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Comparison of STCR and Conventional Fertilizer Approaches for Improved Yield, Uptake and Nutrient Use Efficiency in Greengram

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The present study investigates the effects of various fertilizer recommendation approaches on yield, nutrient uptake and nutrient use efficiency in greengram (BGS-9), conducted at ZARS, GKVK, Bengaluru during summer-2024. Soil test crop response (STCR) based fertilizer

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prescription equations were developed during kharif-2022 by following the methodology of Ramamoorthy et al., (1967) and were validated alongside post-harvest soil test value prediction equations. Results indicated that significantly higher seed yield (17.99 q ha^{-1}) was recorded in the STCR approach for the target yield of 15 q ha-1, where nutrients were applied through integrated approach based on actual soil test values (T3). The highest haulm yield (30.25 q ha^{-1}) was recorded in T2, which followed the STCR inorganic approach targeting 15 q ha^{-1}, based on predicted soil test values. Nutrient uptake results indicated that significantly higher nitrogen (110.73 kg ha^{-1}), phosphorus (11.39 kg ha^{-1}) and potassium (140.06 kg ha^{-1}) uptake were recorded in STCR treatments, particularly in those with an integrated approach. These treatments also validated better nutrient recovery and agronomic use efficiency compared to low, medium and high (LMH) and package of practice (POP) approaches. The findings confirm the accuracy of predicted soil test values in fertilizer prescription, indicating that repeated soil testing between crops may be unnecessary. The STCR based integrated approach provided balanced nutrient application, leading to optimal yield and nutrient uptake. This study highlights the effectiveness of STCR methodologies for efficient nutrient management and improved productivity in greengram.

Keywords: Target yield; prediction equation; partial factor productivity; apparent recovery efficiency; agronomic nutrient use efficiency and internal utilization efficiency.

1. INTRODUCTION

Many tropical and subtropical regions widely cultivate greengram (*Vigna radiata* L.), also known as mung bean, for its rich protein content and role in improving soil health through biological nitrogen fixation (Meena et al., 2018). It is a crucial component of diversified farming systems, contributing to the livelihoods of millions of smallholder farmers due to its relatively short growing season, drought tolerance, and suitability for various cropping systems (Adhikari et al*.,* 2018). Despite its agronomic importance, the productivity of greengram remains suboptimal in many regions, primarily due to imbalanced nutrient management and inconsistent fertilizer application practices (Gabhane et al*.,* 2023).

In many traditional farming systems, nutrient recommendation is often based on broad, generalized fertilizer recommendation packages or categorized into low, medium and high input systems (Krishnamurthy et al*.,* 2023). These approaches are usually designed to provide nutrients based on regular crop responses across large regions, without considering the spatial variability of soil fertility or the crop's real-time nutrient demands. While these methods may be suitable and easy to implement, they often result in under- or over-application of fertilizers, leading to nutrient deficiencies or toxicities, reduced yield potential and inefficient use of resources. This inefficiency is particularly evident in sensitive crops like greengram, where optimal nutrient balance is critical for achieving higher yield and quality (Isha et al*.,* 2024).

In this context, the Soil Test Crop Response (STCR) approach has emerged as a scientifically sound alternative to traditional fertilizer recommendation systems. The STCR approach is based on the principle of applying fertilizers according to the actual nutrient needs of the crop, as determined by pre-sowing soil tests, and the targeted yield that the farmer aims to achieve (Ramamoorthy et al*.,* 1967). This approach integrates soil test values with crop response data to formulate nutrient recommendations that are specific to the crop and the given agro-ecological conditions. The advantage of STCR lies in its ability to tailor fertilizer applications not only to the nutrient status of the soil but also to the physiological needs of the plant at different growth stages, ensuring balanced and efficient nutrient supply throughout the crop cycle (Basavaraja et al*.,* 2014).

The application of STCR in greengram cultivation offers several potential benefits over traditional recommendation systems. First, by linking fertilizer doses directly to the target yield, STCR minimizes the risk of both nutrient overuse and underuse, leading to better nutrient use efficiency (NUE) and reduced environmental impact. Second, it addresses site-specific soil fertility conditions, which is particularly crucial in soils like *Alfisols*, where nutrient leaching and depletion can hinder crop performance (Abhirami et al*.,* 2024). Third, the STCR method supports precision agriculture by making nutrient management more adaptive and responsive to the actual field conditions, promoting sustainable intensification of greengram production.

The present study aims to address this gap by systematically comparing different nutrient recommendation approaches, including low-medium-high input systems, generalized fertilizer recommendations and the STCR method, in greengram cultivation under *Alfisol* conditions. The objective is to validate the performance of these approaches in terms of yield, nutrient uptake and nutrient use efficiency. Particular emphasis will be placed on the potential superiority of the STCR approach in achieving targeted yield goals while maintaining soil health. This research is expected to provide valuable insights into optimizing nutrient management strategies for greengram, offering practical recommendations for improving productivity and sustainability in pulse-based farming systems.

2. MATERIALS AND METHODS

2.1 Experimental Details

Soil test crop response-based fertilizer prescription equations for greengram were developed following the methodology of Ramamoorthy et al., (1967) during the kharif season of 2022. Post-harvest soil test value prediction equations were formulated using multiple regression analysis. The current study aims to validate and compare the nutrient uptake and nutrient use efficiency for different fertilizer recommendation approaches through a verification trial conducted in the summer of 2024 with greengram (BGS-9) at ZARS, GKVK, Bengaluru.

In this verification experiment, different fertilizer recommendation approaches were compared to validate the equation developed in the main test crop experiment, so that this equation can be recommended to the farmers, in addition to validation of post-harvest soil test values developed through post-harvest soil test value prediction equation in comparison with the actual soil test values. The soil at the experimental site was sandy loam in texture and acidic, with a pH of 5.73 (Table 1). The electrical conductivity measured 0.043 dS m^{-1}, and the organic carbon content was 0.47 per cent. Available nitrogen was low (218.97 kg N ha^{-1}), phosphorus was high (196.34 kg P_2O_5 ha^{-1}), and potassium was medium (271.11 kg K_2O ha^{-1}). The experiment was arranged in a randomized complete block design (RCBD) with twelve treatments, each replicated three times (Table 2).

A composite soil sample was collected from each plot at a depth of 0-20 cm after setting up the experiment and prior to its commencement. Based on the soil test results, NPK fertilizers were applied to achieve specific yield targets using the STCR and LMH nutrient approaches. Fertilizer application was also guided by predicted post-harvest soil test values, which were estimated using prediction equations (Table 3) derived from the main STCR experiment for greengram.

Table 1. Initial soil characteristics of the verification trial

Particulars	Values	Methodology
pH (1:2.5)	5.73	Potentiometry (Jackson, 1973)
Electrical conductivity (dS m^{-1})	0.043	Conductometry (Jackson, 1973)
Organic carbon (%)	0.47	Wet oxidation method (Walkley and Black, 1934)
Available N (kg ha^{-1})	218.97	Alkaline peramanganate method (Subbiah and Asija, 1956)
Available P_2O_5(kg ha^{-1})	196.34	Bray's method (Jackson, 1973)
Available K_2O (kg ha^{-1})	271.11	Flame photometry method (Page et al., 1982)
Available S (mg kg^{-1})	23.41	Turbidometry method (Jackson,1973)
Exchangeable calcium [c mol (P^+) kg^{-1}]	4.09	Versenate titration method (Jackson, 1973)
Exchangeable magnesium [c mol (p^+) kg^{-1}]	1.32	
DTPA iron (mg kg^{-1})	10.26	DTPA extraction method (Lindsay and Norvell, 1978)
DTPA manganese (mg kg^{-1})	6.52	
DTPA copper (mg kg^{-1})	2.55	
DTPA zinc (mg kg^{-1})	3.07	

Table 2. Treatment details of greengram in verification trial

T_1	Nutrients applied on ASTV (Inorganics) for STCR target yield 15 q ha^{-1}
T_2	Nutrients applied on PSTV (Inorganics) for STCR target yield 15 q ha^{-1}
T_3	Nutrients applied on ASTV (Integrated) for STCR target yield 15 q ha^{-1}
T_4	Nutrients applied on PSTV (Integrated) for STCR target yield 15 q ha^{-1}
T_5	Nutrients applied on ASTV (Inorganics) for STCR target yield 12 q ha^{-1}
T_6	Nutrients applied on PSTV (Inorganics) for STCR target yield 12 q ha^{-1}
T_7	Nutrients applied on ASTV (Integrated) for STCR target yield 12 q ha^{-1}
T_8	Nutrients applied on PSTV (Integrated) for STCR target yield 12 q ha^{-1}
T_9	Package of practice (RDF + FYM)
T_{10}	LMH through ASTV
T_{11}	LMH through PSTV
T_{12}	Absolute control

ASTV: actual soil test values, PSTV: predicted soil test values

List 1. The following STCR fertilizer adjustment equations were used for fertilizer application to STCR treatments

STCR Inorganic approach	STCR Integrated approach
F.N.=11.056 T – 0.330 SN($KMnO_4$-N)	F.N.=10.541 T – 0.305 SN ($KMnO_4$ -N) – 0.653 OM
F.P_2O_5 =6.946 T – 0.584 SP (Bray's-P_2O_5)	F.P_2O_5=5.955 T – 0.461 SP (Bray's- P_2O_5) – 0.092 OM
F.K_2O.=7.071 T – 0.221 SK (Am.Ace.K_2O)	F.K_2O.=8.554 T – 0.268 SK (Am.Ace.- K_2O) – 0.843 OM

Here, FN, FP_2O_5, and FK_2O represent the amounts of fertilizer nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) in kg ha^{-1}, respectively; T denotes the yield target in q ha^{-1}; SN, SP, and SK refer to available soil nutrients measured as $KMnO_4$-N, Bray's-P_2O_5, and NH_4OAc-K_2O in kg ha^{-1}, respectively; and OM indicates the amount of farmyard manure applied in t ha^{-1}

Table 3. Prediction equations for post-harvest soil nutrient parameters based on yield by Greengram

Inorganic	R^2 value
PHN = 60.642 + 0.649 FN + 0.703 SN - 0.020 Y	0.866**
PHP = - 9.028 + 0.410 FP + 1.196 SP - 0.030 Y	0.939**
PHK = 26.565 - 0.325 FK + 0.822 SK - 0.029 Y	0.881**
Integrated	
PHN = 71.425 - 0.217 FN + 0.679 SN - 0.001 Y	0.808**
PHP = 31.376 + 0.206 FP + 0.778 SP - 0.003 Y	0.902**
PHK = 50.045 + 0.335 FK + 0.815 SK - 0.052 Y	0.831**

*** Significant at P = 0.01*

In this context, FN, FP_2O_5, and FK_2O indicate the quantities of fertilizer nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) in kg ha^{-1}, respectively. T represents the yield target in q ha^{-1}. SN, SP, and SK correspond to the available soil nutrients measured as $KMnO_4$-N, Bray's-P_2O_5, and NH_4OAc-K_2O in kg ha^{-1}, respectively. OM denotes the amount of farmyard manure applied in t ha^{-1}.

The post-harvest soil test values for nitrogen, phosphorus and potassium in kodomillet (the previous crop) were predicted using these regression equations. These predicted values were used as the initial soil test values to prescribe the fertilizer nutrient doses for the verification trial in selected treatments for greengram. Data on kodomillet yield, initial soil test values and applied fertilizer nutrients were obtained from the AICRP on STCR at UAS, GKVK, Bengaluru, to predict the post-harvest soil test values.

The quantities of nutrients applied per hectare for each treatment, using various approaches, are presented in Table 4. For all treatments, 50 per cent of the recommended nitrogen was applied through urea, while the full dose of phosphorus and potassium was supplied at sowing as a basal application using single super phosphate (SSP) and muriate of potash (MoP), respectively. The remaining 50 per cent of nitrogen was applied 30 days after sowing (DAS). At harvest, the seed and haulm yields were determined from the net plot and expressed in quintals per hectare (q ha–1).

The nutrient uptake and nutrient use efficiency i.e., partial factor productivity (PFP), apparent recovery efficiency (ARE), agronomic nutrient use efficiency (ANUE) and internal utilization efficiency (IUE) were computed by using the standard formulae as shown below.

$$\text{NR (kg q}^{-1}\text{)} = \frac{\text{Nutrient uptake (NPK) by seed and haulm (kg ha}^{-1}\text{)}}{\text{Seed yield or any economic produce (q ha}^{-1}\text{)}}$$

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \frac{\text{[Nutrient content (\%)} \times \text{Dry weight (kg ha}^{-1}\text{)}}{100}$$

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

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

$$\text{ANUE (kg kg}^{-1}\text{)} = \frac{\text{[Seed yield in treated plot (kg ha}^{-1}\text{) - Seed yield in control plot (kg ha}^{-1}\text{)]}}{\text{Fertilizer nutrient applied (kg ha}^{-1}\text{)}}$$

$$\text{IUE} = \frac{\text{Seed yield (kg ha}^{-1}\text{)}}{\text{Total uptake (kg ha}^{-1}\text{)}}$$

Table 4. Fertilizer nutrient and farmyard manure application rates per hectare under different approaches based on treatments and soil test values in the verification trial

Treatments	Soil test values (kg ha⁻¹)			FYM (t ha⁻¹)	Fertilizer nutrient (kg ha⁻¹)		
	N	P_2O_5	K_2O		N	P_2O_5	K_2O
T_1	210.93	166.44	266.96	0	96.23	6.99	47.07
T_2	225.65	163.62	282.88	0	91.37	8.64	43.55
T_3	207.95	180.99	275.49	7.5	89.79	5.20	48.16
T_4	227.49	220.62	263.01	7.5	83.83	0.00	51.50
T_5	206.45	190.89	272.23	0	64.54	0.00	24.69
T_6	231.70	183.70	262.96	0	56.21	0.00	26.74
T_7	210.56	195.52	263.89	7.5	57.37	0.00	25.60
T_8	219.92	231.29	262.95	7.5	54.52	0.00	25.85
T_9 :	216.91	208.14	284.71	7.5	25.00	50.00	50.00
T_{10}	212.05	197.97	275.59	7.5	37.50	37.50	50.00
T_{11}	242.18	202.91	300.02	7.5	37.50	37.50	45.83
T_{12}	215.79	213.98	242.63	0	0.00	0.00	0.00

T_1: STCR through inorganics (15 q ha^{-1}) - Actual STV;
T_2: STCR through inorganics (15 q ha^{-1}) - Predicted STV
T_3: STCR through integrated (15 q ha^{-1}) - Actual STV
T_4: STCR through integrated (15 q ha^{-1}) - Predicted STV
T_5: STCR through inorganics (12 q ha^{-1}) - Actual STV
T_6: STCR through inorganics (12 q ha^{-1}) - Predicted STV
T_7: STCR through integrated (12 q ha^{-1}) - Actual STV
T_8: STCR through integrated (12 q ha^{-1}) - Predicted STV
T_9: Package of practice
T_{10}: LMH (STL) - Actual STV
T_{11}: LMH (STL) - Predicted STV
T_{12}: Absolute control

2.2 Statistical Analysis of Data

Experimental data generated in the verification trial was subjected to statistical analysis adopting Fisher's method of analysis of variance as outlined by Gomez and Gomez (1984). 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.

3. RESULTS AND DISCUSSION

3.1 Seed and Haulm yield

The data on seed yield and haulm yield influenced by different fertilizer recommendation approaches, considering both actual and predicted soil test values, are presented in Fig. 1. A significantly higher seed yield of 17.99 q ha^{-1} was recorded in the STCR approach targeting 15 q ha^{-1}, where nutrients were applied using an integrated approach based on actual soil test values (T_3). The lowest seed yield (6.04 q ha^{-1}) was observed in the absolute control (T_{12}). However, the seed yield in T_3 was on par with treatments T_1 (14.77 q ha^{-1}), T_2 (15.78 q ha^{-1}), T_4 (16.49 q ha^{-1}), and T_7 (14.37 q ha^{-1}). Similarly, a significantly higher haulm yield of 30.25 q ha^{-1} was recorded in T_2 [STCR inorganics (15 q ha^{-1}) - Predicted STV], which was comparable to T_1 (29.79 q ha^{-1}), T_3 (29.13 q ha^{-1}), and T_4 (28.48 q ha^{-1}), all targeting a yield of 15 q ha^{-1}. The lowest haulm yield (10.29 q ha^{-1}) was recorded in the absolute control (T_{12}).

"The higher yield in STCR treatments could be attributed to the ability of targeted yield approaches to satisfy the nutrient demand of crop more efficiently. The combination of chemical fertilizers with FYM created a favorable soil environment and provided essential nourishment for improved yield parameters and ultimately resulting in maximum seed yield" (Krishna Murthy et al*.,* 2023). Indeed, the absolute control exhibited the poor yield attributes and lowest seed yield because it did not receive any fertilization, neither chemical nor organic. The absence of nutrient supplementation in this treatment resulted in limited plant growth and productivity (Abhirami et al*.,* 2024).

It is important to notice that application of nutrients based on predicted soil test values for the targets of 15 and 12 q ha^{-1} in both inorganic and integrated approach have recorded higher yield over LMH and POP approaches which was mainly due to increased fertilizer nutrient application. However, there was no significant difference between actual and predicted soil test values indicating the accuracy of soil test values which were predicted making use of data on initial soil test values, fertilizer dose and yield of kodomillet (previous crop in the experimental site) by adopting post-harvest soil test values prediction equations that were developed during the main experiment. Thus, the predicted soil test values could be used with confidence to prescribe the fertilizer nutrient dose in a cropping sequence therefore testing the soil after each crop to recommend the fertilizers can be avoided. Similar results were recorded by Coumaravel et al*.* (2016) for maize and Gangola et al*.* (2017) for maize-chickpea sequence.

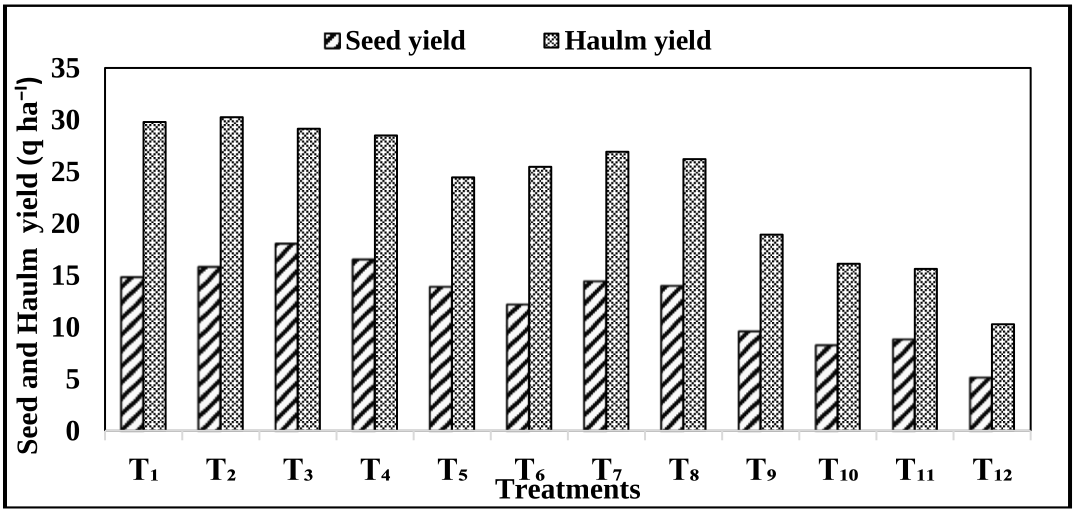

Fig. 1. Influence of different approaches of fertilizer recommendation on seed and haulm yield of greengram

3.2 Nutrient Uptake

3.2.1 Nitrogen

The results on nitrogen uptake by greengram seed, haulm and total uptake as influenced by different nutrient management approaches are presented in Fig. 2.

Significantly higher nitrogen uptake in seed (69.54 kg ha^{-1}) and total uptake (110.73 kg ha^{-1}) were observed in treatment STCR target 15 q ha^{-1} through integrated based on actual soil test whereas,, higher nitrogen uptake in haulm (45.18 kg ha^{-1}) was recorded in treatment STCR target 15 q ha^{-1} through inorganic based on predicted soil test values and was found to be on par with treatments STCR target 15 q ha^{-1} through inorganics based on actual soil test values (T_1) (seed: 56.87, haulm: 44.52 and total uptake: 101.39 kg ha^{-1}) and STCR target 15 q ha^{-1} through integrated approach based on predicted soil test values (T_4) (seed: 67.31, haulm: 43.12 and total uptake: 110.43 kg ha^{-1}). Lower nitrogen uptake was recorded in absolute control (T_{12}) (seed: 16.90, haulm: 10.10 and total uptake: 27.01 kg ha^{-1}).

3.2.2 Phosphorus

It is evident from the Fig. 3 that, significantly higher phosphorus uptake by seed (6.90 kg ha^{-1}) and total uptake (11.39 kg ha^{-1}) were recorded with treatment receiving fertilizer nutrients through STCR approach for the targeted yield of 15 q ha^{-1} based on actual soil test values (T_3) whereas, significantly higher uptake of haulm (4.82 kg ha^{-1}) was recorded in treatment T_2 [STCR inorganic (15 q ha^{-1})- predicted STV]. Here treatment (T_3) in case of seed and total uptake and treatment (T_2) in case of haulm were found to be on par with the treated plots of 15 q ha^{-1} target yield and least was recorded in control plot (T_{12}) (seed: 0.90, haulm: 1.20 and total: 2.11 kg ha^{-1}). The uptake was higher in seed compared to haulm and similarly higher uptake was recorded in all the integrated approaches with both actual and predicted soil test values compared to LMH and package of practice.

3.2.3 Potassium

Significantly higher potassium uptake in seed (58.59 kg ha^{-1}), haulm (81.47 kg ha^{-1} and total uptake (140.06 kg ha^{-1}) were observed in treatment STCR target 15 q ha^{-1} through integrated based on actual soil test value and was found to be on par with treatments STCR target 15 q ha^{-1} through integrated (T_4) based on PSTV and inorganics (T_1 and T_2) based on predicted and actual soil test values. Lower potassium uptake was recorded in absolute control (T_{12}) (seed: 7.59, haulm: 8.84 and total uptake: 16.43 kg ha^{-1}). Higher uptake of potassium was recorded through integrated approach compared to inorganic approach where NPK fertilizers were applied without farmyard manure at 7.5 t ha^{-1}.

Application of increased NPK levels with farmyard manure based on soil test values for the targeted yield of greengram recorded significantly higher uptake of nitrogen, phosphorus and potassium by seed and haulm of greengram over that of LMH approach and package of practice (Fig. 4). This could be attributed to higher yield of greengram and higher application of fertilizer doses that enables the higher availability of nutrients in the vicinity of greengram root thereby proliferation of root system under balanced application leads to ease in absorption of nitrogen, phosphorus and potassium resulted in higher uptake.

The higher uptake of NPK in STCR integrated approach was reported by Krishnamurthy et al. (2023) in brinjal which was attributed to higher yield associated with higher dose of NPK fertilizers and FYM compared to other treatments which might have helped in better availability of these nutrients in the vicinity of plat roots that might have increased the uptake. Similarly, the higher yield with STCR approach compared to general recommended dose and LMH approach could be attributed to balanced application of nutrients considering the crop requirement and contribution from soil, fertilizer and FYM based STCR treatments (Basavaraja et al., 2014).

3.3 Nutrient Requirement

A higher nitrogen requirement for seed production (6.86 kg q^{-1}) was observed in the treatment (Table 5) of STCR inorganic approach based on actual soil test values for a target yield of 15 q ha^{-1} (T_1), followed by the STCR inorganic approach based on predicted soil test values (T_2: 6.83 kg q^{-1}). In contrast, the lowest nitrogen requirement (5.97 kg q^{-1}) was recorded in the LMH approach using predicted soil test values (T_{11}). Similarly, the highest phosphorus (P_2O_5) requirement (0.69 kg q^{-1}) was recorded in the STCR inorganic approach based on actual soil test values for the 15 q ha^{-1} target (T_1), followed by the STCR inorganic approach using predicted soil test values (T_2: 0.68 kg q^{-1}), with the lowest phosphorus requirement (0.60 kg q^{-1}) observed in the LMH approach using predicted soil test values (T_{11}). For potassium (K_2O), the highest requirement (4.79 kg q^{-1}) was recorded in the STCR integrated approach based on predicted soil test values for the 15 q ha^{-1} target (T_4), followed by the STCR inorganic approach for a 12 q ha^{-1} target using predicted soil test values (T_6: 4.54 kg q^{-1}). The lowest potassium requirement (3.27 kg q^{-1}) was recorded in the LMH approach based on predicted soil test values (T_{11}).

Higher nitrogen and potassium requirement might be due to more utilization of nutrients by the crop for higher yield in STCR approach and higher nutrient requirement in STCR treatments might be attributed to application of higher dose of fertilizers thereby increase in the availability of nutrient for plant uptake (Rangaiah et al., 2024).

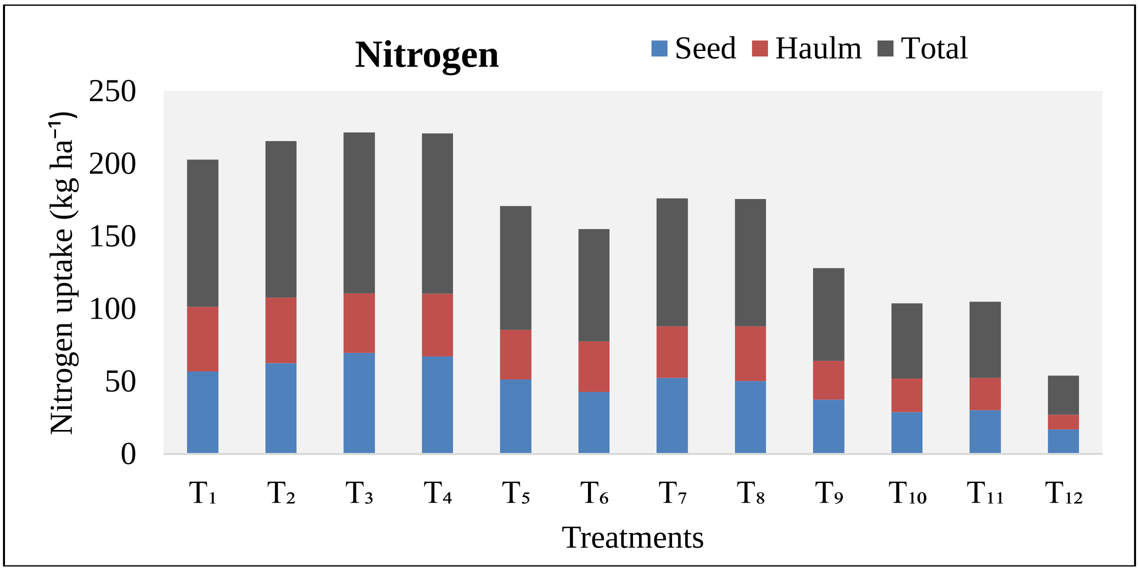

Fig. 2. Influence of different approaches of nutrient application on uptake of nitrogen in greengram

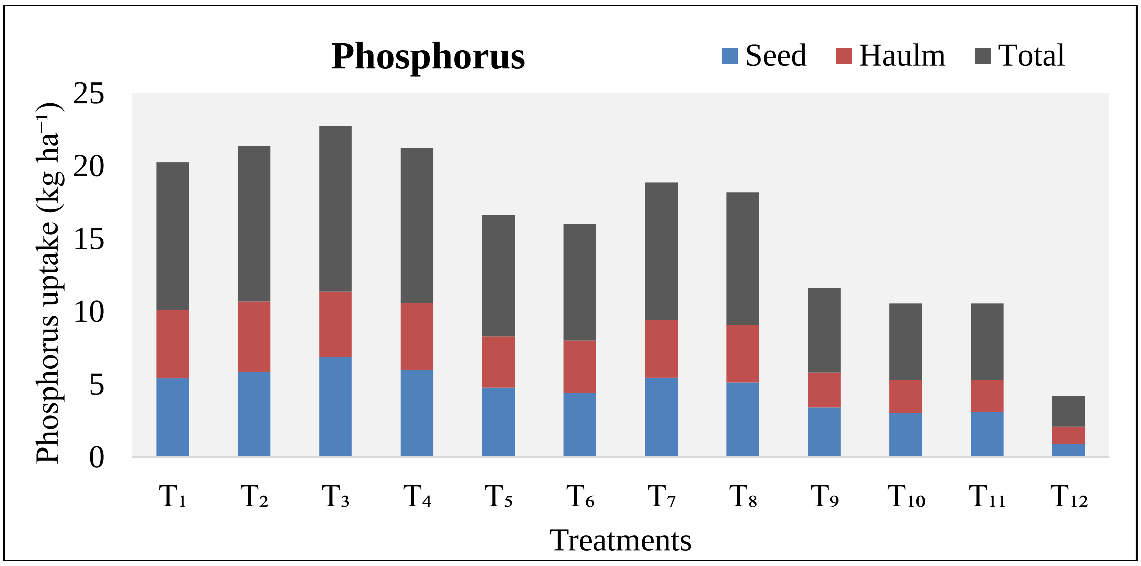

Fig. 3. Influence of different approaches of nutrient application on uptake of phosphorus in greengram

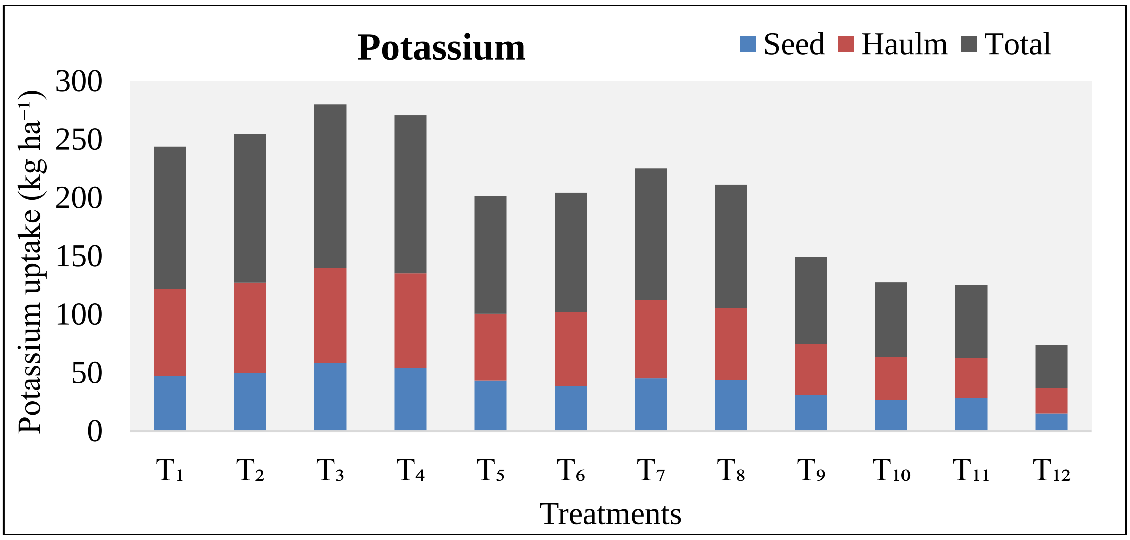

Fig. 4. Influence of different approaches of nutrient application on uptake of potassium in greengram

Table 5. Nutrient requirement (NR) and Partial factor productivity (PFP) of N, P_2O_5 and K_2O as influence of different approaches of nutrient application

Treatments	NR (kg q^{-1})			PFP (q kg^{-1})		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
T_1	6.86	0.69	4.50	18.34	211.33	31.38
T_2	6.83	0.68	4.41	17.27	182.69	36.24
T_3	6.16	0.63	4.48	20.03	345.89	37.35
T_4	6.70	0.64	4.79	19.67	-	32.02
T_5	6.16	0.60	3.82	21.46	-	56.11
T_6	6.38	0.66	4.54	21.62	-	45.44
T_7	6.13	0.66	3.93	25.05	-	56.14
T_8	6.30	0.65	4.28	25.58	-	53.95
T_9	6.69	0.61	3.94	15.34	19.17	19.17
T_{10}	6.30	0.64	3.77	17.29	21.98	16.49
T_{11}	5.97	0.60	3.27	15.98	23.47	19.20
T_{12}	5.27	0.41	3.21	-	-	-

3.4 Partial Factor Productivity

The partial factor productivity (PFP) of nitrogen was highest (25.58 q kg^{-1}) in treatment T_8 [STCR integrated approach for a 12 q ha^{-1} target, based on predicted soil test values], compared to T_{10} (LMH - Actual STV, 17.29 q kg^{-1}), T_{11} (LMH - Predicted STV, 15.98 q kg^{-1}), and POP (15.34 q kg^{-1}) as shown in Table 5. For potassium, the highest PFP (56.14 q kg^{-1}) was observed in the STCR integrated approach targeting 12 q ha^{-1}, based on actual soil test values. In contrast, the lowest PFP (16.49 kg q^{-1}) was recorded in the LMH approach based on actual soil test values (T_{10}). The partial factor productivity of nitrogen was significantly higher in treatment T_8 [STCR integrated (12 q ha^{-1}) - predicted STV] which might be due to higher yield obtained with respect to lower application rate of nitrogen. Similarly, the partial factor productivity of K_2O was significantly in T_7 with target yield of 12 q ha^{-1} which is also attributed to the application of lower dose of fertilizer compared to other treatments. The finding of the present study was supported by Krishnamurthy et al. (2023) who reported that higher PFP was positively correlated with higher yield obtained and lower dose of applied fertilizers in case of brinjal crop.

3.5 Apparent Recovery Efficiency and Agronomic Nutrient Use Efficiency

The apparent recovery efficiency (ARE) and agronomic nutrient use efficiency (ANUE) of nitrogen, based on actual and predicted soil test values (Table 6), ranged from 0.66 to 1.46 kg

Table 6. Apparent recovery efficiency and Agronomic nutrient use efficiency and Internal utilization efficiency of N, P_2O_5 and K_2O as influence of different approaches of nutrient application

Treatment	ARE (kg kg^{-1})			ANUE (kg kg^{-1})			IUE (kg kg^{-1})		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
T_1	0.77	1.15	1.06	10.03	138.05	20.50	14.57	145.77	12.12
T_2	0.89	0.99	1.22	11.67	123.40	24.48	14.64	147.67	12.40
T_3	0.93	1.78	1.33	14.33	247.38	26.71	16.24	157.96	12.84
T_4	1.00	-	1.22	13.56	-	22.07	14.93	155.40	12.17
T_5	0.91	-	1.48	13.53	-	35.36	16.22	166.77	14.75
T_6	0.90	-	1.45	12.50	-	26.28	15.68	151.65	11.89
T_7	1.46	-	1.56	16.12	-	36.13	16.76	152.44	12.75
T_8	1.12	-	1.67	16.18	-	34.13	15.88	153.38	13.19
T_9	1.08	0.07	0.43	15.84	8.92	8.92	14.96	164.96	12.83
T_{10}	0.66	0.09	0.29	8.32	8.32	6.24	15.88	156.01	12.91
T_{11}	0.68	0.09	0.27	9.81	9.81	8.02	13.32	146.63	12.03
T_{12}	-	-	-	-	-	-	18.97	243.16	13.86

kg– 1 for ARE and 8.32 to 16.18 kg kg^{-1} for ANUE. The highest ARE (1.46 kg kg^{-1}) and ANUE (16.18 kg kg^{-1}) were observed in the STCR integrated approach for the target yield of 12 q ha^{-1} based on predicted soil test values and outperformed the POP and LMH approaches. For potassium, ARE ranged from 0.27 to 1.67 kg kg^{-1} and ANUE from 8.02 to 36.13 kg kg^{-1}. The highest ARE (1.67 kg kg^{-1}) and ANUE (36.13 kg kg^{-1}) were also recorded in the STCR integrated approach for the same yield target. Both ARE and ANUE were consistently higher in the STCR integrated approach compared to the inorganic approach across treatments.

"The higher ARE and ANUE of nitrogen in STCR target of 12 q ha^{-1} through integrated based on predicted soil test values can be attributed to higher uptake and yield due to application of higher dose of nitrogen fertilizer compared to other treatments. However, higher ARE and ANUE of potassium was recorded in STCR target 12 q ha^{-1} based on predicted soil test values. This can also be attributed to application of higher dose of potassium fertilizers compared to other treatments. Even though higher dose of potassium fertilizer was applied in LMH approach and package of practice, ARE and ANUE was recorded higher in STCR treated plots which indicates the effective utilization of applied and soil available nutrients in STCR approach" (Krishnamurthy et al., 2023)

3.6 Internal Utilization Efficiency

The internal use efficiency of nitrogen was found to be numerically higher (16.76 kg kg^{-1}) in STCR integrated approach for the targeted yield of 12 q ha^{-1} by considering actual soil test values and lower value (14.57 kg kg^{-1}) were recorded in STCR approach for the targeted yield of 15 q ha^{-1}. With respect to phosphorus apart from control plot it was found to be numerically higher (166.77 kg kg^{-1}) in STCR inorganic approach for the targeted yield of 12 q ha^{-1} by considering actual soil test values. Similarly, in potassium apart from control plot it was found to be numerically higher (14.75 kg kg^{-1}) in STCR integrated approach for the targeted yield of 12 q ha^{-1} by considering actual soil test values. Whereas, lower value was recorded in LMH approach through predicted soil test values (Table 6).

The higher internal use efficiency (IUE) observed in the STCR integrated approach for the lower yield target (12 q ha^{-1}) suggests that this method better synchronizes nutrient availability with crop demand (Bhavya, 2021). In contrast, the reduced IUE at the higher yield target may be attributed to the greater nutrient inputs needed to achieve that yield, resulting in less efficient nutrient utilization. The highest potassium IUE was also recorded in the STCR integrated approach, reflecting a balanced nutrient management strategy that combines organic and inorganic inputs (Basavaraja et al*.,* 2019). Conversely, the lower potassium efficiency in the LMH approach indicates that the applied nutrients may not have fully met the crop's requirements, leading to less efficient nutrient use.

4. CONCLUSION

Based on this study, it can be concluded that the STCR integrated approach demonstrated superior performance in terms of yield, nutrient uptake and nutrient use efficiency of nitrogen, phosphorus and potassium, especially for the targeted yields of 12 and 15 q ha^{-1}. The integrated approach, which combines chemical fertilizers with organic inputs like FYM, effectively met crop nutrient demands, resulting in higher seed and haulm yields, improved internal utilization efficiency and better nutrient recovery compared to the LMH and POP approaches. The use of predicted soil test values proved as effective as actual values, ensuring accurate fertilizer recommendations, which can reduce the need for frequent soil testing between crops. Overall, the STCR approach, particularly when integrating both organic and inorganic inputs, optimized nutrient management and boosted greengram productivity by enhancing nutrient availability, uptake and efficiency.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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