



Long-term effect of rainfall and fertilizer nutrients on sustainability of soybean yield, rainwater use efficiency, monetary returns and soil fertility under semi-arid *Vertisols*

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ABSTRACT

A long-term experiment was conducted to assess the effect of rainfall and plant nutrients on soybean yield and Rainwater Use Efficiency (RWUE) by superimposing T₁: Control; T₂: 20 kg N (urea) + 13 kg P ha⁻¹; T₃: 30 kg N (urea) + 20 kg P ha⁻¹; T₄: 40 kg N (urea) + 26 kg P ha⁻¹; T₅: 60 kg N (urea) + 35 kg P ha⁻¹; T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹; T₇: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha⁻¹; T₈: FYM @ 6 t ha⁻¹; and T₉: Crop residue @ 5 t ha⁻¹ to same plots during 1992-2009 in *Vertisols* at Indore. The yield variability was assessed using regression and Principal Component (PC) models through rainfall and plant nutrients. Based on regression analysis, the model of T₈ gave maximum coefficient of determination (R²) of 0.78 compared to T₁ with minimum of 0.38. Based on PC analysis, 3 PCs explained maximum variability of 74.1% in T₂ compared to minimum of 66.6% in T₆. The 1st PC (P₁) explained variance of 33.3 to 42.1%, compared to 18.1 to 21.6% by 2nd PC (P₂) and 11.3 to 16.5% by 3rd PC (P₃). The regression model of yield through PC scores indicated that T₈ had maximum R² of 0.46, while T₂ had minimum of 0.15. Application of 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹ was superior with significantly higher mean yield of 2182 kg ha⁻¹, RWUE of 2.80 kg ha⁻¹ mm⁻¹, gross returns of ₹ 34814 ha⁻¹, net returns of ₹ 24346 ha⁻¹, BC ratio of 3.33 and SYI of 43.0 and 44.2 based on regression and PC models respectively. The same treatment maintained maximum soil N of 269 kg ha⁻¹, soil P of 23.9 kg ha⁻¹, soil K of 757 kg ha⁻¹ and soil S of 18.0 kg ha⁻¹ at the end of study. This treatment could be adopted by farmers for attaining maximum soybean yield, RWUE and monetary returns and maintain soil fertility under semi-arid *Vertisols*.

1. INTRODUCTION

In India, rainfed agriculture is about 85 million hectare (m ha), constituting about 60% of net cultivated area supporting 40% of population of the country (Sharma *et al.*, 2008). In Sub-Saharan Africa, more than 95% farm land is rainfed compared to 90% in Latin America, 60% in South Asia, 65% in East Asia and 75% in Near East and North Africa (Wani *et al.*, 2009). *Vertisols* are predominantly

found across the world. Majority of acreage of *Vertisols* and associated soils in the world is spread in Australia (70.5 m ha), India (70 m ha), Sudan (40 m ha), Chad (16.5 m ha) and Ethiopia (10 m ha). These five countries constitute over 80% of total area (250 m ha) of *Vertisols* in the world (Dudal, 1965). In India, *Vertisols* are predominant in Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, Karnataka and Tamil Nadu (Murthy, 1981). Their texture

would vary from clay to clay loam, or silty clay loam, with clay content varying from 40 to 60%. They have high bulk density when dry, with clod density ranging from 1.5 to 1.8 g cm⁻³; cation exchange capacity (47 to 65 cmol⁻¹ kg soil); and pH of more than 7.5 (Virmani *et al.*, 1989).

Tropical *Vertisols* are low in organic matter and plant nutrients, particularly N, P and zinc. Researchers reported that soil productivity can be enhanced by supplying adequate nutrients (Virmani *et al.*, 1989; Willey *et al.*, 1989; Burford *et al.*, 1989; Barbarick *et al.*, 2010). Supplementation of N, P and zinc through fertilizer was inevitable to ensure satisfactory production in *Vertisols* (Kanwar, 1972; Randhawa and Tandon, 1982). Imbalanced fertilization and poor recycling of organics resulted in deterioration of soil quality, leading to low productivity (Doran *et al.*, 1996). Ogola *et al.* (2002) observed that Water Use Efficiency (WUE) in maize increased significantly with N application. Turner (2004) reported options for making improvement in rainfall-use efficiency of crops under dryland systems. Amir *et al.*, (1991) examined WUE as influenced by management practices in wheat under arid condition. Maruthi Sankar *et al.* (2011) examined rainfall effects on finger millet yield under semi-arid *Alfisols*. Mingbin Huang *et al.* (2003) examined WUE and sustainability of yield under different rotation systems tested in Loess plateau of China. They stressed efficient assessment of sustainability of yield through different management practices.

Soybean is grown in an area of 8.26 m ha with production of 16.72 million tonnes (m t) and yield of 2024 kg ha⁻¹. Sharma *et al.* (2005, 2008, 2009) studied effects of reduced tillage, integrated nutrient management and residue application on sustainability of yield and soil quality in an *Alfisol*. Blevins and Frye (1993) studied usefulness of conservation tillage as an ecological approach for efficient soil management. Follet (1990) studied effects of tillage practices on soil nutrients under Great Plains in USA. Bhat *et al.* (1991) studied long-term effects of crop residue application on soil properties. Often it was felt necessary to evaluate nutrient management treatments for efficacy and sustainability of yield across a wider agro-climatic situation (Rasmussen *et al.*, 1998; Wanjari *et al.*, 2004). These aspects need to be explored on long-term basis where accurate assessment of practices can be made after detrending effects of rainfall and soil nutrients on yield (Pal *et al.*, 2006; Behera *et al.*, 2007; Maruthi Sankar *et al.*, 2008). The present study was conducted in a semi-arid *Vertisol* with objective of (i) assessing influence of rainfall and fertilizer treatments on soybean yield and changes in soil nutrient status; (ii) establish useful predictive models explaining relationship between yield and sustainability, rainfall, soil nutrients; and (iii) select an efficient treatment for attaining sustainable yield, rainwater use efficiency and soil fertility over years.

2. MATERIALS AND METHODS

Experimental Details

Field experiment was conducted for 18 years during 1992 to 2009 on a permanent site in *kharif* season (June to October) to study the effect of fertilizer treatments on productivity of 'JS-335' variety of soybean (*Glycine max* (L.)) in a semi-arid *Vertisol* under All India Coordinated Research Project for Dryland Agriculture, Indore in Madhya Pradesh. Indore is located at a Latitude of 22°43' N, Longitude of 76°54' E and Altitude of 618 m above msl. Taxonomically soils were *Vertisols* designated as black cotton soils and were low in N, organic matter content, medium to high in P and high in K content. The treatments tested were (i) T₁: Control; (ii) T₂: 20 kg N (urea) + 13 kg P ha⁻¹; (iii) T₃: 30 kg N (urea) + 20 kg P ha⁻¹; (iv) T₄: 40 kg N (urea) + 26 kg P ha⁻¹; (v) T₅: 60 kg N (urea) + 35 kg P ha⁻¹; (vi) T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹; (vii) T₇: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha⁻¹; (viii) T₈: FYM @ 6 t ha⁻¹; and (ix) T₉: Crop residue @ 5 t ha⁻¹. Source of phosphorus has to be mentioned here. The crop residue had a composition of 0.75% N, 0.045% P and 0.14% K, whereas FYM contained 0.66% N, 0.45% P and 0.50% K. Field experiment was conducted in a net plot size of 9.0 x 6.4 m with seed rate of 80 kg ha⁻¹ and row x plant spacing of 30 x 5 cm. The treatments were randomized and superimposed to plots in a Randomized Block Design with 4 replications in the 1st year. From 2nd year onwards, they were superimposed to the same plots as per the schedule of 1st year without any randomization. FYM was applied 10 days prior to sowing, while crop residue was applied as surface mulch after emergence of crop in the prescribed treatments. Before superimposing treatments, initial soil samples were collected from each plot from 0-30 cm depth every year and analyzed for soil N by alkaline permanganate method (Subbaiah and Asija, 1956); soil P by Olsen's method (Olsen *et al.*, 1954); soil K by ammonium acetate method (Jackson, 1973); and soil sulphur (S) by turbidity method (Chesnin and Yien, 1950). Standard agronomic practices of soybean cultivation were adopted from sowing to harvest (Vittal *et al.*, 2003).

Statistical Analysis

The differences in effect of fertilizer treatments on soybean yield were tested in each year and also when pooled over years based on analysis of variance (ANOVA) procedure. The effect of treatments was tested as F-ratio of mean sum of squares of fertilizer and error term. The treatments were compared based on LSD criteria to identify an efficient treatment (Gomez and Gomez, 1984). Similarly, the effects of treatments on soil fertility and plant uptake of N, P, K and S nutrients was tested in each year and also pooled over years. The crop yield could be influenced by rainfall and its distribution, apart from available soil

nutrients and plant uptake of nutrients. Observations on rainfall, soil N, P, K and S nutrients are considered for modeling their effect on yield and identification of a superior treatment. Multivariate regression and principal component models have been explored for assessing the effect of rainfall, soil and plant N, P, K and S nutrients on soybean yield.

Regression Analysis

In order to assess the effect of rainfall on soybean yield attained by treatments, regression model of yield is calibrated as a function of monthly rainfall received during June to October, soil and plant nutrients (Draper and Smith, 1998). The prediction of yield attained by a treatment is assessed based on coefficient of determination (R^2) and prediction error. A regression model is useful for assessing the effect of rainfall received during crop growing period on yield attained by a treatment (Behera *et al.*, 2007; Nema *et al.*, 2008; Maruthi Sankar *et al.*, 2011, 2012a, 2013). A comparison of regression coefficients of individual months would indicate the usefulness of rainfall received in a particular month in influencing the yield. A positive or negative sign of regression coefficient would indicate whether the rainfall received in a given month was deficit or surplus, respectively. The regression model of yield could be postulated as:

$$Y = \alpha \pm \beta_1(\text{Jun RF}) \pm \beta_2(\text{Jul RF}) \pm \beta_3(\text{Aug RF}) \pm \beta_4(\text{Sep RF}) \pm \beta_5(\text{Oct RF}) \pm \beta_6(\text{SN}) \pm \beta_7(\text{SP}) \pm \beta_8(\text{SK}) \pm \beta_9(\text{SS}) \dots (1)$$

Where, α is intercept and β_1 to β_9 are regression coefficients measuring change in yield for a unit change in rainfall and soil nutrients. The superiority of treatments could be assessed based on model (1) by examining R^2 and prediction error ($\tilde{E}_k$) of treatments. The prediction error is used for measuring the sustainability of a treatment over years.

Principal Component Analysis

Based on Principal Component (PC) analysis (Dunteman and Michael Lewis-beek, 1989; Jolliffe, 1986; and Krzanowski, 1979), PCs are determined as a function of rainfall; soil N, P, K and S nutrient variables for explaining variability in data. The i^{th} PC ' P_i ' is given as:

$$P_i = \pm a_{i1}(\text{Jun RF}) \pm a_{i2}(\text{Jul RF}) \pm a_{i3}(\text{Aug RF}) \pm a_{i4}(\text{Sep RF}) \pm a_{i5}(\text{Oct RF}) \pm a_{i6}(\text{SN}) \pm a_{i7}(\text{SP}) \pm a_{i8}(\text{SK}) \pm a_{i9}(\text{SS}) \dots (2)$$

Where, a_{ij} are loadings of variables on ' P_i ', which are chosen such that they satisfy two conditions, viz., (i) PCs are orthogonal with respect to each other; and (ii) 1st PC, say P_1 will account for maximum variance of variables; 2nd PC will account for maximum of remaining variance in variables after eliminating variance accounted by 1st PC *etc.* The computational procedure of 1st PC is repeated for 2nd and

subsequent PCs. We could identify an efficient treatment which has (i) significant PCs which explained maximum variance in data; (ii) variables which have significantly higher loading on PCs. We could derive the PC scores for each treatment and calibrate a regression model of yield through PC scores as:

$$Y = \alpha + \sum_{i=1}^k \beta_i P_i D_i + \varepsilon \dots (3)$$

Where, α is intercept; P_i is i^{th} PC; β_i is regression coefficient corresponding to i^{th} PC; and D_i is a dummy variable which takes value of '1' if the i^{th} PC is included in model and '0' otherwise. The regression model through PC scores could be assessed based on R^2 for predicting yield and sustainability of a treatment over years.

Sustainability Yield Index

An efficient treatment could be identified based on Sustainability Yield Index (SYI) derived as a "ratio of the difference of mean yield and standard error based on regression model and maximum yield attained by any treatment over years" as described by Nema *et al.* (2008), Behera *et al.* (2007), Maruthi Sankar *et al.* (2011, 2012a, 2012b, 2013). The SYI ' $\tilde{A}_k$ ' of treatment 'k' over years could be given as:

$$\tilde{A}_k = [\{ \tilde{Y}_k - \tilde{E}_k \} / Y_{\max}] * 100 \dots (4)$$

Where, $\tilde{Y}_k$ is the mean yield of k^{th} treatment; $\tilde{E}_k$ is prediction error; and $Y_{\max}$ is maximum yield attained by any treatment during study period. In (4), the mean yield of a treatment would get detrended by elimination of unexplained variation measured by rainfall, soil nutrient variables in regression and PC models. The estimate ' $\tilde{A}_k$ ' of a treatment would also indicate how close is the performance of a treatment to the best performance of any treatment under ideal conditions prevailed in a season. The detrended yields are compared with maximum yield for assessing the sustainability of a treatment.

Rainwater Use Efficiency and Profitability of Treatments

The RWUE ($\text{kg ha}^{-1} \text{mm}^{-1}$) of a treatment was derived as a ratio of yield (kg ha^{-1}) attained by a treatment and cumulative rainfall (mm) received from sowing to harvest of soybean. It would indicate the efficiency of a treatment in best utilizing the rainfall that was received from sowing to harvest of the crop. A treatment with maximum mean RWUE and minimum variation over years would be preferable to a treatment with low RWUE and high variation. Using observations of yield attained by treatments and rainfall from June to October, a comparison of ratios of yield and rainfall was made for assessing the performance of treatments (Rockstrom *et al.*, 2003). Based on ANOVA, the treatments which gave significantly higher RWUE could be

considered as superior compared to those with lower RWUE over years.

The cost of cultivation (₹ ha⁻¹) incurred and gross returns, net returns and benefit-cost ratio attained by treatments was derived and identified a profitable treatment. The gross returns (₹ ha⁻¹) was computed as a product of mean yield of each treatment attained over years and value of the crop (Nema *et al.*, 2008). The net returns (₹ ha⁻¹) was derived as a difference of gross returns and cost of cultivation, while benefit-cost ratio was derived as a ratio of gross returns and cost of cultivation for each treatment. An efficient treatment which provided maximum yield, RWUE, net returns, benefit-cost ratio and soil nutrients over years was identified.

3. RESULTS AND DISCUSSION

Rainfall and its Distribution

The monthly rainfall received from June to October and cumulative rainfalls of 5 months (1992 to 2009) were considered for assessing the performance of fertilizer treatments. The cumulative rainfall ranged from 353 mm in 2002 to 1309 mm in 1996 with mean of 829 mm and variation of 28.8% over years. A wide variation in the monthly rainfall was observed during the study period. The rainfall ranged from 55 mm (1996) to 330 mm (2001) in June; 50 mm (2002) to 677 mm (1996) in July; 91 mm (1999) to 430 mm (2006) in August; 9 mm (2000) to 350 mm (2003) in September; and no rainfall (1994, 1998, 2000, 2003, 2005 and 2007) to 80 mm (1996) in October. July month received maximum mean rainfall of 295 mm with variation of 50.5%; followed by 231 mm with variation

of 44.7% in August; 142 mm with variation of 64.3% in September; 132 mm with variation of 52.8% in June; and 29 mm with variation of 97.3% in October. The earliest Date of Sowing (DoS) of soybean was on 17th June in 2004; while the farthest was on 20th July in 1996. The Crop Growing Period (CGP) from sowing to harvest was found to be in the range of 91 days in 1992 to 117 days in 2004 with mean of 106 days and variation of 6.2% over years. The earliest Date of Harvest (DoH) of soybean was on 1st October in 2001, while the farthest was on 29th October in 1996. The mean and variation of DoS, DoH, CGP, rainfall received in different months and Cumulative Rainfall (CRF) are given in Table 1.

Effect of Fertilizer Treatments on Soil Fertility Status

The mean and variation of soil N, P, K and S nutrients observed during 1992 to 2009 are given in Table 2. The soil N ranged from 175 to 269 kg ha⁻¹; soil available P from 12.4 to 23.9 kg ha⁻¹; soil available K ranged from 537 to 757 kg ha⁻¹; and soil S ranged from 12.5 to 18.0 kg ha⁻¹. Based on ANOVA, significant changes in soil nutrients were observed during 1992 to 2009. The LSD criteria indicated the superiority of T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹ with maximum mean soil N of 269 kg ha⁻¹; soil P of 23.9 kg ha⁻¹; soil K of 757 kg ha⁻¹; soil S of 18.0 kg ha⁻¹ over years. T₂: 20 kg N (urea) + 13 kg P ha⁻¹ had lowest variation for soil N (6.8%) and soil K (16.5%); while T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹ had lowest variation for soil P (30.4%) and soil S (22.8%).

In soil available N, maximum increase of 4.4% (218 to 228 kg ha⁻¹) occurred with application of T₄: 40 kg N

Table: 1
Dates of sowing and harvest of soybean and rainfall received during 1992 to 2009

Year	DOS	DOH	CGP	Jun	Jul	Aug	Sep	Oct	CRF
1992	16-Jul	14-Oct	91 ^c	58 ^c	212 ^b	155b	76 ^b	55 ^b	556 ^c
1993	26-Jun	8-Oct	105 ^b	134 ^b	383 ^b	299b	191 ^b	47 ^b	1054 ^b
1994	18-Jun	5-Oct	110 ^b	140 ^b	261 ^b	273b	197 ^b	0 ^c	871 ^b
1995	1-Jul	6-Oct	98 ^c	145 ^b	360 ^b	277b	94 ^b	52 ^b	928 ^b
1996	20-Jul	29-Oct	111 ^b	55 ^c	677 ^a	269b	228 ^b	80 ^a	1309 ^a
1997	24-Jun	13-Oct	112 ^b	192 ^b	462 ^a	370a	50 ^c	34 ^b	1108 ^a
1998	2-Jul	16-Oct	107 ^b	59 ^c	423 ^b	282b	80 ^b	0 ^c	844 ^b
1999	27-Jun	18-Oct	114 ^a	252 ^a	173 ^b	91c	244 ^a	72 ^a	832 ^b
2000	1-Jul	6-Oct	98 ^c	114 ^b	169 ^b	165b	9 ^c	0 ^c	457 ^c
2001	22-Jun	1-Oct	102 ^b	330 ^a	190 ^b	95c	72 ^b	55 ^b	742 ^b
2003	24-Jun	11-Oct	110 ^b	104 ^b	349 ^b	137b	350 ^a	0 ^c	940 ^b
2004	17-Jun	11-Oct	117 ^a	101 ^b	188 ^b	410a	79 ^b	24 ^b	802 ^b
2005	28-Jun	16-Oct	111 ^b	71 ^b	178 ^b	249b	234 ^a	0 ^c	732 ^b
2006	2-Jul	13-Oct	104 ^b	103 ^b	345 ^b	430a	183 ^b	26 ^b	1087 ^a
2007	26-Jun	6-Oct	103 ^b	154 ^b	314 ^b	197b	201 ^b	0 ^c	866 ^b
2008	26-Jun	4-Oct	101 ^b	122 ^b	158 ^b	181b	104 ^b	16 ^b	581 ^c
2009	30-Jun	10-Oct	103 ^b	110 ^b	419 ^b	125c	143 ^b	65 ^a	862 ^b
Mean			106	132	295	231	142	29	829
SD			7	69	149	103	91	28	239
CV (%)			6.2	52.8	50.5	44.7	64.3	97.3	28.8

DoS : Date of sowing; DoH : Date of harvest; CGP : Crop growing period (days); CRF : Cumulative rainfall (mm); SD : Standard deviation ; CV : Coefficient of variation (%)

Table: 2
Effect of fertilizer treatments on soil nutrients (kg ha⁻¹) during 1992 to 2009

Treatments	Nitrogen		Phosphorus		Potassium		Sulphur	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Control	175 ^e	8.4	12.4 ^e	51.4	537 ^e	20.4	12.5 ^d	47.5
20 kg N (urea) + 13 kg P ha ⁻¹	200 ^d	6.8	15.5 ^d	49.1	555 ^{de}	16.5	14.2 ^{cd}	41.0
30 kg N (urea) + 20 kg P ha ⁻¹	206 ^d	9.4	17.8 ^{bcd}	48.9	583 ^{cde}	23.4	14.7 ^{bcd}	42.8
40 kg N (urea) + 26 kg P ha ⁻¹	225 ^c	7.6	18.8 ^{bc}	44.5	551 ^e	17.3	15.5 ^{bc}	41.6
60 kg N (urea) + 35 kg P ha ⁻¹	225 ^c	10.5	20.0 ^b	43.4	628 ^{bcd}	23.2	15.7 ^{abc}	38.8
20 kg N (urea) + 13 kg P + FYM @ 6 t ha ⁻¹	269 ^a	19.3	23.9 ^a	30.4	757 ^a	22.1	18.0 ^a	22.8
20 kg N (urea) + 13 kg P + FYM @ 5 t ha ⁻¹	251 ^b	17.6	17.2 ^{cd}	51.5	644 ^{bc}	21.0	16.9 ^{ab}	30.1
FYM @ 6 t ha ⁻¹	255 ^{ab}	26.0	20.1 ^b	34.0	692 ^{ab}	19.3	16.5 ^{abc}	33.6
Crop residue @ 5 t ha ⁻¹	233 ^c	22.4	17.5 ^{bcd}	45.5	637 ^{bc}	28.5	15.3 ^{bc}	34.5
LSD (p < 0.01 level)	16		2.7		76		2.3	

LSD : Least significant difference; Treatments with same letter (a, b, c,...) in columns are at par with each other; CV : Coefficient of variation (%)

(urea) + 26 kg P ha⁻¹, while maximum decrease of -22.5% (209 to 162 kg ha⁻¹) occurred under T₁: Control. In soil P, maximum increase of 297.6% (7.4 to 29.5 kg ha⁻¹) occurred with application of T₇: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha⁻¹, while minimum increase of 124.7% (13.8 to 30.9 kg ha⁻¹) was observed under T₈: FYM @ 6 t ha⁻¹. In soil K, maximum increase of 123.7% (373 to 835 kg ha⁻¹) occurred with application of T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹, while minimum increase of 56.9% (360 to 565 kg ha⁻¹) was observed under T₃: 30 kg N (urea) + 20 kg P ha⁻¹. In soil K, maximum decrease of 70.2% (22.2 to 6.6 kg ha⁻¹) occurred under T₁: Control, while minimum decrease of 26.6% (24.4 to 17.9 kg ha⁻¹) occurred under T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹. Thus application of T₄: 40 kg N (urea) + 26 kg P ha⁻¹ for soil N, T₇: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha⁻¹ for soil P, T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹ for soil K and soil S were superior based on the pattern of changes in soil fertility, i.e., build-up or depletion in nutrients over years. The changes in soil fertility of N, P, K and S nutrients during 1992 to 2009 are depicted in Fig. 1.

Effect of Fertilizer Treatments on Soybean Yield

The fertilizer treatments gave significantly higher yield compared to T₁: Control in all years except 1995. Application of T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹ was superior with maximum mean yield of 2182 kg ha⁻¹ with variation of 27.6%; while T₁: Control was inferior with minimum yield of 1333 kg ha⁻¹ with variation of 32.0% over years. The superior treatment gave maximum yield in 15 out of 18 years in the range of 1449 to 3501 kg ha⁻¹. It attained the best yield with lowest variation of 27.6%, while T₅: Crop residue @ 5 t ha⁻¹ attained yield with maximum variation of 35.8%. During 18 years, T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹ gave highest yield increase of 63.7%, while T₂: 20 kg N (urea) + 13 kg P ha⁻¹ gave lowest yield increase of 28.7% over T₁: Control. This indicated the

necessity of application of FYM @ 6 t ha⁻¹ for improving the soybean yield under *Vertisols*. Based on pooled ANOVA over years, T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹ gave significantly higher yield compared to all other treatments; while T₅: 60 kg N (urea) + 35 kg P ha⁻¹ was superior compared to T₁, T₂, T₃, T₇, T₈ and T₉. The treatments T₄: 40 kg N (urea) + 26 kg P ha⁻¹; T₇: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha⁻¹ and T₈: FYM @ 6 t ha⁻¹ were at par. Similarly, T₃: 30 kg N (urea) + 20 kg P ha⁻¹ and T₇: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha⁻¹; T₂: 20 kg N (urea) + 13 kg P ha⁻¹ and T₉: Crop residue @ 5 t ha⁻¹ was at par. The yield attained by treatments along with Least Significant Difference (LSD) values for comparison of treatments are given in Table 3. These results are in convergence with those of Sharma *et al.* (2009) who found that judicious application of organic and inorganic fertilizer would give significant response of sorghum-mung bean and improved the sustainability and soil quality under semi-arid *Alfisols*. Similarly, Maruthi Sankar *et al.* (2011) inferred on the superiority of combined application of FYM and inorganic NPK for attaining maximum sustainable yield and monetary returns from finger millet under semi-arid *Alfisols*. Peeyush Sharma *et al.* (2011) and Vikas Abrol *et al.* (2015) found similar results for sustaining the effects of tillage and fertilizer nutrients on soil moisture and productivity of maize and wheat under dry sub-humid Inceptisols. Similar results were also observed by Choulwar *et al.* (2015) while assessing the sustainability of tillage and fertilizer effects on cotton + soybean and soybean + pigeonpea systems under rotation in a semi-arid *Vertisol*.

Effect of Fertilizer Treatments on Rainwater Use Efficiency

Application of organic and inorganic fertilizer treatments gave significantly higher RWUE compared to T₁: Control in all years except 1995, which received normal and well distributed rainfall. T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹ gave maximum mean RWUE of 2.80

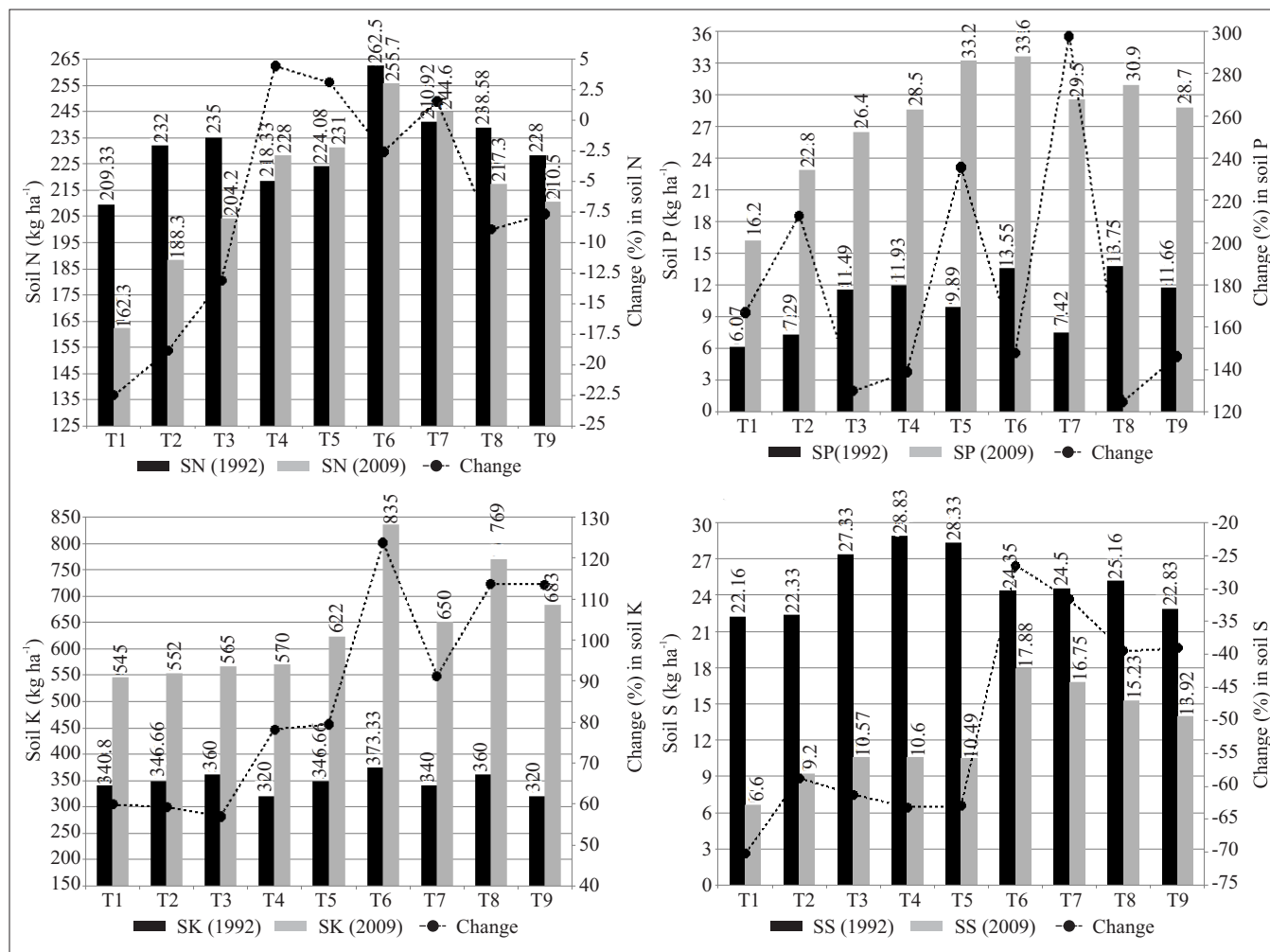
Fig. 1. Changes in soil fertility of nutrients under semi-arid *Vertisols* during 1992 to 2009

Table: 3

ANOVA of soybean yield (kg ha⁻¹) attained by fertilizer treatments in different years

Year	T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈	T ₉	LSD
1992	1764 ^e	1905 ^d	2099 ^b	2322 ^a	2343 ^a	2169 ^b	2058 ^{bc}	2046 ^{bc}	1958 ^{cd}	126
1993	1675 ^e	2234 ^d	2616 ^c	2828 ^b	2904 ^b	3051 ^a	2545 ^c	2810 ^b	2504 ^c	142
1994	1229 ^d	1652 ^{bc}	1811 ^b	2081 ^a	2172 ^a	2131 ^a	1640 ^{bc}	2099 ^a	1564 ^c	226
1995	2066	2258	2415	2318	2308	2365	2311	2222	2140	NS
1996	691 ^g	1161 ^e	1318 ^{cd}	1410 ^c	1574 ^b	1795 ^a	1211 ^{de}	1282 ^{cde}	940 ^f	152
1997	719 ^f	987 ^d	1147 ^{cd}	1250 ^{bc}	1371 ^{ab}	1449 ^a	997 ^d	1378 ^{ab}	897 ^{ef}	198
1998	949 ^e	1105 ^d	1186 ^{bcd}	1273 ^{bc}	1308 ^b	1476 ^a	1152 ^{cd}	1152 ^{cd}	1117 ^d	133
1999	1126 ^g	1253 ^f	1386 ^{de}	1536 ^{bc}	1609 ^b	1785 ^a	1366 ^{ef}	1487 ^{cd}	1285 ^{ef}	119
2000	885 ^f	1094 ^e	1348 ^{cd}	1476 ^{bc}	1649 ^{ab}	1690 ^a	1256 ^{de}	1319 ^{cd}	1163 ^{de}	190
2001	1606 ^c	1956 ^b	1958 ^b	2012 ^b	2093 ^{ab}	2368 ^a	2118 ^{ab}	1949 ^b	1949 ^b	330
2002	1085 ^d	1268 ^{bcd}	1381 ^{abc}	1444 ^{ab}	1497 ^a	1526 ^a	1323 ^{abc}	1438 ^{ab}	1193 ^{cd}	207
2003	1241 ^c	1875 ^b	2124 ^{ab}	2205 ^{ab}	2222 ^a	2240 ^a	2106 ^{ab}	2199 ^{ab}	2072 ^{ab}	334
2004	1143 ^d	1454 ^{bc}	1458 ^{bc}	1568 ^{bc}	1716 ^{ab}	1903 ^a	1468 ^{bc}	1565 ^{bc}	1413 ^{cd}	282
2005	1481 ^d	1644 ^{cd}	1649 ^{cd}	1788 ^{bcd}	2089 ^{ab}	2234 ^a	2191 ^a	1944 ^{abc}	1811 ^{bc}	322
2006	1464 ^d	2448 ^c	2720 ^{bc}	2772 ^{ab}	3050 ^{ab}	3247 ^a	3102 ^{ab}	3061 ^{ab}	2431 ^c	520
2007	2251 ^c	3206 ^{ab}	3287 ^{ab}	3299 ^{ab}	3345 ^{ab}	3501 ^a	3108 ^b	3247 ^{ab}	3194 ^{ab}	343
2008	1259 ^d	1525 ^{bc}	1573 ^{bc}	1637 ^{ab}	1720 ^a	1742 ^a	1540 ^{bc}	1555 ^{bc}	1458 ^c	145
2009	1357 ^d	1862 ^c	2122 ^{bc}	2380 ^{ab}	2374 ^{ab}	2600 ^a	2313 ^{ab}	2389 ^{ab}	2261 ^{ab}	365
Mean	1333 ^f	1716 ^e	1867 ^d	1978 ^{bc}	2075 ^b	2182 ^a	1878 ^d	1952 ^{cd}	1742 ^e	101
CV (%)	32.0	33.4	32.2	29.9	28.2	27.6	34.5	31.9	35.8	

LSD : Least significant difference at p < 0.05 level; Treatments with same letter (a, b, c, ...) within column are at par with each other

kg ha⁻¹ mm⁻¹ with minimum variation of 30.7%, while T₁: Control gave minimum of RWUE of 1.76 kg ha⁻¹ mm⁻¹ with maximum variation of 41.5%. The RWUE attained by treatments along with LSD values are given in Table 4. Importance of RWUE was also emphasized by Jat *et al.* (2012); Turner (2004) and Rockstrom *et al.* (2003), who gave suitable strategies for enhancing RWUE of crops under dryland condition. The importance of RWUE was also observed by Maruthi Sankar *et al.* (2012a), while optimizing the tillage and nutrient requirement for pearl millet grown under semi-arid *Vertisols*, *Inceptisols* and *Aridisols*. The studies have indicated that a treatment with maximum mean yield and RWUE over years would always be preferable to a treatment which gave maximum yield in a few normal years but lower RWUE under erratic rainfall conditions.

Effect of Rainfall and Soil Nutrients on Soybean Yield

The regression model of yield attained by T₈: FYM @ 6 t ha⁻¹ gave maximum coefficient of determination (R²) of 0.78, while T₁: Control gave minimum R² of 0.38. Among soil nutrients, organic carbon, soil N, P and K have significantly influenced the yield attained by T₇: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha⁻¹ and T₈: FYM @ 6 t ha⁻¹, while organic carbon and soil N were significant in influencing the yield attained by T₉: Crop residue @ 5 t ha⁻¹ based on the regression models calibrated the observations recorded in different years. The July rainfall significantly influenced the yield attained by T₇: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha⁻¹, while the September

rainfall significantly influenced the yield attained by T₅: 60 kg N (urea) + 35 kg P ha⁻¹. The prediction error ranged from 459 kg ha⁻¹ for T₈: FYM @ 6 t ha⁻¹ to 729 kg ha⁻¹ for T₃: 30 kg N (urea) + 20 kg P ha⁻¹.

The positive effect of variables indicated an improvement in yield, while the negative effect indicated a decline in yield over years. The regression models of yield through rainfall and soil nutrients, R² and prediction error ($\bar{E}_k$) of each treatment are given in Table 5. Sharma *et al.* (2013) reported similar effects of rainfall and soil nutrients on yield of maize attained by organic and inorganic fertilizer treatments under dry sub-humid *Inceptisols*; while Maruthi Sankar *et al.* (2011) reported for cotton under semi-arid *Vertisols* and finger millet under semi-arid *Alfisols*, respectively. The results on effect of uptake on soybean yield are in agreement with those observed by Barbarick *et al.* (2010) for wheat based on a 15-year long-term study. Behera *et al.* (2007) and Nema *et al.* (2008) reported significant effects of monthly rainfall on rice and pearl millet yield, respectively and identified efficient fertilizer treatments with maximum SYI yield on multivariate regression models.

Principal Components of Yield Through Rainfall and Plant Nutrients

Based on the PC model, 9 variables of rainfall and soil N, P, K and S nutrients were used to determine PCs for explaining variability in the data. Three PCs explained maximum variability of data in the range of 66.6% by T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹ to 74.1% by T₂: 20 kg N (urea) + 13 kg P ha⁻¹. The PC coefficients or eigen

Table: 4
ANOVA of rainwater use efficiency (kg ha⁻¹ mm⁻¹) attained by fertilizer treatments in different years

Year	T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈	T ₉	LSD
1992	3.18 ^e	3.43 ^d	3.78 ^b	4.18 ^a	4.22 ^a	3.91 ^b	3.71 ^{bc}	3.69 ^{bc}	3.53 ^{cd}	0.23
1993	1.59 ^e	2.12 ^d	2.48 ^c	2.68 ^b	2.76 ^b	2.90 ^a	2.42 ^c	2.67 ^b	2.38 ^c	0.13
1994	1.41 ^d	1.90 ^{bc}	2.08 ^b	2.39 ^a	2.50 ^a	2.45 ^a	1.88 ^{bc}	2.41 ^a	1.80 ^c	0.26
1995	2.23	2.24	2.60	2.50	2.49	2.55	2.49	2.40	2.31	NS
1996	0.53 ^f	0.89 ^d	1.01 ^{cd}	1.08 ^{bc}	1.20 ^b	1.37 ^a	0.93 ^d	0.98 ^{cd}	0.72 ^e	0.12
1997	0.65 ^e	0.89 ^{cd}	1.04 ^{bc}	1.13 ^{ab}	1.24 ^a	1.31 ^a	0.90 ^{cd}	1.24 ^a	0.81 ^{de}	0.18
1998	1.12 ^e	1.31 ^d	1.40 ^{bcd}	1.51 ^{bc}	1.55 ^b	1.75 ^a	1.36 ^{cd}	1.36 ^{cd}	1.32 ^d	0.16
1999	1.35 ^f	1.51 ^c	1.67 ^{cd}	1.85 ^b	1.93 ^b	2.14 ^a	1.64 ^{de}	1.79 ^{bc}	1.54 ^{de}	0.14
2000	1.93 ^f	2.39 ^e	2.95 ^{cd}	3.23 ^{bc}	3.61 ^{ab}	3.69 ^a	2.75 ^{de}	2.88 ^{cd}	2.54 ^{de}	0.42
2001	2.17 ^c	2.64 ^b	2.64 ^b	2.72 ^b	2.83 ^{ab}	3.20 ^a	2.86 ^{ab}	2.63 ^b	2.63 ^b	0.38
2002	3.06 ^d	3.58 ^{bcd}	3.90 ^{abc}	4.08 ^{ab}	4.23 ^a	4.31 ^a	3.74 ^{abc}	4.06 ^{ab}	3.37 ^{cd}	0.58
2003	1.32 ^c	1.99 ^b	2.26 ^{ab}	2.34 ^{ab}	2.36 ^a	2.38 ^a	2.24 ^{ab}	2.34 ^{ab}	2.20 ^{ab}	0.36
2004	1.42 ^d	1.81 ^{bc}	1.82 ^{bc}	1.95 ^{bc}	2.14 ^{ab}	2.37 ^a	1.83 ^{bc}	1.95 ^{bc}	1.76 ^{cd}	0.35
2005	2.02 ^d	2.24 ^{cd}	2.25 ^{cd}	2.44 ^{bcd}	2.85 ^{ab}	3.05 ^a	2.99 ^a	2.65 ^{abc}	2.47 ^{bc}	0.44
2006	1.35 ^d	2.25 ^c	2.50 ^{bc}	2.55 ^{abc}	2.81 ^{ab}	2.99 ^a	2.85 ^{ab}	2.82 ^{ab}	2.24 ^c	0.48
2007	2.60 ^c	3.70 ^{ab}	3.80 ^{ab}	3.81 ^{ab}	3.87 ^{ab}	4.05 ^a	3.59 ^b	3.75 ^{ab}	3.69 ^{ab}	0.40
2008	2.16 ^d	2.62 ^{bc}	2.70 ^{bc}	2.81 ^{ab}	2.96 ^a	3.00 ^a	2.65 ^{bc}	2.67 ^{bc}	2.51 ^c	0.25
2009	1.58 ^d	2.16 ^c	2.46 ^{bc}	2.76 ^{ab}	2.76 ^{ab}	3.02 ^a	2.69 ^{ab}	2.77 ^{ab}	2.63 ^{ab}	0.42
Mean	1.76 ^e	2.22 ^d	2.41 ^{bcd}	2.56 ^{abc}	2.68 ^{ab}	2.80 ^a	2.42 ^{bcd}	2.50 ^{abcd}	2.25 ^{cd}	0.32
CV	41.5	36.6	35.5	34.8	33.4	30.7	35.7	33.5	36.9	47.4

LSD : Least significant difference at p < 0.05 level; CV : Coefficient of variation (%); Treatments with same letter (a, b, c, ...) within column are at par with each other

values which indicate the variance explained by PCs and the cumulative variance of PCs are given in Table 6. The 1st PC explained variance of 33.3% (T₇: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha⁻¹) to 42.1% (T₂: 20 kg N (urea) + 13 kg P ha⁻¹); while 2nd PC explained variance of 18.1% (T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹) to 21.6% (T₁: Control). Similarly, 3rd PC explained variance of 11.3% (T₉: Crop residue @ 5 t ha⁻¹) to 16.5% (T₁: Control).

Loadings of Rainfall and Soil Nutrients on PCs

The loadings of rainfall and soil nutrients on PCs given in Table 7 indicated that the PCs were significantly influenced by variables in capturing the variability in data. Among soil nutrients, organic carbon, soil N and soil S had a significant positive loading on the 1st PC of all the 9

treatments. Soil P had a significant negative loading on P₁ of T₁: Control, and P₂ of T₃: 30 kg N (urea) + 20 kg P ha⁻¹, T₅: 60 kg N (urea) + 35 kg P ha⁻¹ and T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹, while it had a significant positive loading on P₂ of T₈.

Among rainfall variables, June rainfall was negatively loaded on P₂ of T₁: Control, T₂: 20 kg N (urea) + 13 kg P ha⁻¹, T₇: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha⁻¹, T₈: FYM @ 6 t ha⁻¹ and T₉: Crop residue @ 5 t ha⁻¹; while it was positively loaded on P₂ of T₃: 30 kg N (urea) + 20 kg P ha⁻¹ and T₄: 40 kg N (urea) + 26 kg P ha⁻¹. July rainfall was positively loaded on P₁ of T₄: 40 kg N (urea) + 26 kg P ha⁻¹, T₅: 60 kg N (urea) + 35 kg P ha⁻¹, T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹, T₈: FYM @ 6 t ha⁻¹ and T₉: Crop residue @ 5 t ha⁻¹. September

Table: 5
Regression models of soybean yield through monthly rainfall during crop growth period and soil fertility variables

Treatment	Regression model	R ²	PE
Control	Y = - 4470 - 4024.5 (OC) + 41.76 (SN) + 4.74 (SP) + 0.36 (SK) - 51.10 (SS) - 1.23 (Jun) + 0.079 (Jul) + 0.68 (Aug) + 1.81 (Sep) + 2.52 (Oct)	0.38	526
20 kg N (urea) + 13 kg P ha ⁻¹	Y = 1422 + 14667.8 (OC) - 27.63 (SN) + 12.11 (SP) - 2.01 (SK) - 76.68 (SS) - 3.78 (Jun) + 0.86 (Jul) - 0.57 (Aug) + 1.83 (Sep) + 0.87 (Oct)	0.51	628
30 kg N (urea) + 20 kg P ha ⁻¹	Y = 1975 + 10468.9 (OC) - 28.71 (SN) + 36.27 (SP) - 1.55 (SK) - 3.69 (SS) + 5.76 (Jun) + 1.29 (Jul) - 0.996 (Aug) + 0.77 (Sep) - 4.63 (Oct)	0.39	729
40 kg N (urea) + 26 kg P ha ⁻¹	Y = 1039 - 15240.9 (OC) + 40.32 (SN) - 12.53 (SP) - 1.75 (SK) + 16.36 (SS) + 2.95 (Jun) + 1.03 (Jul) + 1.33 (Aug) + 3.60 (Sep) - 1.75 (Oct)	0.64	552
60 kg N (urea) + 35 kg P ha ⁻¹	Y = 2133 - 19568.2 (OC) + 49.25 (SN) - 29.15 (SP) - 2.41 (SK) + 13.72 (SS) + 1.66 (Jun) + 1.61 (Jul) + 1.71 (Aug) + 4.49* (Sep) + 0.87 (Oct)	0.67	523
20 kg N (urea) + 13 kg P + FYM @ 6 t ha ⁻¹	Y = 4158 - 474.2 (OC) - 6.08 (SN) + 12.37 (SP) - 1.19 (SK) - 18.59 (SS) + 1.78 (Jun) + 1.77 (Jul) - 0.06 (Aug) + 1.60 (Sep) - 0.18 (Oct)	0.48	677
20 kg N (urea) + 13 kg P + FYM @ 5 t ha ⁻¹	Y = 18678* + 30256* (OC) - 117.18* (SN) - 8.44 (SP) - 6.91* (SK) - 224.82* (SS) - 0.44 (Jun) + 4.04* (Jul) - 4.42 (Aug) + 2.36 (Sep) + 11.36 (Oct)	0.71*	541
FYM @ 6 t ha ⁻¹	Y = 13531* + 8400* (OC) - 39.95* (SN) - 16.75 (SP) - 6.97* (SK) - 178.15* (SS) - 2.19 (Jun) + 1.33 (Jul) + 0.33 (Aug) + 1.69 (Sep) - 0.30 (Oct)	0.78*	459
Crop residue @ 5 t ha ⁻¹	Y = 6786* + 9425.9* (OC) - 44.48* (SN) - 38.25 (SP) - 1.19 (SK) + 11.38 (SS) + 0.93 (Jun) - 0.36 (Jul) - 0.10 (Aug) + 2.39 (Sep) + 7.60 (Oct)	0.68	547

R² : Coefficient of determination; PE : Prediction error (kg ha⁻¹); * and ** indicate significance at p < 0.05 and p < 0.01 level, respectively

Table: 6
Eigen values and variance of effects of fertilizer treatments explained by principal components

Treatments	Eigen values			Variance (%)			Total
	P ₁	P ₂	P ₃	P ₁	P ₂	P ₃	
Control	3.45	2.16	1.65	34.5	21.6	16.5	72.6
20 kg N (urea) + 13 kg P ha ⁻¹	4.21	1.91	1.29	42.1	19.1	12.9	74.1
30 kg N (urea) + 20 kg P ha ⁻¹	4.04	2.11	1.16	40.4	21.1	11.6	73.1
40 kg N (urea) + 26 kg P ha ⁻¹	3.80	1.94	1.58	38.0	19.4	15.8	73.2
60 kg N (urea) + 35 kg P ha ⁻¹	4.03	1.99	1.34	40.3	20.0	13.5	73.8
20 kg N (urea) + 13 kg P + FYM @ 6 t ha ⁻¹	3.50	1.81	1.35	35.0	18.1	13.5	66.6
20 kg N (urea) + 13 kg P + FYM @ 5 t ha ⁻¹	3.33	2.01	1.46	33.3	20.1	14.6	68.0
FYM @ 6 t ha ⁻¹	3.49	1.88	1.46	34.9	18.8	14.6	68.3
Crop residue @ 5 t ha ⁻¹	3.90	2.13	1.13	39.0	21.3	11.3	71.6

P₁, P₂ and P₃ are leading principal components with eigen value > 1

Table: 7
Loadings of rainfall and soil fertility variables on PCs of treatments in soybean

PC	Rainfall variables					Soil fertility variables				
	Jun	Jul	Aug	Sep	Oct	OC	SN	SP	SK	SS
T ₁ : Control										
P1	0.15	0.24	-0.14	-0.17	0.62	0.86*	0.87*	-0.84*	-0.20	0.84*
P2	-0.79*	0.68	0.61	0.39	0.03	-0.11	-0.21	0.12	-0.57	0.41
P3	0.34	0.59	-0.11	0.35	0.50	-0.39	-0.39	-0.28	0.63	0.13
T ₂ : 20 kg N (urea) + 13 kg P ha ⁻¹										
P1	-0.37	0.60	0.26	0.08	0.50	0.91*	0.91*	-0.57	-0.77*	0.91*
P2	-0.78*	0.09	0.59	0.17	-0.62	0.16	0.01	0.65	-0.24	-0.19
P3	0.05	0.60	0.02	0.81*	0.28	-0.18	-0.22	0.18	0.24	0.11
T ₃ : 30 kg N (urea) + 20 kg P ha ⁻¹										
P1	-0.51	0.67	0.31	0.16	0.46	0.94*	0.94*	-0.41	-0.52	0.89*
P2	0.71*	0.09	-0.46	-0.19	0.63	-0.01	-0.01	-0.79*	0.55	0.20
P3	0.13	0.41	-0.16	0.91*	0.21	-0.10	-0.09	0.23	0.08	-0.10
T ₄ : 40 kg N (urea) + 26 kg P ha ⁻¹										
P1	-0.22	0.79*	0.20	0.33	0.63	0.94*	0.94*	-0.43	0.11	0.79*
P2	0.84*	-0.22	-0.61	-0.20	0.47	0.08	0.01	-0.64	0.30	-0.19
P3	0.18	0.19	0.02	0.56	-0.17	0.14	0.20	0.41	0.81*	-0.54
T ₅ : 60 kg N (urea) + 35 kg P ha ⁻¹										
P1	-0.52	0.75*	0.31	0.34	0.43	0.95*	0.91*	-0.18	-0.60	0.83*
P2	0.68	0.04	-0.45	-0.19	0.69	0.07	-0.09	-0.81*	0.25	0.29
P3	0.30	0.34	-0.13	0.73*	0.16	0.12	0.20	0.34	0.52	-0.35
T ₆ : 20 kg N (urea) + 13 kg P + FYM @ 6 t ha ⁻¹										
P1	-0.52	0.75*	0.25	0.22	0.42	0.79*	0.76*	0.24	-0.63	0.86*
P2	0.69	-0.01	-0.50	-0.16	0.72*	0.17	0.14	-0.70*	-0.08	0.12
P3	-0.22	0.01	0.33	0.06	0.15	-0.52	-0.55	-0.43	-0.51	0.39
T ₇ : 20 kg N (urea) + 13 kg P + FYM @ 5 t ha ⁻¹										
P1	-0.40	0.69	0.18	0.25	0.51	0.71*	0.73*	-0.44	-0.62	0.85*
P2	-0.70*	0.17	0.54	0.26	-0.34	-0.37	-0.43	0.67	-0.42	0.28
P3	-0.34	0.01	0.27	-0.06	-0.63	0.56	0.50	0.16	0.39	-0.36
T ₈ : FYM @ 6 t ha ⁻¹										
P1	-0.43	0.72*	0.26	0.13	0.44	0.78*	0.77*	-0.38	-0.63	0.88*
P2	-0.75*	0.17	0.54	0.33	-0.50	-0.11	-0.18	0.75*	0.02	0.14
P3	0.08	0.08	-0.18	0.46	0.51	-0.53	-0.55	0.06	-0.48	0.34
T ₉ : Crop residue @ 5 t ha ⁻¹										
P1	-0.38	0.75*	0.24	0.23	0.48	0.87*	0.90*	-0.50	-0.44	0.92*
P2	-0.82*	0.07	0.50	0.20	-0.50	-0.15	-0.25	0.67	-0.61	0.15
P3	0.12	0.22	-0.36	0.89*	0.20	-0.05	-0.11	0.30	0.06	-0.01

* Significant loadings (≥ 0.70 or ≤ -0.70) of variables on principal components

rainfall was positively loaded on P₃ of T₂: 20 kg N (urea) + 13 kg P ha⁻¹, T₃: 30 kg N (urea) + 20 kg P ha⁻¹, T₅: 60 kg N (urea) + 35 kg P ha⁻¹ and T₉: Crop residue @ 5 t ha⁻¹. October rainfall was positively loaded on P₂ of T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹.

The PC scores were derived for treatments using observations of rainfall and soil nutrients observed in each year, along with loadings of variables on P₁, P₂ and P₃ calibrated for the data over years. The regression models of soybean yield through PC scores were calibrated and are given in Table 8 along with estimates of R² and prediction error of each treatment. The model of T₈: FYM @ 6 t ha⁻¹ had maximum R² of 0.46, while T₂: 20 kg N (urea) + 13 kg P ha⁻¹ had lowest R² of 0.15. The regression models indicated positive effect of P₁ on yield attained by T₁:

Control, T₂: 20 kg N (urea) + 13 kg P ha⁻¹, T₄: 40 kg N (urea) + 26 kg P ha⁻¹, T₅: 60 kg N (urea) + 35 kg P ha⁻¹, T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹, while P₂ had a positive effect on the yield attained by T₂: 20 kg N (urea) + 13 kg P ha⁻¹, T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹, T₇: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha⁻¹, T₈: FYM @ 6 t ha⁻¹ and T₉: Crop residue @ 5 t ha⁻¹. Similarly, P₃ had a positive effect on the yield attained by T₂: 20 kg N (urea) + 13 kg P ha⁻¹, T₃: 30 kg N (urea) + 20 kg P ha⁻¹, T₅: 60 kg N (urea) + 35 kg P ha⁻¹, T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹, T₈: FYM @ 6 t ha⁻¹ and T₉: Crop residue @ 5 t ha⁻¹. The regression model of yield through P₁, P₂ and P₃ indicated that the prediction error was minimum of 460 kg ha⁻¹ under T₁: Control, while it was maximum of 664 kg ha⁻¹ in T₇: 20 kg N (urea) + 13 kg P + FYM @ 5 t ha⁻¹.

Effect of Treatments on Sustainability Yield Index and Monetary Returns

Based on the study, mean yield, RWUE, cost of cultivation (₹ ha⁻¹), gross returns (₹ ha⁻¹), net returns (₹ ha⁻¹), benefit-cost ratio and sustainability yield index attained by different treatments over years are given in Table 9. Based on the regression model of yield through rainfall and soil nutrients, application of T₅: 60 kg N (urea) + 35 kg P ha⁻¹ was superior with maximum SYI of 44.3%, while T₁: Control attained minimum SYI of 23.1%. Based on PC model, T₆: 20 kg N (urea) + 13 kg P + FYM @ 6t ha⁻¹ was superior with SYI of 44.2%, while T₁: Control attained minimum SYI of 24.9% over years. The study indicated that T₆: 20 kg N (urea) + 13 kg P + FYM @ 6t ha⁻¹ attained maximum mean yield of 2182 kg ha⁻¹, RWUE of 2.80 kg ha⁻¹ mm⁻¹, gross returns of ₹ 34814 ha⁻¹, net returns of ₹ 24346 ha⁻¹ and BC ratio of 3.33 over years. Further, T₆: 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹ maintained maximum mean soil N of 269 kg ha⁻¹; soil P of

23.9 kg ha⁻¹; soil K of 757 kg ha⁻¹ and soil S of 18.0 kg ha⁻¹ over years. Although T₅: 60 kg N (urea) + 35 kg P ha⁻¹ was superior with maximum BC ratio of 3.57, it was the 2nd best for attaining yield of 2075 kg ha⁻¹, RWUE of 2.68 kg ha⁻¹ mm⁻¹, gross returns of ₹ 33178 ha⁻¹, net returns of ₹ 23877 ha⁻¹ with SYI of 44.3% based on the regression and 41.6% based on the PC model. These results are in agreement with those reported by Sharma *et al.* (2005, 2008 and 2009); Wanjari *et al.* (2004); Sharma *et al.* (2013) and Maruthi Sankar *et al.* (2008, 2011, 2013 and 2014) for profitability and sustainability of organic and inorganic fertilizer treatments tested for different rainfed crops. Based on our study, we recommend that farmers could benefit with an application of 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹ for soybean for attaining maximum yield, RWUE, net profit, SYI, apart from maintaining soil fertility under semi-arid *Vertisols*.

4. CONCLUSIONS

Based on a study conducted during 1992 to 2009 at Indore, 20 kg N (urea) + 13 kg P + FYM @ 6 t ha⁻¹ obtained

Table: 8
Regression model of soybean yield attained by different treatments through principal components

Treatment	Principal component model	R ²	PE
Control	Y = 1608** + 0.628 (P ₁) - 0.172 (P ₂) - 0.654 (P ₃)	0.21	460
20 kg N (urea) + 13 kg P ha ⁻¹	Y = 1541** + 0.179 (P ₁) + 0.092 (P ₂) + 0.461 (P ₃)	0.15	624
30 kg N (urea) + 20 kg P ha ⁻¹	Y = 1911** - 0.717 (P ₁) - 1.561 (P ₂) + 1.872 (P ₃)	0.35	619
40 kg N (urea) + 26 kg P ha ⁻¹	Y = 2169* + 0.458 (P ₁) - 0.218 (P ₂) - 0.689 (P ₃)	0.18	642
60 kg N (urea) + 35 kg P ha ⁻¹	Y = 1794* + 0.375 (P ₁) - 1.158 (P ₂) + 0.661 (P ₃)	0.29	617
20 kg N (urea) + 13 kg P + FYM @ 6 t ha ⁻¹	Y = 2984* + 0.339 (P ₁) + 1.482 (P ₂) + 2.403 (P ₃)	0.30	634
20 kg N (urea) + 13 kg P + FYM @ 5 t ha ⁻¹	Y = 3784* - 1.106 (P ₁) + 2.410 (P ₂) - 4.886 (P ₃)	0.37	664
FYM @ 6 t ha ⁻¹	Y = 3126** - 0.858 (P ₁) + 0.962 (P ₂) + 4.374 (P ₃)	0.46	609
Crop residue @ 5 t ha ⁻¹	Y = 2084** - 1.083 (P ₁) + 1.547 (P ₂) + 2.469 (P ₃)	0.38	636

R² : Coefficient of determination; PE : Prediction error (kg ha⁻¹)

Table: 9
Effect of fertilizer treatments on monetary returns and sustainability yield index over years

Treatments	Yield (kg ha ⁻¹)	Yield increase (%) over control	RWUE (kg ha ⁻¹ mm ⁻¹)	Cost of cultivation (₹ ha ⁻¹)	Gross returns (₹ ha ⁻¹)	Net returns (₹ ha ⁻¹)	B:C Ratio	PE (RM)	PE (PCaM)	SYI (RM)	SYI (PCM)
Control	1333 ^f		1.76 ^e	8512 ^a	21293 ^e	12781 ^e	2.50 ^e	526	460	23.1	24.9
20kg N (urea)+ 13 kg P ha ⁻¹	1716 ^e	28.7 ^e	2.22 ^d	8784 ^b	28937 ^d	20153 ^{cd}	3.29 ^{ab}	628	624	31.1	31.2
30 kg N (urea) + 20 kg P ha ⁻¹	1867 ^d	40.1 ^d	2.41 ^{bcd}	8904 ^c	30557 ^{cd}	21653 ^{bc}	3.43 ^a	729	619	32.5	35.6
40 kg N (urea) + 26 kg P ha ⁻¹	1978 ^{bc}	48.4 ^{bc}	2.56 ^{abc}	9037 ^c	31629 ^{bc}	22592 ^{ab}	3.50 ^a	552	642	40.7	38.2
60 kg N (urea) + 35 kg P ha ⁻¹	2075 ^b	55.7 ^b	2.68 ^{ab}	9301 ^c	33178 ^{ab}	23877 ^{ab}	3.57 ^a	523	617	44.3	41.6
20 kg N (urea) + 13 kg P + FYM @ 6 t ha ⁻¹	2182 ^a	63.7 ^a	2.80 ^a	10467 ^d	34814 ^a	24346 ^a	3.33 ^{ab}	677	634	43.0	44.2
20 kg N (urea) + 13 kg P + FYM @ 5 t ha ⁻¹	1878 ^d	40.9 ^{cd}	2.42 ^{bcd}	12162 ^e	31676 ^{bc}	19514 ^{cd}	2.60 ^c	541	664	38.2	34.7
FYM@ 6 t ha ⁻¹	1952 ^{cd}	46.4 ^{cd}	2.50 ^{abcd}	10206 ^d	31765 ^{bc}	21559 ^{bc}	3.11 ^b	459	609	42.6	38.4
Crop residue @ 5 t ha ⁻¹	1742 ^e	30.7 ^e	2.25 ^{cd}	12126 ^e	30264 ^{cd}	18138 ^d	2.50 ^c	547	636	34.1	31.6
Mean	1858	44.3	2.40	9944	30457	20513	3.09				
CV	13.3	26.8	12.7	14.1	12.6	17.2	14.2				
LSD	101	7.8	0.32	916	2502	2302	0.29				

RWUE: Rainwater use efficiency; RM : Regression model; PCM: Principal component model; PE: Prediction error (kg ha⁻¹); CV: Coefficient of variation (%); LSD: Least significant difference at p < 0.05 level; SYI: Sustainability yield index (%); Treatments with same letter (a, b, c, ...) in same column are at par with each other

significantly higher yield, RWUE and monetary returns. Three PCs explained maximum variance of 74.1% in the plot with application of T_2 : 20 kg N (urea) + 13 kg P ha^{-1} . The 1st PC explained variance of 33.3 to 42.1%, while 2nd PC explained 18.1 to 21.6% and 3rd PC explained 11.3 to 16.5%. The regression model of yield through PC scores indicated application of 20 kg N (urea) + 13 kg P + FYM @ 6 t ha^{-1} maintained maximum soil N of 269 kg ha^{-1} ; soil P of 23.9 kg ha^{-1} ; soil K of 757 kg ha^{-1} ; and soil S of 18.0 kg ha^{-1} at the end of the study. This treatment could be adopted for attaining maximum soybean yield, RWUE, net returns and SYI and maintain maximum soil fertility under semi-arid *Vertisols*.

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