STCR NPK Targeted Yield 100 q ha^{-1}	152.89	151.20	252.12	231.25	330.67	290.49	216.50	154.19
T_2	STCR NPK + FYM Targeted Yield 100 q ha^{-1}	141.50	129.31	269.55	235.85	322.01	274.81	226.27	148.85
T_3	STCR NPK Targeted Yield 90 q ha^{-1}	144.29	140.29	196.41	190.73	330.71	293.79	239.63	171.43
T_4	STCR NPK + FYM Targeted Yield 90 q ha^{-1}	145.12	132.56	186.25	164.78	283.99	237.89	186.97	109.82
T_5	General Recommended dose	167.93	160.47	255.94	241.28	305.27	286.61	165.27	110.46
T_6	Soil Fertility Rating Approach	147.77	129.51	284.13	251.27	315.40	281.75	188.90	128.74
T_7	Absolute control	133.96	87.59	228.85	178.28	323.00	269.83	189.37	107.86
SE		-	4.08	-	6.34	-	8.92	-	4.54
C.D. @ 5 %		-	11.62	-	18.08	-	25.43	-	12.94

other treatments.

Discussion

Soil pH was found to be higher under the NPK+FYM approach compared to NPK alone, irrespective of the yield target. The rise in pH can be ascribed to the release of basic cations such as calcium, magnesium and potassium during the decomposition of FYM, which helps in neutralizing soil acidity. In addition, the organic matter contributed by FYM improves soil structure, stimulates microbial activity and enhances the buffering capacity of the soil. This improved buffering effect contributes to the stabilization of soil pH, thereby explaining the observed increase.

Among the treatments, plots receiving STCR-based fertilizer recommendations integrated with FYM (T2 and T4) consistently exhibited higher post-harvest soil pH values than those receiving only chemical fertilizers (T1 and T3). This finding is consistent with previous reports (16, 17), which indicate that FYM incorporation enhances soil buffering capacity, reduces the acidifying effects of mineral fertilizers and contributes to long-term soil pH stabilization.

In contrast, plots under T1 [STCR NPK (100 q ha^{-1})] recorded the lowest pH values, particularly in low-fertility (5.70) and farmers' field strips (4.82). This suggests that prolonged use of inorganic fertilizers without organic amendments can gradually increase soil acidity. Sharma and Prasad (18) also observed such a decline in soil pH under intensive chemical fertilization due to the accumulation of acidic residues. Notably, the absolute control (T_7) exhibited the highest soil pH across all fertility levels, which may be attributed to the absence of acidifying effects caused by fertilizer application.

The post-harvest increase in soil EC observed under the STCR NPK and NPK+FYM treatments is likely attributable to the release of soluble salts from decomposing FYM and the higher inorganic fertilizer loads applied in the STCR NPK plots. This aligns with findings by (19), who noted a marginal rise in EC following STCR -based fertilization, primarily due to the accumulation of soluble salts under prevailing environmental conditions. Fertilizer application guided by soil test values, particularly under the STCR approach when combined with FYM, may therefore cause a moderate increase in EC due to processes of nutrient mineralization and solubilization. Nonetheless, all EC values recorded were within the safe threshold (<1 dS m^{-1}), indicating no risk of salinity for succeeding crops.

A marginal post-harvest increase in soil organic carbon was recorded across all treatments, likely stemming from the cumulative effect of nutrient management practices-especially the incorporation of FYM within the STCR-based integrated nutrient management framework. Though the variation was not statistically significant, relatively higher organic carbon values were consistently recorded in the plots that received FYM along with inorganic fertilizers (T_2 and T_4), suggesting their potential to gradually improve soil carbon status over time. These results are in line with (20), who highlighted that the addition of organic sources enhances microbial biomass and decomposition processes, thereby contributing to higher soil organic carbon.

Organic carbon levels were comparatively higher in the STCR NPK+FYM, LMH and RDF approaches, primarily due to the incorporation of FYM at 7.5 t ha^{-1}. The addition of FYM at this rate, together with the gradual decomposition of maize plant residues and root biomass, significantly enriched the soil organic carbon pool. On the other hand, in the absolute control where no FYM was applied, such improvement was absent. Treatments receiving only inorganic fertilizers (T_1 and T_3) also showed a slight increase in organic carbon, which may be attributed to the contribution of root biomass and crop residues left in the soil. Nevertheless, the combined application of organics and inorganics proved more effective in maintaining soil organic matter (21).

The rise in organic carbon content, even in absolute control plots, can be attributed to the contribution of root biomass from maize and the activity of native soil microbes. In contrast, the comparatively higher values observed in the high fertility strip and the Farmer's field at STZ, Shivamogga, likely reflect the cumulative effect of better inherent soil fertility and organic matter status, as highlighted by Srinivasarao et al. (22). Variations in organic carbon across treatments could also be linked to differences in microbial-mediated organic matter oxidation rates (23). Since organic carbon is fundamental for sustaining soil health, its improvement during the crop cycle indicates a positive impact of fertilizer application. This further emphasizes that integrating inorganic fertilizers with organic amendments can bring about notable enhancements in soil quality. Soil test-based integrated nutrient management practices led to higher post-harvest soil organic carbon in rice systems, contributing to the buildup and long-term maintenance of soil fertility (24).

Although FYM addition is expected to improve soil organic carbon, the present study showed that Soil organic carbon (SOC) increased marginally across all treatments, including inorganic-only and absolute control plots-indicating that short-term SOC changes were influenced more by maize residue return than by treatment differences. In the low fertility strip, for example, SOC increased from 0.46 to 0.49 % in T_2 (STCR NPK+FYM, 100 q ha^{-1}) and from 0.41 to 0.45 % in T_4 (STCR NPK+FYM, 90 q ha^{-1}), but similar increases were also observed in T_1 (0.42 → 0.45 %) and T_3 (0.40 → 0.42 %), which received only inorganic fertilizers. Even the absolute control (T_7) showed an increase (0.93 → 0.96 % in farmers field), highlighting the contribution of maize root biomass, rhizodeposition and partial residue retention to SOC buildup. The modest differences between FYM and non-FYM treatments suggest that the applied FYM rate (7.5 t ha^{-1}) and the single-season duration were insufficient to produce statistically detectable SOC gains, particularly in tropical Alfisols where rapid decomposition limits short-term carbon accumulation. Thus, the observed uniform improvement in SOC across treatments is consistent with the slow nature of SOC response and the dominant influence of crop-derived carbon inputs over short experimental periods.

The available nitrogen content in soil differed across the various nutrient management approaches, irrespective of the fertilizer application rate based on soil test values. This variation can be attributed to the differences in the quantity of nitrogen fertilizer applied under each approach, which influenced the soil nitrogen status among treatments. Applying higher amounts of fertilizers in combination with FYM increased available nitrogen in soil, whereas lower crop uptake under Grain residue decomposition (GRD) and Standard fertilizer recommendation (SFR) approaches resulted in greater residual nitrogen. In contrast, in STCR-based treatments, higher crop uptake led to comparatively lower levels of available nitrogen in soil. Similar trends were observed in the present investigation (25).

The increased available nitrogen in post-harvest soil under the general recommended dose and soil fertility rating methods can be explained by the way fertilizers are applied in these approaches. In the GRD system, fertilizers are recommended without prior soil testing, leading to a generalized application pattern. Such blanket application often causes uniform or excessive addition of nitrogen, irrespective of the actual soil nutrient status, which in turn results in residual nitrogen build-up after harvest (26). Such over-application, although beneficial in the short term, may reduce fertilizer use efficiency and lead to environmental concerns over time. Similarly, the SFR approach recommends fertilizer application based on broad soil fertility categories- low, medium and high- rather than precise soil test values. When a soil slightly borders a lower fertility class, the recommendation typically includes an additional 25 % of the recommended dose of nitrogen fertilizers to avoid underapplication (27). This conservative approach leads to higher nitrogen availability post-harvest, especially in medium fertility soils where slight underestimation of soil N levels results in higher fertilizer inputs than necessary. In contrast, the STCR approach is based on actual soil test values and crop yield targets, enabling more balanced and site-specific nitrogen management. This ensures efficient utilization of nitrogen with reduced residual accumulation (28). Thus, while GRD and SFR can lead to enhanced available nitrogen, they may not always align with principles of precision nutrient management.

The increase in available nitrogen content of post-harvest soils across the fertility strips can be ascribed to the combined contribution of applied inorganic nitrogen fertilizers and in certain treatments, the addition of organic inputs like FYM. The higher nitrogen availability observed under integrated treatments (STCR NPK+FYM) may be linked to the slow mineralization of organic nitrogen from FYM. This process not only enriched the soil with readily available nitrogen but also enhanced soil structure and moisture-holding capacity, thereby minimizing nitrogen losses (29).

In low fertility soils, significantly higher available nitrogen was observed under the soil fertility rating approach (T_6), which might be due to site-specific application of nitrogen that matched crop requirement based on the initial fertility status. This precise nutrient application could have minimized losses and increased nitrogen use efficiency, especially in nutrient-deficient soils. Moreover, organic amendments such as FYM used in NPK+FYM treatments ($T_2$and T_4) might have supported microbial activity, leading to increased mineralization and availability of nitrogen (30). In medium fertility soils, the increased available nitrogen may also be a result of higher nitrogen input in T_6 due to lower initial soil test values, which prompted higher fertilizer N application. This is consistent with earlier reports where nitrogen availability improved under predicted soil test-based fertilization due to slightly higher nutrient doses (31). In high fertility soils, even though the baseline nitrogen was high, T_3 and T_6 continued to maintain significantly higher post-harvest nitrogen levels. In these soils, the response to nitrogen was more reflective of efficient utilization rather than deficiency correction. Treatments like T_3 (STCR NPK for 90 q ha^{-1}) and T_6 ensured a balanced supply of nitrogen relative to crop demand, preventing depletion of soil N pools. The use of FYM in T_2 and T_4 might have promoted microbial proliferation and enhanced nitrogen mineralization, contributing further to nitrogen retention.

In fields of STZ, Shivamogga, the general recommended dose (T_5) resulted in the higher available nitrogen after harvest. This could be ascribed to uniform and possibly higher nitrogen application rate that exceeded the actual requirement, especially in already fertile soils. While T_1, T_3 and T_6 also recorded high nitrogen levels, the slight differences can be linked to variations in crop uptake, microbial activity and residual nitrogen dynamics. The consistently lower nitrogen in absolute control (T_7) across all strips is likely due to the depletion of native N due to continuous crop removal without any external supplementation. Integrated nutrient management approaches combining STCR with FYM were particularly effective in sustaining nitrogen levels, especially in low to medium fertility soils, due to the synergistic effects of mineralization, microbial activity and improved soil physical conditions (32).

Despite the high initial available P levels across all three sites, nano-DAP was included in the study because its primary role in this experiment was not to correct P deficiency, but to evaluate its contribution to nutrient use efficiency, foliar supplementation and residual nutrient dynamics under STCR-based nutrient management. In high-P Alfisols, soil-applied P is often prone to fixation by Fe and Al oxides, resulting in low recovery of applied P; therefore, foliar-applied nano-DAP provides a high-efficiency, low-dose P source that bypasses soil fixation and supports crop P demand during critical growth stages. Moreover, nano-DAP was integrated to examine whether precise foliar supplementation can reduce the need for higher soil-applied P in STCR prescriptions, thereby minimizing unnecessary residual accumulation, as reflected in the lower post-harvest P under STCR treatments compared to GRD and SFR approaches. Including nano-DAP thus allowed assessment of how a targeted, efficient P source interacts with STCR-based recommendations to enhance uptake efficiency, maintain soil fertility and potentially reduce long-term P buildup-even in soils that initially test high in available P.

Differences in post-harvest available P content across the fertility strips were primarily governed by the type and quantity of P sources applied, inherent soil fertility status and soil reaction. Treatments under the STCR-based NPK approach (T1 and T3) recorded significantly higher available P, which is attributable to the greater application of inorganic P fertilizers in these plots. In contrast, the NPK+FYM treatments showed comparatively lower available P, since part of the nutrient requirement was supplied through FYM. This reduction could also be linked to the lower initial P status of those soils and the gradual release of P from organic sources due to slower mineralization. However, the difference between NPK alone and NPK+FYM approaches was not always statistically significant, indicating that both strategies were effective in maintaining P availability.

The GRD and SFR treatments resulted in relatively higher phosphorus availability compared to the NPK+FYM treatments. In the GRD system, the phosphorus fertilizers are applied without knowledge of the soil's initial P content, leading to uniform but often excessive application. As P is less mobile in the soil and subject to fixation, a portion of the applied P tends to accumulate in the soil, particularly when not fully utilized by the crop (26). This accumulation contributes to higher available P in post-harvest soils under GRD. In the SFR approach, a similar pattern is seen due to the addition of 25 % extra RDF when soil P levels are near the boundary of a lower fertility category. As this system does not account for exact soil test values, overestimation of fertilizer requirements is common, especially in soils with borderline medium fertility, leading to residual buildup of P in the soil (27).

The inclusion of foliar nano-DAP in the STCR-based treatments likely contributed to improved nutrient uptake efficiency and helped moderate post-harvest soil nutrient residues. Nano-DAP, owing to its nanoscale particle size and high surface reactivity, provides a readily absorbable source of N and P through the foliage, bypassing soil-related losses such as fixation, leaching and immobilization that are common in acidic Alfisols. This targeted foliar supplementation during critical growth stages may have enabled the crop to meet part of its N and P demand without relying solely on soil-applied fertilizers, thereby reducing the pool of nutrients remaining unused in the soil. Evidence from the present study supports this: STCR treatments integrating nano-DAP (T_1-T_4) consistently recorded lower post-harvest residual N and P compared to GRD and SFR approaches, even though initial P levels were high. For instance, in the medium fertility strip, available P in STCR+FYM (T_2 = 315.1 kg ha^{-1}) was considerably lower than in GRD (T_5= 394.2 kg ha^{-1}) and SFR (T_6 = 441.6 kg ha^{-1}), suggesting more efficient uptake and reduced accumulation. Similar trends were observed for nitrogen. These patterns indicate that foliar nano-DAP improved nutrient acquisition efficiency and partially substituted the need for higher soil-applied N and P, aligning with the principles of precision nutrient management and contributing to balanced nutrient removal with minimal residual buildup.

The soils in the study area were acidic (pH 5.95) and such conditions are known to increase phosphorus fixation resulting from Al^{3+} and Fe^{3+} ions forming insoluble complexes with phosphate. Under such conditions, phosphorus from inorganic fertilizers becomes more responsive and remains available in the soil for a longer time. The increased available phosphorus in acidic soils due to the combined application of FYM and fertilizers (31). The incorporation of organic matter in Soil Test Crop Response – Integrated Plant Nutrient System (STCR-IPNS) treatments can lead to mild acidification of soil, helping in solubilizing otherwise fixed forms of phosphorus, thereby improving its availability to plants (33).

The lower phosphorus content recorded in the absolute control (T_7), where neither inorganic fertilizers nor organic manure were applied, could be attributed to continuous crop removal without replenishment, leading to nutrient mining from the soil. This trend of declining phosphorus levels in unfertilized soils has also been reported by (30), who noted that omission of phosphorus inputs results in net depletion due to plant uptake and removal at harvest.

The available K content after harvest showed a decreasing trend across all treatments, which is largely attributed to crop uptake and possible leaching losses under field conditions. However, the magnitude of reduction varied significantly among the different fertilizer recommendation approaches. The higher available potassium content in the STCR-based NPK and NPK+FYM treatments, particularly T_3 and T_4, may be ascribed to combined contribution from soil native potassium, application of K fertilizers and the mineralization of FYM, which released K gradually during crop growth. The integrated use of FYM with inorganic fertilizers also enhanced microbial activity, leading to improved soil structure and greater nutrient retention, ultimately maintaining higher available K in the soil (30, 25).

In treatments like Grain residue decomposition GRD and Standard fertilizer recommendation SFR, the application of higher K doses without soil testing or with elevated RDF adjustments in response to minor changes in fertility status led to a build-up of residual potassium, particularly in medium and high fertility strips. The STCR-IPNS approach helped maintain higher available potassium by reducing nutrient losses and enhancing nutrient use efficiency (34). Increased post-harvest K levels under STCR treatments due to optimized and elevated application of NPK fertilizers based on crop demand and soil test values (35). The reduced available K in absolute control plots is directly linked to continuous crop removal without replenishment, emphasizing the importance of nutrient budgeting in sustainable farming systems. The role of STCR-IPNS in maintaining soil fertility by compensating for nutrient removal through precise and integrated input management (36).

Conclusion

This verification study demonstrated that integrating STCR-based fertilizer prescriptions with FYM and foliar nano-DAP applications effectively improved post-harvest soil fertility while sustaining maize productivity in Alfisols. The combined STCR NPK+FYM treatments enhanced soil pH buffering capacity and maintained or slightly improved soil organic carbon relative to inorganic fertilizers alone, supporting better soil biological activity and nutrient turnover. Electrical conductivity remained within safe limits across all sites, indicating that the integrated nutrient application strategy did not contribute to salt accumulation. Consistent with the study objective of assessing nutrient-use efficiency, STCR treatments led to lower residual nitrogen and phosphorus compared to GRD and SFR approaches, evidencing more efficient nutrient uptake by the crop. Importantly, these improvements in soil fertility aligned with higher or comparable maize yields under STCR-IPNS treatments (STCR NPK+FYM), confirming that balanced nutrient budgeting, targeted nutrient delivery and FYM mineralization collectively supported both soil health and crop performance. Potassium status was also better maintained under STCR+FYM due to reduced depletion and improved the nutrient recycling. Thus, the results affirm that STCR integrated with organic amendments and nano-DAP offers a more sustainable and yield-supportive nutrient management strategy than blanket recommendations in nutrient-deficient Alfisols.

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Authors' contributions

ANN Conceptualized and designed the study, conducted the experiments, analyzed the data, interpreted the results and wrote the manuscript. Served as the corresponding author and coordinated the research activities. KMR Provided critical guidance on experimental design, contributed to the data interpretation and reviewed the manuscript. Supervised the implementation of balanced NPK fertilization techniques. TMN Provided inputs on agrometeorological aspects influencing nutrient uptake and soil sustainability. Assisted in data analysis and the interpretation of results related to environmental sustainability. SJ Offered technical expertise in soil science and agricultural chemistry, contributed to refining the research methodology and assisted in the critical review and improvement of the manuscript. VP Contributed to field-level implementation and data collection. Provided technical assistance in soil and plant sample analysis and collaborated on manuscript review. All authors read and approved the final manuscript. BN Contributed to editing and supervision in writing the manuscript.

Compliance with ethical standards

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

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