Soil Test Crop Response based Fertilizer Prescriptions for Achieving Target Yields of Linseed in Varanasi

Abstract

Soil Test Crop Response (STCR) study was conducted at farmer's field of Varanasi during 2017-2018 by following the inductive cum target yield model to get the fertilizer prescription equations for NPK fertilizer recommendation for linseed, with and without farmyard manure (FYM) under integrated plant nutrient management (IPNM) system. It was noticed that 3.68, 1.15 and 3.84 kg of N, P and K, respectively were required for producing one quintal of linseed grain. The percentage contribution of nutrients from soil, FYM were 10.31, 47.00 and 8.82 for N, 52.66, 45.06 and 5.59 for P, and 14.74, 115.18 and 12.27 for K, respectively. Further, Ready reckoner of fertilizer doses at varying soil test values for different targeted yield (15, 18 and 21 q ha^{-1}) were also developed. Adoption of STCR-IPNM system saved up to 15.5% N, 47.1% P_2O_5 and 27.6% K_2O fertilizer, when applied in combination with 10t ha^{-1} FYM. Multiple linear regression model identified '+ - -' response type for P and K, and quantified their critical soil test values (24.8 kg ha^{-1} and 279.9 kg ha^{-1}, respectively). Good agreements between measured and predicted post-harvest soil test (N, P and K) values were observed while calibrating the model. Thus, this STCR approach could be adopted for making site-specific NPK recommendations for experimental site or regions with similar soil and agro-climatic conditions to achieve targeted yield of linseed crop.

Keywords: Linseed; soil test crop response**;** target yield; fertilizer prescription equations; integrated plant nutrient management.

Introduction

Linseed (*Linum usitatissimum* L.) is a dual purpose crop grown for its fiber and oil content. Among the various *rabi* oilseed crops grown in India, linseed stands next only to rapeseed-mustard in terms of area (0.33 million ha) and production (0.17 million tonnes) (MOA 2018). Currently, linseed is gaining interest in the trending market of functional food because of its higher oil (41%), protein (20 %) and α-linolenic acid (16%) content (Morris 2007). In spite of nutritional, industrial and other miscellaneous benefits (Saleem et al. 2020; Ebrahimi et al. 2021), area under linseed cropping is gradually shrinking from the last few decades due its constrained production (Meena et al. 2020). Although rainfed cultivation, erratic precipitation pattern, poor soil fertility etc. were the reasons behind its poor productivity in India, fertilization at sub-optimal doses also a concerning factor (Kumar, Singh, and Vishwakarma 2018; Dhaliwal et al. 2022). Such imbalanced fertilization not only mirrors stagnant or declining linseed yield but also hampers soil fertility. Thus, there is a need for conveying proper knowledge among farmers about the exact fertilizer demand of linseed for the target yield they want to achieve along with sustained soil health. Integrated plant nutrition system (IPNS) (conjunctive use of organic manures, chemical fertilizers and bio-fertilizers) in combination with target yield approach might be the proper solution of the aforesaid problem (Khan et al. 2020; Tayade, Bhaskaran, and Anusha 2020).

Theory of fertilizer prescription based on target yield approach was given by Troug (1960) which was later on modified by Ramamoorthy, Narasimhan, and Dinesh (1967) as inductive cum target yield model or Inductive approach of Soil Test Crop Response (STCR) correlation studies. It involves basic parameters i.e., nutrient requirement for 1q grain production (NR), percentage contribution of nutrient from soil (Cs), fertilizer (Cf) and farmyard manure (Cfym) by using plot wise initial soil test values, amount of fertilizer and FYM applied, NPK uptake and grain yield of linseed in order to generate fertilizer adjustment equations and calibration chart for recommending fertilizer doses based on soil test and target yield of linseed. Moreover, prior to sowing of any crop, it is essential to have proper knowledge of soil nutrient status;otherwise, it could manifest deficiency or toxicity of nutrients in crop due to inadequate/excessive use of fertilizers. Conversely, it is not feasible for small and marginal farmers of India to go for soil testing prior to every crop. Thus, STCR made use of post-harvest prediction equation(Ramamoorthy and Velayutham 1971) on the basis of which it was easy to predict the post-harvest status of soil from which fertilizer prescriptions can be made not only for single crop but also for entire cropping system grown in succession (Mahajan et al. 2019). Further, the fertilizer prescription equations are valid for similar type of varieties (mainly yield potential) for which it was originally developed. If variety is changed and the yield potential differs (say from open pollinated variety to hybrid), we need to develop fertilizer prescription equation again. For change of location, there is process called refinement experiment for reconstructing the fertilizer prescription equation (Goyal, Bhardwaj, and Dey 2023). According to Velayutham, Reddy, and Sankar1984, if the targeted yield was achieved within ± 10 per cent variation, then the equations are found to be valid. Rani et al. 2022 achieved yield targets of 3.0 and 3.5 t ha^{-1} of pearl millet within deviations of − 2.2 to + 1.0 and − 2.0 to + 0.9%, respectively even after completion of 10 cycles of Pearl millet-Wheat cropping system using STCR approach. Similarly, Sharma, Pandey, and Sharma 2015 also achieved the target yield of pearl millet and wheat within ± 10 per cent variation after completion of 8 pearl millet – wheat cropping sequence.

To date, plentiful studies were conducted by using STCR model to calibrate fertilizer prescription equations and to recommend fertilizers via ready reckoner chart for specific yield target for different crops (Singh et al. 2015 on jute, rice and garden pea; Mazumdar et al. 2020 on potato). Literatures are also available on developing response type of fertilizers and critical soil test values of N, P and K (Bhaduri and Gautam 2013; Chatterjee and Srivastava 2015) along with prediction of post-harvest soil test values of N, P and K (Coumarvel and Santhi 2016; Mondal et al. 2020) but with lower level of precision. However, all these information regarding linseed were meager. Thus, the present experiment was conducted at farmer’s field with the following objectives (i) to obtain the target yield of linseed along with the fertilizer prescription equations and calibration chart for fertilizer recommendation (ii) to develop multiple quadratic regression equation of soil test values, doses of fertilizers and FYM on linseed grain yield (iii) to develop response type of fertilizes and critical soil test values of N, P and K from multiple regression equation (iv) to predict and validate post-harvest soil test values for N, P and K by using Multiple linear regression (MLR) model for Loharpur village of Varanasi.

Material and methods

Details of experimental area

This experiment was initiated at farmer's field of Loharpur village in Varanasi during 2017-2018. Varanasi is located at 25°18′N, 80°36′E, and 80.7 m above mean sea level and comes under subtropical climate. During the experimental trial 647.4 mm of rainfall received, mean maximum and minimum temperature were 30ºC and18ºC and, 69–96% and 24–89% maximum and minimum relative humidity were observed (Figure S1). Taxonomically soils are classified under Inceptisol representing alluvial soil. The surface soil (0-15 cm) of experimental area was clay loam in texture with slightly alkaline pH (7.49), 0.243 dSm^{-1}electrical conductivity and medium in oxidizable organic carbon (0.57%). Moreover, soil was low in available (alkaline $KMnO_4$ extractable) nitrogen (245 kg ha^{-1}), medium in Olsen extractable phosphorus (18.44 kg ha^{-1}) and medium in ammonium acetate (NH_4OAc) extractable potassium (206 kg ha^{-1}).

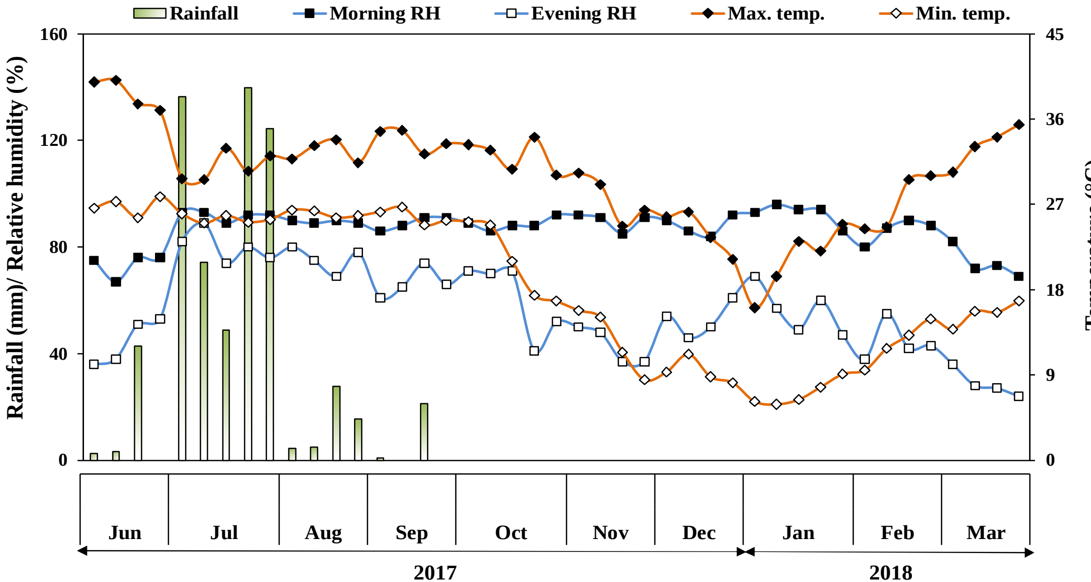

Figure S1. Meteorological data of experimental site of Varanasi, India during experimental season 2017- 2018. RH, relative humidity, temperature

Fertility gradient experiment

The variation in soil fertility was created by following the procedures of inductive methodology (Ramamoorthy, Narasimhan, and Dinesh 1967; Ramamoorthy and Velayuthum 1971). Selected 1269.6 m^2 (52.9 m × 24 m) field was divided into three equal sized strips (L_0, L_1 and L_2) and different fertilizer doses, low (0, 0, 0), medium (120, 60, 60) and high (240, 120, 120) kg ha^{-1}of N, P_2O_5 and K_2O, were applied to L_0, L_1 and L_2 strips, respectively. HUR-105 variety of rice was grown as an exhaust crop during *kharif* season 2017 and after harvesting its biomass (grain and straw) yield was estimated.

STCR experiment

Test crop linseed was grown after exhaust crop (rice) during *rabi* season 2017. The treatments comprised of selected combination of four levels of nitrogen (0, 40, 80, 120 kg N ha^{-1}), phosphorus (0, 25, 50, 75 kg P_2O_5 ha^{-1}), potassium (0, 20, 40, 60 kg K_2O ha^{-1}) and three levels of FYM (0, 5, 10 FYM t ha^{-1}) (Table S1). Experiment was outlined in fractional factorial randomized block design and layout of field along with treatments. Each strip was divided into 24 plots of equal sized (4 m x 3 m=12 m^2) to accommodate 24 fertilizer treatments (21 treatments and 3 controls) and replicated thrice, resulting in total of 72 (24 x 3) plots. Subsequently, three blocks (A, B, C) comprising of 8 fertilizer treatments were made within each strip randomized with FYM levels. FYM was mixed thoroughly in the soil as per treatment structure during land preparation (before fertilizer application). 10 t ha^{-1} FYM had 38% moisture, 0.5% N, 0.3% P_2O_5 and 0.5% K_2O. Urea (46% N), single super phosphate (16% P_2O_5) and muriate of potash (60% K_2O) were used as source of N, P and K, respectively. Full doses of P and K fertilizers were applied as basal dose and N was applied in two equal splits, half as basal and remaining half at 30 days after sowing of linseed. Plot-wise nutrient levels were estimated before applying treatments and to do so soil samples (0-15 cm) from all the 72 plots were collected, processed and analyzed for available nitrogen (Subbiah and Asija 1956), available phosphorus (Olsen et al. 1954) and available potassium (Hanway and Heidal 1952). Linseed (variety Mukta) was sown at a spacing of 30 cm ×10 cm in a plot by following recommended package of practices. After harvesting, plot-wise grain and straw yield of linseed were recorded separately and representative plant samples were collected, processed and analyzed for N, P and K contents (Jackson 1973). Corresponding nutrient uptake was calculated by multiplying N, P and K content with dry matter yield. Post-harvest soil samples were also collected, processed and analyzed for N, P and K.

Basic parameters i.e.,NR, Cs, Cf (Ramamoorthy, Narasimhan, and Dinesh 1967) and Cfym (Santhi, Selvakumari, and Perumal 1999) were calculated.

Table S1. Details of treatments

S. No.	Treatment combinations				Amount of fertilizers (kg ha^{-1})			FYM (tha^{-1})
	N	P	K	FYM	N	P_2O_5	K_2O	
1	0	0	0	2	0	0	0	10
2	3	3	1	2	120	75	20	10
3	0	2	2	2	0	50	40	10
4	3	2	2	2	120	50	40	10

5	2	1	2	2	80	25	40	10
6	2	2	3	2	80	50	60	10
7	1	1	2	2	40	25	40	10
8	3	3	3	2	120	75	60	10
9	0	0	0	1	0	0	0	5
10	3	1	1	1	120	25	20	5
11	2	2	0	1	80	50	0	5
12	1	2	2	1	40	50	40	5
13	2	1	2	1	80	25	40	5
14	1	1	1	1	40	25	20	5
15	1	2	1	1	40	50	20	5
16	3	3	2	1	120	75	40	5
17	0	0	0	0	0	0	0	0
18	3	2	1	0	120	50	20	0
19	2	0	2	0	80	0	40	0
20	2	2	2	0	80	50	40	0
21	2	2	1	0	80	50	20	0
22	2	1	1	0	80	25	20	0
23	2	3	3	0	80	75	60	0
24	3	2	3	0	120	50	60	0

Method of developing the basic parameters

1. **Nutrient requirement in kg q^{-1} of grain (NR)**

$$\text{kg of N/P}_2\text{O}_5\text{/K}_2\text{O required per quintal of grain production}$$

$$= \frac{\text{Nutrient uptake of N/P}_2\text{O}_5\text{/K}_2\text{O (kg ha}^{-1})}{\text{Yield of grain (q ha}^{-1})}$$

2. **Percentage of nutrient contribution from soil to total nutrient uptake (Cs)**

$$\text{Percentage contribution of N/P}_2\text{O}_5\text{/K}_2\text{O from soil}$$

$$= \frac{\text{Total uptake of N/P}_2\text{O}_5\text{/K}_2\text{O in control plot (kg ha}^{-1})}{\text{Soil test values for available N/P}_2\text{O}_5\text{/K}_2\text{O in control plot (kg ha}^{-1})} \times 100$$

3. **Percentage of nutrient contribution from fertilizer to total nutrient uptake (Cf)**

$$\text{Percentage contribution of N/P}_2\text{O}_5\text{/K}_2\text{O from fertilizer}$$

$$= \frac{\begin{array}{c}\text{Total uptake of N/P}_2\text{O}_5\text{/K}_2\text{O in treated plot (kg ha}^{-1}) - \\ \text{Soil test values for available N/P}_2\text{O}_5\text{/K}_2\text{O in treated plot (kg ha}^{-1}) \times \text{Average Cs}\end{array}}{\text{Fertilizer N/P}_2\text{O}_5\text{/K}_2\text{O applied (kg ha}^{-1})} \times 100$$

4. **Percentage of nutrient contribution from FYM to total uptake (Cfym)**

Percentage contribution of N/P/K from farmyard manure

$$= \frac{\text{Total uptake of N/P/K in FYM treated plot (kg ha}^{-1}) - \text{Soil test values for available N/P/K in FYM treated plot (kg ha}^{-1}) \times \text{Average Cs}}{\text{N/P/K added through FYM (kg ha}^{-1})} \times 100$$

These parameters were used to develop target yield equations for soil test based fertilizer recommendations in the form of ready reckoner table to achieve desired yield targets of linseed under NPK alone and NPK with FYM.

Targeted yield equations

Fertilizer nitrogen (FN)

$$\text{FN(without FYM)} = \frac{\text{NR}}{\text{Cf}/100}\text{T} - \frac{\text{Cs}}{\text{Cf}} \times \text{SN}$$

$$\text{FN(with FYM)} = \frac{\text{NR}}{\text{Cf}/100}\text{T} - \frac{\text{Cs}}{\text{Cf}} \times \text{SN} - \frac{\text{Cfym}}{\text{Cf}} \times \text{ON}$$

Fertilizer phosphorous (FP_2O_5)

$$\text{FP}_2\text{O}_5\text{(without FYM)} = \frac{\text{NR}}{\text{Cf}/100}\text{T} - \frac{\text{Cs}}{\text{Cf}} \times 2.29 \times \text{SP}$$

$$\text{FP}_2\text{O}_5\text{(with FYM)} = \frac{\text{NR}}{\text{Cf}/100}\text{T} - \frac{\text{Cs}}{\text{Cf}} \times 2.29 \times \text{SP} - \frac{\text{Cfym}}{\text{Cf}} \times 2.29 \times \text{OP}$$

Fertilizer potassium (FK_2O)

$$\text{FK}_2\text{O(without FYM)} = \frac{\text{NR}}{\text{Cf}/100}\text{T} - \frac{\text{Cs}}{\text{Cf}} \times 1.21 \times \text{SK}$$

$$\text{FK}_2\text{O(with FYM)} = \frac{\text{NR}}{\text{Cf}/100}\text{T} - \frac{\text{Cs}}{\text{Cf}} \times 1.21 \times \text{SK} - \frac{\text{Cfym}}{\text{Cf}} \times 1.21 \times \text{OK}$$

where FN, FP, and FK were fertilizer N, P and K dose (kg ha^{-1}); SN, SP and SK were available soil-test values of N, P and K (kg ha^{-1}); ON, OP and OK were quantity of N, P and K respectively applied through FYM; and T is yield target (q ha^{-1}).

Multiple regression equation

Multiple regression equation (Panse and Sukhatme 1962) using quadratic model was used to calculate the doses of nutrients required to achieve maximum crop yield under definite set of experimental conditions as given below-

$$\text{Y} = \pm \text{A} \pm b_1\text{SN} \pm b_2\text{SN}^2 \pm b_3\text{SP} \pm b_4\text{SP}^2 \pm b_5\text{SK} \pm b_6\text{SK}^2 \pm b_7\text{FN} \pm b_8\text{FN}^2 \pm b_9\text{FP} \pm b_{10}\text{FP}^2 \pm b_{11}\text{FK} \pm b_{12}\text{FK}^2 \pm b_{13}\text{FNSN} \pm b_{14}\text{FPSP} \pm b_{15}\text{FKSK}$$

where, Y = linseed grain yield (q ha^{-1}); A = intercept (kg ha^{-1}), b_i =regression coefficients (kg ha^{-1}); SN, SP and SK were available soil nitrogen, phosphorus and potassium (kg ha^{-1}) respectively and FN, FP and FK were fertilizer nitrogen, phosphorus and potassium respectively in kg ha^{-1}.

Generally it was observed that at a given soil test values, the yield of crop increases with increase in doses of fertilizer up to a certain limit beyond which yield will not increases but decreases following the ‘Law of diminishing return’ (Chatterjee, Srivastava, and Singh 2010). In quadratic type response curve, this happens only when linear term of fertilizer nutrient is positive and its quadratic and interaction terms are negative i.e., (+ - -) response type. That’s why, critical soil test value was calculated for only those nutrients which gives (+ - -) response type by dividing regression coefficient of linear term of fertilizer by regression coefficient of interaction term of soil and fertilizer nutrient in multiple regression equation of treated plots.

Prediction equations for post-harvest soil test values

Multiple Linear Regression (MLR) equations for predicting post-harvest soil test values (Ramamoorthy, Agarwal, Singh 1971) were used. Plot wise soil test values before sowing of test crop, fertilizer and FYM doses, uptake of nutrients each for N, P and K along with grain yield of linseed were taken as independent variable and post-harvest soil test values as dependent variable. The functional relationship was as follows-

$$\text{PHS} = f\,(\text{F, ISTV, Y/ NU})$$

where, PHS = post-harvest soil test values; F = amount of fertilizer doses applied; FYM= amount of FYM applied; ISTV = initial soil test values of N, P and K; Y = grain yield of linseed and NU = nutrient uptake.

Mathematical form of this equation was as follows-

$$\text{PHS} = a + b_1\text{F} + b_2\text{ISTV} + b_3\text{Y/NU}$$

where, ‘a’ was absolute constant and b_1, b_2, b_3 and b_4 were respective regression coefficient. By using these regression equations after linseed, post-harvest soil test values of N, P and K were predicated.

Precision level of MLR analysis were tested by using coefficient of determination (R^2), root mean square error (RMSE), relative error (RE), ratio of performance to deviation (RPD) which were computed by using Microsoft excel as follows-

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(A_i - P_i)^2}{n}}$$

$$\text{RE} = \sqrt{\frac{\sum_{i=1}^{n}\{(A_i - P_i)^2/A_i\}^2}{n}} \times 100$$

where, A_i and P_i were actual and predicted post-harvest soil test values of given nutrient at i^{th}data point and n was total number of data point. RMSE indicate proximity of actual and predicted post-harvest soil test values. Lower the value of RMSE better will be the predictability. RE value used to show the relative difference between actual and predicted values and was expressed in percentage. Prediction was considered excellent, good, fair and poor when RE was < 10%, in between 10 to 20%, in between 20 to 30% and > 30%, respectively (Mahajan et al. 2019).

RPD indicate accuracy of prediction. RPD was the ratio of standard deviation of prediction (SD_P) to standard error of prediction (SE_P) (Williams and Norris 1987).

$$\mathrm{RPD} = \frac{\mathrm{SD_P}}{\mathrm{SE_P}}$$

where,

$$\mathrm{SE_P} = \sqrt{\frac{\sum_{i=1}^{n}(A_i - P_i)^2}{n-1}}$$

RPD values <1 indicate irrelevant prediction, between 2 and 3 considered as adequate screening and > 3 specify satisfactory prediction (Malley et al. 2000).

Statistical analysis and data visualization

Data were analyzed using analysis of variance (ANOVA) (Gomez and Gomez 1984) and treatment means were separated by using Duncan's multiple range test (DMRT) ($p < 0.05$). Statistical analyses (Multiple regression equations, coefficient of determination, root mean square error, relative error, ratio of performance to deviation, standard deviation and coefficient of variation) were conducted by following standard procedures (previously described) and by using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA), IBM SPSS software version 27.0.1 (Statistical Package for the Social Science, SPSS, Chicago, IL, USA) and data were visualized by using GraphPad Prism 9.0 (GraphPad Software Inc., La Jolla, CA, USA).

Result and discussion

Effect of fertility gradient on test crop

Development of the soil fertility gradient by culturing exhaust crop (rice) is prerequisite for test crop (linseed) experiment as it creates variability among the strips with respect to available nutrient status (N, P and K) via natural transformation of added fertilizer nutrients. Rice biomass yield and corresponding post-harvest soil nutrient contents among the strips showed that strip III had significantly highest corresponding values which indicated development of fertility gradient among the strips which is prerequisite for test crop in STCR experiment (Table S2). Multiple linear regression (MLR) study demonstrated that the effect of the strips on the soil test values of N, P, and K (considered as a dependent variable) was statistically significant, separately for whole plots (Table 1). Thus, it is proved that the current experiment generated a significant fertility gradient (Mahajan et al. 2014; Singh 2014; Singh et al. 2021). Further, the effect of fertility gradient was also prominent in linseed yield and nutrient uptake status (Table 2) as they increases from strip I to strip III. There was an increasing trend in the linseed yield and nutrient uptake from the gradients of strip I to strip III. Highest linseed grain yield (19.0 q ha^{-1}), straw yield (36.4 q ha^{-1}) and corresponding nutrient uptake were obtained upon application of higher rates of fertilizers i.e., 120, 75 and 60 kg ha^{-1} N, P_2O_5 and K_2O with 10 t ha^{-1} FYM. After cultivating exhaust crop (rice) the biomass yield and soil test values significantly influenced by the established fertility gradient (across different strips). Further, cultivation of test crop (linseed) also strengthened the effect of established fertility gradient with statistically significant effect. Thus, it can be said that presence of variation I soil test values were very well reflected by variability exhibited by grain yield, straw yield and uptake of N, P and K. CV for grain yield was>14.17% and for nutrient uptake (NPK) were >20.15% after cultivating linseed, demonstrating the existence of operational variability in aforesaid parameters which were prerequisite for calculating basic parameters and fertilizer prescription equations for calibrating fertilizers doses for achieving specific target yield (Chatterjee, Srivastava, and Singh 2010; Singh et al. 2021).

Table S2. Descriptive statistics of exhaust crop (rice) biomass and available soil nutrients after fertility gradient experiment

Parameters	Strip-I		Strip-II		Strip-III	
	Range	Mean ± SD (CV)	Range	Mean ± SD (CV)	Range	Mean ± SD (CV)
Rice biomass (t ha^{-1})	6.04-8.91	7.48±1.08c (14.4%)	9.66-12.49	11.07±0.87b (7.85%)	12.78-14.94	13.84±1.54a (11.12%)
Alkaline $KMnO_4$-N (kg ha^{-1})	214.60-252.66	235.40 ± 21.25c (9.02%)	223.86-259.72	245.46 ±19.25b (7.84%)	228.75-270.36	255.37 ± 17.01a (6.66%)
Olsen's-P (kg/ha)	11.00-23.88	17.35±4.15c (23.91%)	12.40-27.86	19.42±3.82b (19.64%)	13.35-31.85	23.36±3.15a (13.48%)
NH_4OAc-K (kg ha^{-1})	178.31-214.95	199.81±19.38c (9.69%)	184.70-233.18	216.27±13.94b (6.44%)	191.75-235.46	229.56±10.73a (4.67%)

SD, Standard deviation; CV, coefficient of variation (%). Different letters indicates significant difference at 5 % level of significance based on Duncan's multiple range test

Table1. R^2,CV(%),andSDofwholeplots

Dependent Variable	R2	Average	SD	CV(%)
SN	0.383**	242.40	20.36	8.4
SP	0.315**	20.04	4.39	21.9
SK	0.536**	210.21	16.29	7.75

SN,SP,andSKdenotesoilnitrogen,phosphorus, andpotassium,correspondingly.
**denotessignificanceat1%level

Table2.Descriptivestatisticsoflinseedgrain,straw yieldand nutrient(NPK)uptake

Parameters	Strip-I	Strip-II	Strip-III

	Range	Mean ± SD^a(CV^b)	Range	Mean ± SD^a(CV^b)	Range	Mean ± SD^a(CV^b)
Grainyield (qha^{-1})	7.25-17.10	13.84±2.40c (17.36)	8.75-18.03	14.89±2.29b (15.40)	10.10-19.00	16.52±2.34a (14.17)
Strawyield (qha^{-1})	14.30-34.55	28.25±4.79c (16.95)	15.10-35.60	30.81±4.64b (15.07)	23.60-36.40	33.45±3.21a (9.61)
UptakeofN (kgha^{-1})	13.09-76.94	47.12±15.04c (31.93)	18.53-81.45	56.32±16.20b (28.77)	24.17-87.50	68.0817.29a (25.39)
UptakeofP (kgha^{-1})	3.25-23.97	13.82±4.91c (35.54)	4.67-23.42	18.29±4.77b (26.09)	7.49-26.88	21.41±4.88a (22.78)
UptakeofK (kgha^{-1})	17.15-68.15	46.35±12.09c (26.08)	19.88-75.11	58.80±13.07b (22.23)	30.00-85.17	72.31±14.57a (20.15)

Differentlettersindicates significantdifferenceat 5%levelofsignificancebasedonDuncan'smultiplerangetest

Basic parameters

Perusal of data revealed that 3.68 kg N, 1.15 kg P and 3.84 kg K were required for producing one quintal of linseed grain (Table 3). The requirement of K was highest among the primary nutrients followed by N and least for P, which was attributed to greater requirement of K for linseed biomass (Shaaban and Abou El-Nour 2012; Dey et al. 2022).

Contribution of nutrients (N, P and K) form soil, fertilizers and FYM were delineated in Table 3. The relatively low Cs (10.31%) and Cfym (8.81%) of N might be attributed to lower rates of mineralization in soil N as low soil temperature prevails during winter season (Paul et al. 2011) and split application of N-fertilizer at critical stage of crop growth resulted in its higher uptake by linseed from fertilizer source (Omar 2020) and ultimately enhanced Cf (47.00%) of N. For P, comparable contributions were observed from Cs (52.66%) and Cf (45.06%). Submerged rice (exhaust crop) cultivation might improve the Cs of P in linseed (Mahajan et al. 2013). However, K is an element which increases the fiber content in linseed stem and also increases lodging resistance (Dey et al. 2022). K is also assimilated at higher rate in early growth stages and after flowering the stem becomes equally important like capsules as sink for K in linseed (Hassan and Leitch 2000; Kundu et al. 2021). Those were the reasons behind the very high Cf of K in linseed. In general the contribution of nutrients from fertilizer was higher than soil (Mahajan et al. 2014). Contribution of nutrients from FYM was low which might be due to lower mineralization rate of FYM (Verma et al. 2017; Singh, Jatav, and Bharteey 2020).

Table3.Basicdataoflinseed

	Basicparameters

Nutrients	Nutrient requirement(kgq^{-1}grain)	Soil efficiency(%) orCs	Fertilizer efficiency (%)orCf	Organic efficiency(%)or Cfym
N	3.68b	10.31c	47.00b	8.82b
P	1.15c	52.66a	45.06b	5.59c
K	3.84a	14.74b	115.18a	12.27a

Differentlettersindicates significantdifferenceat 5%levelofsignificancebasedonDuncan'smultiplerangetest

Fertilizers prescription equations for target yield of linseed and prescription of fertilizers under IPNM

By using basic parameters, soil test based fertilizer prescription equations were developed for obtaining desired targeted yield of linseed with and without IPNS (Table 4). Farmers can simply put their desired target yield in these simpler equations along with the existing available soil nutrient status, amount of applicable FYM (under IPNS) and in that way required amount of applicable fertilizers doses can be known. In IPNS, application of FYM not only reduces the fertilizer doses for achieving targeted yield but also maintain the fertility status of the soil (Mitra et al. 2010; Ammal et al. 2020). Khan et al. (2021) reported improved linseed production, fertility status of soil and water retention capacity after application of organic fertilizers. Such kind of fertilizer prescription equations were documented on different crops by several workers (Deshpande, Shiralkar, Pawar 2016 on groundnut; Singh et al. 2020 on coriander; Singh et al. 2021 on rice).

By using fertilizer prescription equations, a ready reckoner table was prepared for NPK alone and IPNS (NPK+FYM) system for getting target yield of 15, 18 and 21 q ha^{-1} of linseed under wide range of soil test values (Table 5). It was clearly revealed that IPNS saved 7.51-15.52% N, 8.89-47.13% P_2O_5 and 10.73-27.59% K_2O, respectively over sole NPK application when different targeted yield (15, 18 and 21 qha^{-1}) were considered. From perusal of data it was obvious that, for given targeted yield, with the increase in soil test values of N, P and K there were concomitant decrease in amount of fertilizer requirement. Similar types of fertilizer savings under IPNS were also demonstrated by Katharine et al. (2013) on cotton and Singh et al. (2015) on jute, rice and garden pea.

Table4.Fertilizerprescriptionequationsforlinseed

Fertilizationprogramme	Fertilizerprescriptionequations

NPKalone	$FN = 7.83T – 0.22SN$ $FP = 2.55T – 1.17SP$ $FK = 3.34T – 0.13SK$
NPK+FYM	$FN = 7.83T – 0.22SN – 0.19ON$ $FP = 2.55T – 1.17SP – 0.12OP$ $FK = 3.34T – 0.13SK – 0.11OK$

FN, FP, and FK are fertilizer N, P, and K (kg ha^{-1}), respectively; T is target yield (q ha^{-1}); SN,SP,andSKare availablesoil-testvaluesofalkaline $KMNO_4$-N,OlsenP,andNH_4OAc-Krespectively in kg ha^{-1}; and ON, OP, and OK are quantity of N, P, and K supplied through FYM(tha^{-1})respectively.

Table 5. Soil test based fertilizer prescription for target yields (15, 18 and 21 q ha-1) of linseed under integrated plant nutrient management (IPNM) system

Soil test values (kg ha^{-1})	NPK (kg ha^{-1}) NPK	NPK+ Per cent alone FYM reduction (10t ha$^{-1)}$ over		NPK alone NPK	NPK+ FYM reduction (kg ha^{-1}) (10 tha$^{-1)}$ over	Per cent	NPK alone NPK	NPK+ FYM reduction (kg ha^{-1}) (10t ha$^{-1)}$ over	Per cent
Target yield (q ha^{-1})	15			18			21		
Available nitrogen (KMnO4-N)									
180	77.98	68.60	12.03	101.47	92.09	9.24	124.96	115.58	7.51
200	73.59	64.21	12.75	97.08	87.70	9.66	120.57	111.19	7.78
220	69.21	59.83	13.55	92.70	83.32	10.12	116.19	106.81	8.07
240	64.82	55.44	14.47	88.31	78.93	10.62	111.80	102.42	8.39
260	60.44	51.06	15.52	83.93	74.55	11.18	107.42	98.04	8.73
Available phosphorus (Olsen-P)									
10	26.56	22.84	14.01	34.20	30.49	10.85	41.85	38.13	8.89
14	21.88	18.16	17.00	29.53	25.81	12.60	37.18	33.46	10.01

18	17.21	13.49	21.62	24.86	21.14	14.96	32.50	28.79	11.42
22	12.53	8.82	29.61	20.18	16.46	18.43	27.83	24.11	13.37
26	7.83	4.14	47.13	15.51	11.79	23.98	23.16	19.44	16.06
Available (NH4OAc-K)									
160	29.56	24.23	18.03	39.57	34.24	13.47	49.57	44.25	10.73
180	27.00	21.67	19.74	37.01	31.68	14.40	47.01	41.69	11.32
200	24.44	19.11	21.81	34.45	29.12	15.47	44.45	39.13	11.97
220	21.88	16.55	24.36	31.89	26.56	16.71	41.89	36.57	12.70
240	19.32	13.99	27.59	29.33	24.00	18.17	39.33	34.01	13.53

Multiple regression equation

Relationship between grain yield as a dependent variable and soil test values, fertilizer doses, farm yard manure, interaction between fertilizer doses and soil test values as independent variables were established through quadratic model of multiple regression equation.

Multiple regression equation for whole plots (72 plots)

$$Y = -13.7452 + 0.069944\ SN + 0.413358\ SP + 0.011171\ SK + 0.054666\ FN + 0.061982\ FP + 0.168781\ FK + 0.00513\ FYM + 0.0000118719\ FN^2 - 0.00033\ FP^2 - 0.00038\ FK^2 - 0.00016\ FNSN - 0.00261\ FPSP - 0.00062\ FKSK - 0.00096\ FYM^2\ [R^2=0.979]$$

Multiple regression equation for treated plots (69 plots, after excluding three absolute control plots)

$$Y = -12.0677 + 0.066423\ SN + 0.393016\ SP + 0.009079\ SK + 0.038572\ FN + 0.059108\ FP + 0.152539\ FK - 0.01568\ FYM + 1.1642825\ FN^2 - 0.00034\ FP^2 - 0.00039\ FK^2 - 0.00009483\ FNSN - 0.002384\ FPSP - 0.000545\ FKSK + 0.000794\ FYM^2\ [R^2=0.973]$$

R^2 value of 0.979 indicates good fit of equation as 97.9% variation in linseed grain yield can be explained by variation in soil test values, fertilizer doses and interaction between them along with farm yard manure.

Response type and critical soil test value

Phosphorus and potassium followed the 'law of diminishing' return as '+ - -' response type were observed for them which showed positive and decreasing response to applied fertilizer doses and negative correlation between soil and fertilizer nutrient. However, '+ + -' response type was observed for nitrogen (Table 6). In this way, critical soil test value were worked out for phosphorus and potassium only and their corresponding values were 24.79 kg ha^{-1} and 279.88 kg ha^{-1} for Olsen-P and NH_4OAc-K, respectively (Table 6). From which it was evident that if soil test values were less than critical soil test values then there will be positive and increasing response of doses of P and K fertilizer will be expected. At and above these critical soil test value, no response to fertilizer doses will be expected by Mukta variety of linseed. Similar responses of fertilizers were also observed by Bhaduri and Gautam (2013).

Table6.Response typeandcriticallimitofsoiltestvalues obtainedbyregressionequationof treatedplotsinlinseed

R^2	Nutrient	Responsetype	Criticalsoiltestvalue (Maximum)
0.973	Phosphorus	+--	24.79kgha^{-1}
	Potassium	+--	279.88 kgha^{-1}

Prediction of post-harvest soil test values of available N, P and K by MLR model

MLR model was performed to predict the post-harvest soil N, P and K after linseed. Model showed very good performance for N, P, K with R^2 = 0.936, 0.960, 0.829 ($p < 0.01$), RMSE= 3.648 kg, 1.142 kg, 6.611 kg, RE= 1.558%, 4.411%, 3.009% and RPD =3.820, 4.927, 2.204 respectively when grain yield was considered along with other independent variables. Similarly, when uptake (N, P and K) was considered over grain yield of linseed in MLR model, R^2= 0.943, 0.962, 0.833 ($p <0.01$), RMSE =3.446 kg, 1.123 kg, 6.530 kg, RE = 1.456%, 4.367%, 3.012% and RPD = 4.058, 5.006, 2.237 were observed respectively. Data obtained from aforementioned two different ways were more or less equal with negligible difference proving accuracy of prediction. Results of MLR model were presented in the form of predication equations were shown in Table 7. Accuracy of model was also satisfied from trend line between actual and predicted post-harvest soil test values each for N, P and K which coincided with 1:1 line and distribution of predicted soil N, P and K were close to 1:1 line.

Table 7. Prediction equations of post-harvest soil test values (PHSTVs) of available N, P and K for linseed

Prediction equations PHSTVs	R^2
YPHSN= 33.215 + 0.782 SN** + 0.061 FN**+ 0.026 FYM-N + 0.666GY	0.936**
YPHSN= 78.981 + 0.578 SN** + 0.044 FN* + 0.016 FYM-N + 0.279 UN**	0.943**
YPHSP = 8.689 + 0.952 SP** + 0.084 FP** - 0.039FYM-P** - 0.054 GY	0.960**
YPHSP= 7.832 + 1.041SP** + 0.084 FP** - 0.039FYM-P** - 0.098 UP	0.962**
YPHSK = 91.599 + 0.618 SK** + 0.309 FK** - 0.190 FYM-K** + 0.164 GY	0.829**
YPHSK = 65.300 + 0.800 SK** + 0.332 FK** - 0.195 FYM K** - 0.186 UK	0.833**

* and ** are significant at 0.05 and 0.01 level of probability. YPHSN, YPHSP and YPHSK are post-harvest soil test values of available nitrogen, phosphorus and potassium, respectively; FN, FP and FK are doses of fertilizer (kg ha^{-1}) nitrogen, phosphorus and potassium, respectively; SN, SP and SK are available nitrogen, phosphorus and potassium in kg ha^{-1}, respectively.

Rising of linseed crop with and without fertilizers and FYM led to enhanced or maintained soil fertility in treated plots and depletion of nutrients from control plots created high variability in soil nutrients. This higher variability was further utilized for calibrating the prediction of post-harvest soil nutrients. High coefficient of determination, R^2 significant at $p<0.01$, lower RMSE, RE (<10%), RPD (>3) shows satisfactory prediction except in case of RPD for K, values were in between 2-3 which indicates adequate screening and scatter plot of actual versus predicted post-harvest values were very close to 1:1 line indicated excellent prediction for all the three nutrients (Mahajan et al. 2019). It was even interesting to note that prediction did not vary much when yield and uptake of nutrients was taken as one of independent variable along with other independent variables (Gangola et al. 2017; Kirankumar et al. 2019).

Conclusion

In the current study, soil-test-based fertilizer prescriptions equation and their recommendation for linseed were developed on alluvial soil of Varanasi. Critical soil test values and prediction of post-harvest soil test values were also successfully determined by using MLR models. Critical soil test values helps in determining stage of soil condition up to which application of fertilizers is feasible. The prediction of post-harvest soil test values with higher precision level (R^2 >0.75, lower RMSE RE <10% and RPD >3) could ease the burden of laborious soil testing after subsequent cropping which is not economically feasible for resource poor farmers. Conjunctive use of organic (10 t FYM) and inorganic fertilizers results into saving of 15.5% N, 47.1% P_2O_5 and 27.6% K_2O under STCR- IPNS based on targeted yield and soil test values. So, these recommendations can be successfully used in the larger part of alluvial soils of eastern India or region with similar soils and agro climatic conditions as effective guides for efficient integrated nutrient management for achieving specific target yield of linseed.

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