Sustaining Soil Quality and Maize Productivity through FYM and Targeted Nutrient Application of Fertilization in Acid Alfisols of Northwest Himalayas, India

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Abstract: Long-term evaluation of nutrient management practices is vital for enhancing soil quality and sustaining crop productivity. A 13-year field experiment, established in 2007 in acid Alfisols of the Northwest Himalayas, assessed the effects of prescription-based fertilization and farmyard manure on soil properties and maize yield under continuous cultivation. The experiment followed a randomized block design with seven nutrient management treatments and one control, each replicated thrice. Post-harvest (2019) surface soil samples (0–15 cm) were analysed for key physical and chemical properties. The combined application of soil test crop response-based chemical fertilizers targeting a 4 t ha⁻¹ yield along with 5 t ha⁻¹ farmyard manure not only improved soil physical and chemical properties but also significantly increased nutrient availability. This treatment also resulted in the highest maize grain yield (4.27t ha⁻¹). The soil quality index increased from 0.72 under soil test-based fertilization to 0.82 under STCR without farmyard manure (FYM) and reached 0.95 with the integration of FYM. Strong positive correlation (r^2 = 0.88) between SQI and grain yield highlights the synergy between STCR-based nutrient management and FYM application. These findings demonstrate the potential of integrated nutrient strategies in enhancing maize productivity and sustaining long-term soil quality.

1. INTRODUCTION

As the global population rises, the pressure to enhance food production has driven the adoption of intensive agricultural practices, often reliant on synthetic fertilizers, pesticides, and monoculture systems to maximize short-term yields. However, this pursuit has frequently overlooked soil quality, which underpins long-term productivity. Fertilizer use, though vital, remains suboptimal in India as recommendations are largely based on broad agro-climatic zones, ignoring soil heterogeneity. Significant variability in soil texture and nutrient status within zones affects crop response, making uniform application inefficient. This leads to over- or under-fertilisation, causing soil degradation, acidification, micronutrient deficiencies, and groundwater contamination or nutrient depletion and loss of soil fertility (Lal, 2015). Prolonged dependence on synthetic inputs further deteriorates soil structure, organic matter, and microbial activity (Sarkar et al., 2016). While organic farming offers an alternative, its inconsistent nutrient release often fails to meet crop demand (Tilman et al., 2002).

To address these challenges, precision nutrient management approaches such as soil test crop response (STCR)-based fertilization integrated with farmyard manure (FYM) offer a sustainable solution. The targeted yield concept aligns fertilizer doses with attainable crop yields under specific conditions, ensuring efficient nutrient utilization and reducing environmental risks (Singh et al., 2015). Integrating FYM with fertilizers synchronizes nutrient supply with crop demand, fertilisers providing immediate nutrients, and FYM improving the soil's physical, chemical, and biological properties (Antil et al., 2011). Evidence shows that conjoint application enhances soil organic matter, nutrient availability, hydraulic conductivity, and microbial activity, while reducing compaction (Singh et al., 2015; Moharana et al., 2017; Parmar et al., 2023). Thus, STCR-based integrated nutrient management (INM) has emerged as a promising strategy for sustaining soil quality and crop productivity across diverse ecosystems.

Maize, the staple of North India's farming systems, occupies 9.89 M ha with an annual production of 31.65 Mt in India (GOI 2022), and 0.255 M ha producing 0.708 Mt in Himachal Pradesh (Anonymous, 2023). Given its role in

food, feed, and industry, sustaining soil health in maize-based systems is critical. Soil quality, defined as the soil's capacity to sustain productivity and ecosystem functions (Doran & Parkin, 1994;), can be evaluated through key indicators such as pH, organic carbon, nutrient status, and microbial activity. Since soil quality changes occur gradually, long-term experiments are essential for understanding the sustainability of nutrient management practices (Krause et al., 2022; Das et al., 2023).

Despite growing evidence from rice and wheat systems (Mittal et al., 2018), studies on the long-term effects of STCR-based fertilization in maize, particularly under acid Alfisols of the NW Himalayas, remain scarce. Based on this gap, we hypothesized that integrating prescription-based fertilization with FYM over the long term would improve maize yield while sustaining soil quality. Therefore, the objectives of this study were: (i) to assess changes in soil physical and chemical properties under long-term STCR fertilization in maize, (ii) to evaluate the effect of FYM integration on soil quality and productivity, and (iii) to identify key soil quality indicators and their interrelationships.

2. MATERIALS AND METHODS

2.1. Site Location

The field experiment was conducted at the experimental farm of CSK HPKV, Palampur, India (32°6′N, 76°3′E; 1290 m amsl), representing the mid-hill wet temperate agro-climatic zone of North-West India. The region experiences mild summers and cool winters, with an average annual rainfall of 2500–3000 mm, about 75% of which occurs during the monsoon season (June–September) (Figure 1). The soil is classified as Typic Hapludalf (Alfisol) with silty loam texture. Initial soil physico-chemical properties (0–15 cm) are presented in Table 1.

2.2. Experimental Design and Treatments

A long-term maize–wheat cropping system experiment was initiated in kharif 2007 under the AICRP on Soil Test Crop Response (STCR). The experiment comprised seven nutrient management treatments and an unfertilized control, laid out in a randomized block design with three replications (Table 2). Fertilizer doses were calculated using STCR-based fertilizer adjustment equations for maize, with and without farmyard manure (FYM), targeting specific yield levels as proposed by Verma et al. (2007).

FYM was applied at 5 t ha^{-1} (dry weight basis) under integrated plant nutrient system (IPNS) treatments and contained 1.17% N, 0.62% P, and 0.78% K. Fertilizer requirements were computed using the following equations:
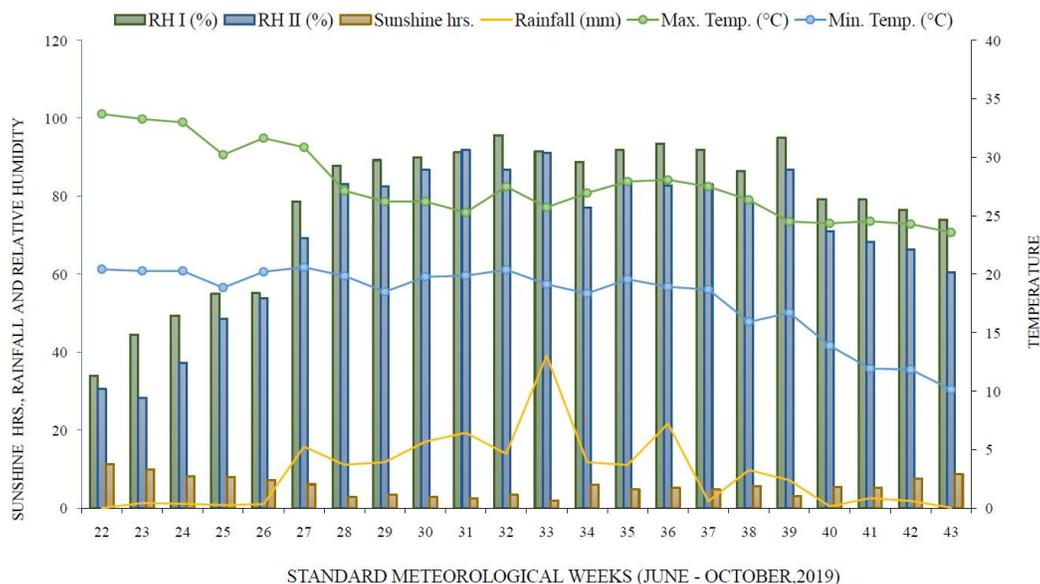
$$FN = 5.88T - 0.23SN - 0.90ON$$
$$FP = 4.87T - 1.22SP - 0.81OP$$
$$FK = 3.66T - 0.49SK - 0.51OK$$

where FN, FP, and FK represent fertilizer N, P$_2$O$_5$, and K$_2$O (kg ha^{-1}), respectively; T is the targeted yield (t ha^{-1}); SN, SP, and SK denote soil-available nutrients; and ON, OP, and OK represent nutrient contributions from FYM.

2.3. Field Techniques

Maize hybrid 'Kanchan' was sown on 20 June 2019 using a

Figure 1. Weekly mean meteorological data during the experimental period

seed rate of 20 kg ha⁻¹ at 60 × 40 cm spacing in plots of 5 × 3 m. Fertilizers were applied as per treatment specifications. Full doses of P_2O_5 and K_2O and one-third of N were applied basally at sowing, while the remaining N was top-dressed in

two equal splits at knee-high and tasseling stages. FYM (5 t ha⁻¹) was incorporated in treatments targeting 3.0 and 4.0 t ha⁻¹ yields. The crop was harvested at physiological maturity on 22 October 2019, and grain and stover yields were recorded.

2.4. Soil Analysis

Surface soil samples (0–15 cm) were collected post-harvest in 2019 from five random locations within each plot and composited. Samples were air-dried, ground, sieved (<2 mm), and analyzed for physical and chemical properties using standard methods (Table 3).

2.5. Minimum Data sets and Soil Quality Index (SQI)

The soil quality index (SQI) was computed following the four-step approach described by Andrews et al. (2002a). Principal component analysis (PCA) was used to identify the minimum data set (MDS) from soil variables showing significant treatment effects. Principal components with eigenvalues >1 and explaining ≥5% variance were retained. Within each PC, variables with factor loadings within 10% of the highest value were selected, and redundant variables were eliminated using correlation analysis. Selected indicators were scored using a "more is better" approach and weighted according to the proportion of variance explained by each PC. The SQI was calculated as (eq 1):

$$SQI = \sum_{i=1}^{n} Wi \times Si \dots\dots\dots\dots\dots\dots\dots\dots(1)$$

Where Wi is the weight of the variable derived from PCA and Si is the score of the variable.

2.6. Statistical Analysis

Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) was used to compare means and Duncan's Multiple Range Test (p=0.05) was calculated running online OPSTAT software (Sheoran et al., 1998). Pearson correlation analysis was employed using the corrplot package in R (version 4.4.0) (Wei and Simko, 2021) to visualize the linear

Table 1. Initial physico-chemical properties of the soil prior to the commencement of the experiment (2007)

Soil characteristics	Value
Mechanical composition	
Sand (%)	22.5
Silt (%)	43.6
Clay (%)	31.7
Texture	Silty clay loam
Bulk density (Mg m⁻³)	1.28
Water holding capacity (%)	47.8
Particle density (Mg m⁻³)	2.68
Porosity (%)	48.9
pH (1:2.5)	5.2
EC (dS m⁻¹)	0.19
Organic carbon (g kg⁻¹)	7.2
Available nutrients	
N (kg ha⁻¹)	236
P (kg ha⁻¹)	41
K (kg ha⁻¹)	272
S (kg ha⁻¹)	15.1
Ca (c mol(p⁺)kg⁻¹)	0.68
Mg (c mol(p⁺)kg⁻¹)	0.84
DTPA exractable (mg kg⁻¹)	
Fe (mg kg⁻¹)	23.2
Mn (mg kg⁻¹)	21.4
Zn (mg kg⁻¹)	1.25
Cu (mg kg⁻¹)	0.75

Table 2. Treatment-specific quantities of fertilizers and FYM applied in the study

Treatments	N (kg ha⁻¹)	P (kg ha⁻¹)	K (kg ha⁻¹)	FYM (t ha⁻¹)
T₁=Unfertilized/unmanured control	0.00	0.00	0.00	-
T₂=Farmers' practice (25 % general recommended dose of N to maize + 5 t ha⁻¹ FYM)	30.00	0.00	0.00	5
T₃=GRD (general recommended dose of 120 N, 60 P_2O_5 and 40 K_2O kg ha⁻¹ to maize)	120.00	60.00	40.00	-
T₄=STB (NPK on soil test values)	150.00	45.00	40.00	-
T₅=STCR-based fertilizer NPK alone for grain yield target of 3.0 t ha⁻¹	110.12	85.93	0.00	-
T₆=STCR-based fertilizer NPK + 5 t ha⁻¹ FYM for grain yield target of 3.0 t ha⁻¹	53.29	43.52	0.00	5
T₇=STCR-based fertilizer NPK alone for grain yield target of 4.0 t ha⁻¹	166.10	118.27	8.09	-
T₈=STCR-based fertilizer NPK + 5 t ha⁻¹ FYM for grain yield target of 4.0 t ha⁻¹	109.67	81.61	0.00	5

relationship between individual soil properties and maize grain yield. The PCA was performed in XLSTAT 2024 and PCA biplots were obtained from PAST version 4.03. Bar diagrams and linear regression graphs were prepared in Microsoft Excel 2019.

3. RESULTS AND DISCUSSION

3.1. Soil Physical Properties

Different fertilization strategies significantly influenced soil physical properties, with pronounced improvements under FYM-integrated treatments. Bulk density was highest in the control (1.36 Mg m⁻³) and lowest under the STCR-based treatment targeting 4 t ha⁻¹ with FYM (T8; 1.20 Mg m⁻³), which was statistically at par with the 3 t ha⁻¹ target supplemented with FYM (Table 4). The reduction in bulk density under FYM treatments can be attributed to enhanced soil organic matter accumulation, improved aggregation, and increased pore development, resulting in better aeration (Gangwar et al., 2006; Islam et al., 2012; Mahmood et al., 2017). Particle density followed a similar trend, with the highest value in the control (2.61 Mg m⁻³) and the lowest in T8 (2.51 Mg m⁻³). Treatments receiving fertilizers, with or without FYM, recorded significantly lower particle density than the control and were statistically comparable among themselves. This decline is likely associated with increased microbial activity and organic matter decomposition, which promote soil aggregation and porosity through microbial by-products (Whalen and Chang, 2002; Sepehya et al., 2012). Soil porosity and water holding capacity were markedly improved under FYM-integrated STCR treatments. The

highest porosity (52.0%) and water holding capacity (56.6%) were observed in T8, compared to the lowest values in the control (47.8% and 46.6%, respectively). These improvements reflect the positive role of FYM in enhancing soil structure, aggregate stability, and pore continuity, thereby increasing moisture retention (Bhattacharya et al., 2008; Nagwanshi et al., 2018).

3.2. Soil Chemical Properties

3.2.1. pH, EC and OC: Treatments targeting grain yields of 3 and 4 t ha⁻¹ with FYM, along with farmers' practice, recorded slightly higher soil pH (5.43–5.45) compared to the control (Figure 2). This marginal increase in pH under FYM-amended treatments is likely due to the chelation of

Table 4. Long-term effects of STCR-based target yield approach on soil physical properties

Treatment	Bulk density (Mg m⁻³)	Particle density (Mg m⁻³)	Porosity (%)	Water holding capacity (%)
T1	1.36ᵈ	2.61ᶜ	47.8ᵉ	46.6ᶠ
T2	1.23ᵃ	2.53ᵃᵇ	51.6ᵃᵇ	52.4ᶜᵈᵉ
T3	1.30ᶜ	2.57ᵇᶜ	49.0ᵈ	49.8ᵉ
T4	1.27ᵇ	2.56ᵇ	50.4ᶜ	50.6ᵈᵉ
T5	1.26ᵇ	2.55ᵃᵇ	50.8ᶜ	52.8ᶜᵈ
T6	1.22ᵃ	2.52ᵃᵇ	51.7ᵃᵇ	56.2ᵃᵇ
T7	1.25ᵇ	2.55ᵃᵇ	51.0ᵇᶜ	53.7ᵇᶜ
T8	1.20ᵃ	2.51ᵃ	52.0ᵃ	56.6ᵃ

Different lowercase letters within the same row indicates significant difference (Duncan's multiple range test, p<0.05)

Table 3. Methodology employed for determination of various soil properties

| Chemical properties	Method/Extractant	References
OC (g kg⁻¹)	Wet Digestion	Walkley and Black (1934)
Soil pH	(1:2.5, soil:water)	Jackson (1973)
Soil EC	(1:2, soil:water)	Jackson (1973)
Available N (kg ha⁻¹)	Alkaline permanganate	Subbiah and Asija (1956)
Available P (kg ha⁻¹)	0.5N NaHCO₃ (pH 8.5)	Olsen et al. (1954)
Available K (kg ha⁻¹)	1N Neutral NH₄OAc	Black (1965)
Available S (kg ha⁻¹)	I N CaCl₂	Williams and Steinbergs (1959)
Exch. Ca & Mg ({cmol (p⁺) kg⁻¹})	I N NH₄OAC	Jackson (1973)
DTPA-Fe, Mn, Cu and Zn (mg kg⁻¹)	DTPA extraction	Lindsay and Norvell (1978)
Physical Properties	**Method/Extractant**	**References**
BD (Mg m⁻³)	Core Sampler	Singh (1980)
PD (Mg m⁻³)	Pycnometer method	Gupta and Dhakshinamoorthy (1980)
Porosity (%)	Empirical method	Gupta and Dhakshinamoorthy (1980)
WHC (%)	Keen's moisture box	Piper (1950)

exchangeable Al^{3+} by organic ligands released during FYM decomposition, thereby reducing soil acidity (Choudhary et al., 2019). Soil electrical conductivity (EC) varied significantly among treatments, with the lowest value in the control (0.17 dS m^{-1}) and the highest in the STCR-based treatment targeting 4 t ha^{-1} with FYM (0.23 dS m^{-1}). The increase in EC under fertilizer and FYM application may be attributed to enhanced base saturation and greater availability of soluble ions, a trend commonly reported following organic matter additions (Gonzalez et al., 2010; Durani et al., 2017). Soil organic carbon (SOC) content increased markedly with FYM integration, ranging from 6.6 g kg^{-1} in the control to 8.9 g kg^{-1} under the 4 t ha^{-1} target yield with FYM (Figure 2). This improvement reflects continuous carbon inputs from FYM along with crop residues, root biomass, and exudates over the long term, leading to sustained SOC accumulation (Verma et al., 2012; Choudhary et al., 2019).

3.2.2. Available NPK: Available nitrogen varied significantly among treatments, with the highest value recorded under the STCR-based treatment targeting 4 t ha^{-1} with FYM (313.6 kg ha^{-1}) and the lowest in the control (145.5 kg ha^{-1}) (Figure 3). STCR-based target yields of 30 and 40 q ha^{-1} without FYM showed higher available N than the general recommended dose and soil test-based treatments, while FYM integration further enhanced N availability by 2.8–3.9% over their non-IPNS counterparts. The improvement in soil N status under FYM-amended treatments can be attributed to enhanced microbial activity and increased mineralization of organically bound nitrogen, leading to a sustained build-up of available N (Kumari and Tripathi, 2018). Available phosphorus ranged from 21.0 kg ha^{-1} in the control to 74.2 kg ha^{-1} in the 4 t ha^{-1} target yield treatment with FYM (Figure 3). Farmers' practice markedly increased soil P compared to the control, while STCR-based fertilization without FYM outperformed the general recommended dose and soil test-based application due to balanced nutrient supply. Integration of FYM further
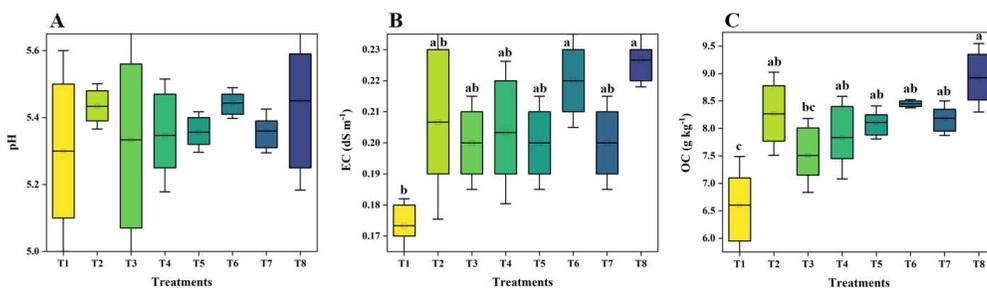
Figure 2. Long-term effects of STCR-based target yield approach on **(A)** soil pH, **(B)** electrical conductivity (EC) and **(C)** organic carbon (OC) content. Box plots show the median, interquartile range, and variability. Vertical bars represent the standard error of the mean. Bars followed by different lowercase letters are significantly different at P < 0.05 according to Duncan's Multiple Range Test (DMRT)
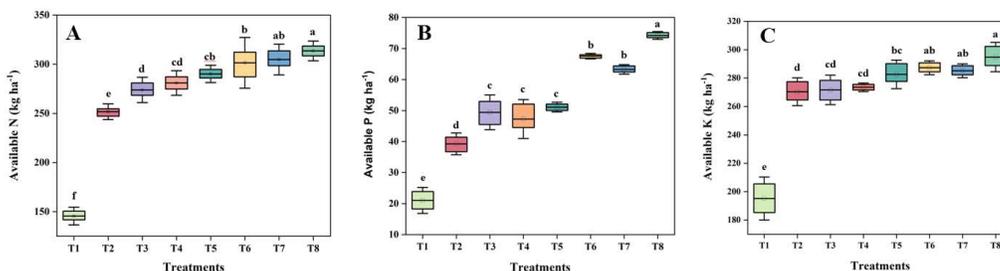
Figure 3. Long-term effects of STCR-based target yield approach on available macronutrient status in soil: **(A)** nitrogen (N), **(B)** phosphorus (P) and **(C)** potassium (K). Box plots show the median, interquartile range, and variability. Vertical bars represent the standard error of the mean. Bars followed by different lowercase letters are significantly different at P < 0.05 according to Duncan's Multiple Range Test (DMRT)

enhanced P availability across target yield treatments, likely due to the release of organic acids during FYM decomposition that facilitated phosphorus solubilization (Prasad et al., 2010; Kumari & Tripathi, 2018). Potassium availability followed a similar trend, with the highest value observed under the 4 t ha^{-1} target yield with FYM (294.8 kg ha-1) and the lowest in the control (195.2 kg ha-1). FYM-integrated STCR treatments significantly improved available K over conventional fertilizer practices, possibly due to reduced K fixation and enhanced release from clay–organic matter interactions (Sharma et al., 2001). In contrast, continuous nutrient removal without external inputs resulted in depletion of available NPK in the control treatment (Yadav et al., 2019).

3.2.3. Secondary and micronutrients: In addition to primary nutrients, fertilization strategies significantly influenced secondary and micronutrient availability.

Table 5. Long-term effects of STCR-based target yield approach on exchangeable calcium (Ca), magnesium (Mg) (c mol(p$^+$) kg^{-1}), and available sulphur (S) (kg ha^{-1})

Treatment	Ca	Mg	S
T1	0.54^d	0.77^f	13.86^f
T2	1.39^{bc}	0.92^e	17.37^e
T3	1.28^c	0.96^{de}	18.07^e
T4	1.42^{bc}	1.05^e	20.00^d
T5	1.54^{bc}	1.03^{cd}	21.23^c
T6	1.64a^{bc}	1.23^b	22.63^b
T7	1.69^{ab}	1.10^c	22.46^b
T8	1.93^a	1.51^a	23.68^a

Different lowercase letters within the same row indicates significant difference (Duncan's multiple range test, p<0.05)

Available sulphur ranged from 13.8 kg ha^{-1} in the control to 23.7 kg ha^{-1} under the STCR-based treatment targeting 4 t ha^{-1} with FYM (Table 5). FYM integration consistently enhanced soil S availability compared to non-IPNS treatments, primarily due to mineralization of organically bound sulphur and the use of single super phosphate, which supplies soluble S (Babu et al., 2017). Exchangeable calcium (Ca) and magnesium (Mg) showed a clear increasing trend with fertilizer application, with the lowest values in the control and markedly higher concentrations under FYM-integrated STCR treatments. While sole fertilizer treatments resulted in moderate improvements, the incorporation of FYM increased Ca and Mg availability by 15–36% and 17–38%, respectively, compared with GRD and STB treatments (Table 5). These improvements may be attributed to indirect Ca supply through fertilizers, enhanced nutrient mobilization by deeper root systems, and increased microbial activity associated with organic matter addition (Shivashankar et al., 2018).

Micronutrient availability responded strongly to FYM integration. The highest DTPA-extractable Fe (31.4 mg kg^{-1}) and Mn (27.2 mg kg^{-1}) were recorded under the 4 t ha^{-1} target yield with FYM, reflecting substantial increases over non-IPNS treatments (Table 6). Enhanced Fe and Mn availability is likely due to organic acid release and chelation processes during FYM decomposition, which promote micronutrient solubilization under acidic soil conditions (Prashanth et al., 2019). Similarly, Zn availability increased progressively with FYM addition, reaching a maximum of 1.45 mg kg^{-1} under the 4 t ha^{-1} target yield with FYM, owing to direct nutrient inputs and reduced fixation through organic complexation (Chauhan et al., 2018). Copper followed a comparable trend, increasing from 0.44 mg kg^{-1} in the

Table 6. Long-term effects of STCR-based target yield approach on DTPA-extractable micronutrients

Treatment	DTPA extractable micronutrients (mg kg^{-1})			
	Fe	Mn	Zn	Cu
Control	14.4	16.1	0.81	0.44
Farmers' practice	26.3	23.0	1.33	0.76
General recommended dose of fertilizers	23.1	20.9	1.21	0.73
Soil test-based fertilizer application	24.0	21.6	1.27	0.75
Target yield 30q ha^{-1}	26.8	23.2	1.34	0.77
Target yield 30q ha^{-1} with FYM @ 5t ha^{-1}	29.6	25.5	1.41	0.79
Target yield 40q ha^{-1}	27.7	23.7	1.37	0.78
Target yield 40q ha^{-1} with FYM @ 5t ha^{-1}	31.4	27.2	1.45	0.82
CD (p=0.05)	3.0	4.1	0.19	0.08

control to 0.82 mg kg^{-1} under FYM-integrated STCR treatment, likely due to the formation of stable organo-Cu complexes and enhanced microbial activity (Bolan and Duraisamy, 2003; Meng et al., 2005).

3.3. Pearson's Correlation

Maize grain yield showed significant positive correlations with available nitrogen (r = 0.763) and water holding capacity (r = 0.838), indicating the importance of nutrient availability and soil physical conditions in determining crop productivity (Figure 4). The integrated application of FYM and chemical fertilizers likely improved the soil physical environment, thereby promoting better crop growth, whereas no significant relationship was observed between grain yield and soil bulk or particle density. Grain yield was also positively correlated with soil EC (r = 0.733) and organic carbon (r = 0.860), while no significant association was observed with soil pH. The positive relationship between EC and yield may be attributed to the fine-textured nature of the soils, which enhances nutrient retention and availability. Improved SOC levels under integrated nutrient management, driven by sustained inputs of organic residues and root biomass, contributed to enhanced nutrient supply and crop performance. Strong positive correlations were observed between grain yield and available N, P, and K, with r values of 0.939, 0.942, and 0.905, respectively. In addition, secondary nutrients (S, Ca, and Mg) and micronutrients (Fe,

Mn, Zn, and Cu) exhibited significant positive relationships with yield (Figure 4). These results underscore the cumulative benefits of integrated nutrient management in improving nutrient availability across multiple pools, thereby enhancing maize productivity, consistent with earlier findings (Moharana et al., 2017).

3.4. Selection of MDS and Principal Component Analysis

Following laboratory analysis, soil quality indicators were subjected to principal component analysis (PCA), and components with eigenvalues >1 were retained (Figure 5A). The first two principal components (PC1 and PC2) explained 89.5% and 5.3% of the total variance, respectively, together accounting for 94.9% of the variability in soil properties (Table 7). PC1 was strongly associated with multiple chemical, physical, and biological indicators, indicating its dominant role in explaining soil quality variation under different nutrient management practices. Based on high factor loadings, vector lengths, and orientations in the PCA biplot (Figure 5B), six variables; organic carbon (OC), available phosphorus (P), exchangeable calcium (Ca), manganese (Mn), water holding capacity (WHC), and microbial biomass carbon (MBC) were identified as the most influential contributors to soil quality. These indicators showed strong positive associations, suggesting that improvements in fertility, physical structure, and biological activity are closely

Variables	GY	pH	OC	N	P	K	S	Ca	Mg	Fe	Mn	Zn	Cu	BD	PD	Porosity	WHC
GY	1	0.564	0.860	0.939	0.943	0.905	0.955	0.980	0.903	0.897	0.888	0.887	0.875	-0.803	-0.762	0.763	0.839
pH	0.564	1	0.888	0.589	0.666	0.658	0.621	0.606	0.738	0.830	0.866	0.771	0.690	-0.926	-0.953	0.905	0.878
OC	0.860	0.888	1	0.867	0.864	0.901	0.869	0.876	0.895	0.984	0.988	0.959	0.910	-0.991	-0.980	0.971	0.959
N	0.939	0.589	0.867	1	0.913	0.988	0.926	0.959	0.804	0.928	0.895	0.956	0.969	-0.829	-0.802	0.792	0.832
P	0.943	0.666	0.864	0.913	1	0.877	0.963	0.969	0.926	0.914	0.924	0.871	0.838	-0.822	-0.815	0.762	0.915
K	0.905	0.658	0.901	0.988	0.877	1	0.886	0.925	0.781	0.950	0.914	0.981	0.995	-0.874	-0.853	0.841	0.844
S	0.955	0.621	0.869	0.926	0.963	0.886	1	0.986	0.932	0.914	0.913	0.887	0.849	-0.823	-0.794	0.800	0.906
Ca	0.980	0.606	0.876	0.959	0.969	0.925	0.986	1	0.925	0.922	0.917	0.907	0.890	-0.823	-0.797	0.782	0.881
Mg	0.903	0.738	0.895	0.804	0.926	0.781	0.932	0.925	1	0.886	0.924	0.815	0.752	-0.848	-0.838	0.808	0.919
Fe	0.897	0.830	0.984	0.928	0.914	0.950	0.914	0.922	0.886	1	0.992	0.984	0.947	-0.968	-0.957	0.942	0.964
Mn	0.888	0.866	0.988	0.895	0.924	0.914	0.913	0.917	0.924	0.992	1	0.957	0.909	-0.972	-0.969	0.938	0.980
Zn	0.887	0.771	0.959	0.956	0.871	0.981	0.887	0.907	0.815	0.984	0.957	1	0.986	-0.946	-0.926	0.928	0.908
Cu	0.875	0.690	0.910	0.969	0.838	0.995	0.849	0.890	0.752	0.947	0.909	0.986	1	-0.893	-0.872	0.865	0.833
BD	-0.803	-0.926	-0.991	-0.829	-0.822	-0.874	-0.823	-0.823	-0.848	-0.968	-0.972	-0.946	-0.893	1	0.992	-0.987	-0.950
PD	-0.762	-0.953	-0.980	-0.802	-0.815	-0.853	-0.794	-0.797	-0.838	-0.957	-0.969	-0.926	-0.872	0.992	1	-0.967	-0.950
P	0.763	0.905	0.971	0.792	0.762	0.841	0.800	0.782	0.808	0.942	0.938	0.928	0.865	-0.987	-0.967	1	0.927
WHC	0.839	0.878	0.959	0.832	0.915	0.844	0.906	0.881	0.919	0.964	0.980	0.908	0.833	-0.950	-0.950	0.927	1

Values in bold are significant at level p=0.5

Figure 4. Pearson correlation matrix showing relationships among grain yield (GY) and various soil physico-chemical properties (pH, electrical conductivity (EC), organic carbon (OC), available macronutrients (N, P, K, S), secondary nutrients (Ca, Mg), micronutrients (Fe, Mn, Zn, Cu), and soil physical properties (bulk density (BD), particle density (PD), porosity, and water holding capacity (WHC)

interlinked. Following established criteria for soil quality assessment and essentiality (Arnon & Stout, 1939; Andrews et al., 2002b), one representative variable each from primary (P), secondary (Ca), and micronutrients (Mn), along with key physical (WHC) and biological (MBC) indicators, was selected for the minimum data set (MDS). Organic carbon was additionally retained due to its sensitivity to long-term FYM application and its central role in regulating soil physical, chemical, and biological processes (Lal, 2008; Dhull et al., 2004).

In PC2, soil pH was the only variable retained due to its highest factor loading, with no other indicator falling within the 10% selection threshold (Table 7). Given the acidic nature of the study soils, pH was considered a critical indicator directly influencing nutrient availability and crop productivity. The Pearson correlation analysis further supported the inclusion of the selected indicators (Figure 4). In contrast, physical properties such as bulk density (BD) and particle density (PD) exhibited shorter vector lengths and orientations opposite to fertility and biological indicators in the PCA biplot (Figure 5B), indicating that integrated nutrient management reduced soil compaction and improved structural conditions conducive to root growth and microbial activity. The PCA biplot also revealed clear treatment clustering, with FYM-integrated STCR treatments positioned along the positive axis of PC1 and closely associated with key soil quality indicators, reflecting enhanced fertility, biological activity, and maize yield. Conversely, the control and non-STCR treatments were grouped along the negative axis of PC1, indicating poorer soil quality. Accordingly, the final minimum data set (MDS)

Table 7. Principal Component Analysis (PCA) of soil quality indicators showing eigenvalues, percentage variability and cumulative variance explained by the first two principal components (PC1 and PC2), along with factor loading values for each soil property

Principal components	PC1	PC2
Eigenvalue	17.023	1.016
Variability (%)	89.592	5.347
Cumulative %	89.592	94.939

Soil quality indicators	Factor loading values for each Principal component	
pH	0.837	**__-0.525__**
OC	**__0.985__**	-0.121
N	**0.922**	0.370
P	**__0.932__**	0.204
K	**0.935**	0.278
S	**0.931**	0.244
Ca	**__0.936__**	0.309
Mg	**0.919**	-0.001
Fe	**0.996**	0.011
Mn	**__0.997__**	-0.057
Zn	**0.971**	0.103
Cu	**0.930**	0.220
BD	**-0.968**	0.206
PD	**-0.957**	0.252
P	**0.938**	-0.240
WHC	**__0.973__**	-0.146
MBC	**__0.964__**	-0.076
DHA	**0.915**	-0.230
LC	**0.966**	0.089

*Boldface component loadings were considered as highly weighted. Among them bold-underlined values were retained in minimum data sets
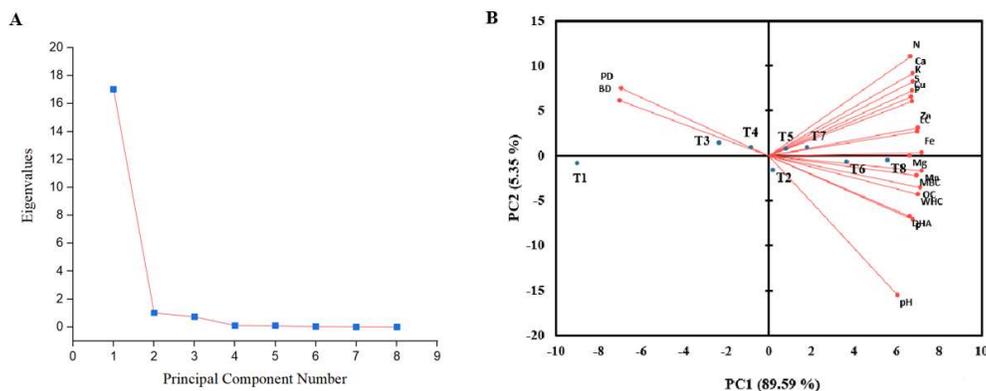
Figure 5. (A) Scree plot showing eigenvalues corresponding to each principal component, indicating that the first two components explain most of the variability. **(B)** PCA biplot illustrating the distribution of treatments (T1 to T8) and the loading values of different soil variables. PC1 (89.59%) and PC2 (5.35%) together account for 94.94% of the total variance. Arrows represent the direction and magnitude of each variable's contribution to the components

comprised OC, P, Ca, Mn, WHC, MBC, and pH.

For SQI computation, all indicators were scored using a "more is better" approach (Table 8). Weights were assigned based on the proportion of variance explained by each principal component: PC1 contributed a total weight of 0.94, distributed equally (0.15 each) across six indicators, and PC2 assigned a weight of 0.05 to pH. Indicator scores were normalized using their respective maximum values, and the weighted scores were summed to derive the soil quality index:

$$SQI = (0.15 \times S_{OC}) + (0.15 \times S_{P}) + (0.15 \times S_{Ca}) + (0.15 \times S_{Mn}) + (0.15 \times S_{WHC}) + (0.15 \times S_{MBC}) + (0.05 \times S_{pH})$$

Where S is the score of the selected variable

3.5. Grain Yield and Soil Quality Index

All fertilization treatments significantly increased maize grain yield compared to control, which recorded the lowest yield (1.36 t ha^{-1}), while the STCR-based treatment targeting 4 t ha^{-1} with FYM achieved the highest yield (4.27 t ha^{-1})

(Figure 6A). Both general recommended dose and soil test-based fertilization improved yield over farmers' practice, with greater increment observed under the targeted yield approach. The superior performance of FYM-integrated STCR treatments may be attributed to improved root growth, balanced nutrient supply, and enhanced nutrient uptake, collectively supporting higher photosynthetic efficiency and crop productivity (Kumar and Santhi, 2017; Suresh and Santhi, 2018). In addition, soil test-based fertilizer recommendations promote efficient and economical fertilizer use, supporting sustainable crop production (Tegegnework et al., 2015).

Soil quality index (SQI) values ranged from 0.49 in the control to 0.95 under the 4 t ha^{-1} target yield with FYM, representing a 94% improvement over the control (Table 8). STCR-based treatments consistently recorded higher SQI than general recommended and farmers' practice treatments, with further enhancement observed following FYM
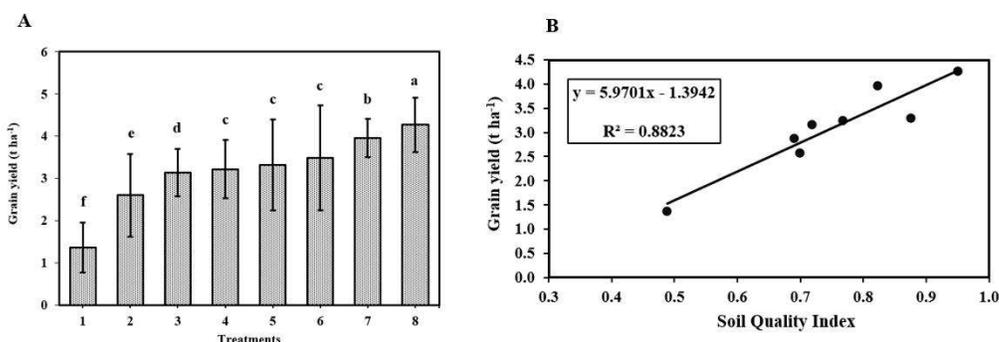
Figure 6. (A) Long-term effects of STCR-based target yield approach on grain yield (t ha^{-1}) of maize. Results are presented with standard error of mean (Sem ±). Bars with different lowercase letters indicate statistically significant differences among treatments at P < 0.05 according to Duncan's Multiple Range Test (DMRT). **(B)** The linear relationship between maize grains yield (t ha^{-1}) and soil quality index

Table 8. Soil quality index (SQI) and normalized scores (S) with their respective weights (W) for selected soil quality indicators under different nutrient management treatments

Treatments	OC		P		Ca		Mn		WHC		MBC		pH		SQI
	S	W	S	W	S	W	S	W	S	W	S	W	S	W	
Control	0.74	0.15	0.28	0.15	0.28	0.15	0.59	0.15	0.82	0.15	0.21	0.15	0.97	0.05	0.49
FP	0.93	0.15	0.53	0.15	0.56	0.15	0.85	0.15	0.93	0.15	0.54	0.15	0.99	0.05	0.70
GRD	0.84	0.15	0.67	0.15	0.66	0.15	0.77	0.15	0.88	0.15	0.46	0.15	0.97	0.05	0.69
STB	0.88	0.15	0.64	0.15	0.74	0.15	0.79	0.15	0.89	0.15	0.53	0.15	0.98	0.05	0.72
T30	0.91	0.15	0.69	0.15	0.80	0.15	0.85	0.15	0.93	0.15	0.61	0.15	0.98	0.05	0.77
T30FYM5	0.95	0.15	0.91	0.15	0.85	0.15	0.94	0.15	0.99	0.15	0.86	0.15	0.99	0.05	0.88
T40	0.92	0.15	0.85	0.15	0.87	0.15	0.87	0.15	0.95	0.15	0.70	0.15	0.98	0.05	0.82
T40FYM5	1.00	0.15	1.00	0.15	1.00	0.15	1.00	0.15	1.00	0.15	1.00	0.15	1.00	0.05	0.95

integration. In contrast, omission of FYM resulted in a 7–23% reduction in SQI across targeted yield treatments, underscoring the importance of organic amendments in sustaining soil quality. Even farmers' practice improved SQI by 43% over the control, highlighting the long-term benefits of FYM addition (Shahid et al., 2013; Ram et al., 2016; Singh et al., 2015; Sankhyan et al., 2024). Organic carbon (OC) and water holding capacity (WHC) emerged as the most influential contributors to SQI, followed by Mn, Ca, P, microbial biomass carbon (MBC), and pH (Figure 7). The strong positive relationship between OC and WHC (r = 0.95) reflects the role of FYM in enhancing soil aggregation and moisture retention. MBC, due to its sensitivity to management practices, further contributed to nutrient cycling and soil functioning (Chinnadurai et al., 2014). Given the acidic nature of the soils, pH also played a critical role in regulating nutrient availability and soil processes (Amoakwah et al., 2023). A strong linear relationship between maize grain yield and SQI ($R^2 = 0.88$) confirms that integrated use of organic and inorganic nutrient sources is essential for improving productivity while sustaining long-term soil quality (Figure 6B).

4. CONCLUSION

The outcomes from this 13-year study on STCR based target yield model, effectively reinforce this perspective, demonstrating that integration of FYM (5 t ha^{-1}) with STCR based nutrient recommendations for target yield of 4 t ha^{-1} not only maximized maize productivity but also

Figure 7. Relative contribution (%) of individual indicators to the soil quality index

substantially improved soil physical and chemical properties. This strategy not only meets the productivity goals for maize but also plays a vital role in maintaining soil quality thus making prescription-based integrated nutrient management a promising approach. Promoting such an approach particularly in mid hills of North-west Himalayas could lead to more precise and balanced fertilizer recommendations, enhanced nutrient use efficiency and conservation of soil health, besides economizing the use of costly fertilizer inputs.

Credit Authorship Contribution Statement

Varun Parmar: Conceptualization, Writing original draft, Methodology, Investigation, Formal analysis, Data curation. Naveen Datt: Conceptualization, Validation, Supervision & Funding Acquisition. Shahi Pal Dixit: Validation, Funding Acquisition Rushali: Editing, Review and Methodology.

Disclosure Statement

The authors report there are no competing interests to declare.

Data availability statement

The data with respect to this study is available from the corresponding author upon reasonable request.

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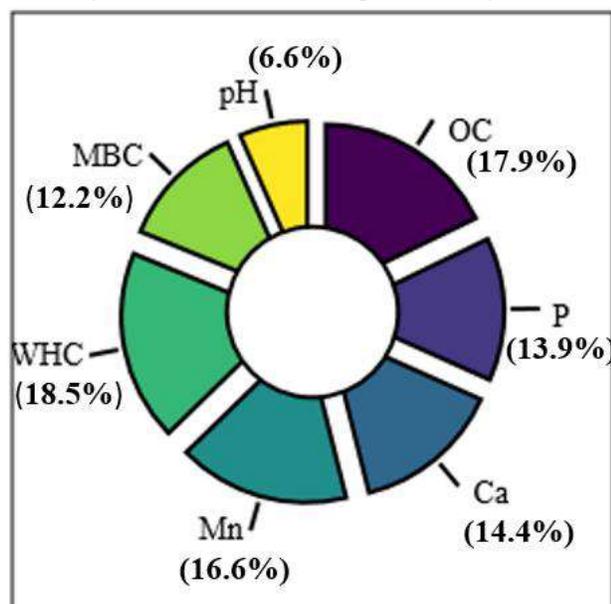
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