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Soil moisture and optimum nitrogen requirement for sustainable productivity of sorghum grown in Vertisols of Solapur district, Maharashtra

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Abstract : An attempt was made to optimize fertilizer N at varying levels of available soil N and soil moisture for rainfed sorghum grown in Vertisols under semi-arid condition at Solapur. The study was based on 20 field experiments conducted with 8 combinations of organic and inorganic fertilizers under receding moisture conditions in a permanent site from 1985 to 2004. The soil had a mean moisture profile of 219 mm with variation of 34.7% at sowing. Similarly, the soil had a mean available N of 148 kg ha^{-1} with variation of 11.2% and P of 16 kg ha^{-1} with variation of 42.7%. The mean sorghum yield of 946 kg ha^{-1} with variation of 40.2% was attained over years. The results indicated that combination of 25 kg N ha^{-1} (crop residue + 25 kg N ha^{-1} *(Leucaena)* was superior with a significant yield predictability (0.85**) and minimum prediction error of 193 kg ha^{-1}. This was efficient with maximum mean yield of 1109 kg ha^{-1} and sustainable yield index of 0.54 over years. The pooled model of treatments gave a significant predictability (0.38**) with prediction error of 282 kg ha^{-1}. The study further indicated that when soil moisture ranged from 100 to 300 mm, optimal ferti izer N ranged from 26 to 76 kg ha^{-1} at a soil-N of 120 kg ha^{-1} and 14 to 64 kg ha^{-1} at a soil-N of 140 kg ha^{-1}. At a soil-N of 200 kg ha^{-1} and soil moisture of 160 mm, fertilizer N of 26 kg ha^{-1} was optimum for attaining sustainable sorghum yield. Since the treatment 50% N (crop residue) + 50% N *(Leaucaena)* ,gave maximum sustainable yield index, mean yield and yield predictability with minimum prediction error, optimum fertilizer N could be applied at the rate of 50% through crop residue and the remaining through Leaucaena.

Additional key words: *Soil nutrients, soil moisture, organic and inorganic fertilizer, regression model, prediction, optimization, sustainable yield index*

Introduction

Sorghum (*Sorghum bicolor* L.) is an important cereal crop grown under rainfed conditions in Maharashtra, Andhra Pradesh, Karnataka, Tamil Nadu and other states of India. It is grown in monsoon season (June to September) and also in post-monsoon season (October to February) under receding soil moisture conditions. It is predominantly grown as a sole crop in post-monsoon season in semi-arid Vertisols of Maharashtra. Among different parameters, sufficient soil moisture at sowing is essential for good crop establishment and yield in a post-monsoon season. This would influence crop response to applied fertilizer under dryland conditions. The soil moisture content, retention and supply are directly influenced by quantity of rainfall and its distribution in the monsoon season. Prihar and Gajri (1988) described strategies for rationalizing fertilizer application in relation to seasonal water supply and innate soil fertility. Singh *et al.* (1975) examined the effect of fertilizer N on yield and water use efficiency of winter wheat as affected by stored water and rainfall. Venkateswarlu and Singh (1982) reviewed soils research in India and described responses of rainfed crops to applied nutrients in limited water conditions.

The permanent manurial experiments with combinations of organic and inorganic fertilizer nutrients are being conducted for rainfed crops at 22 research centers of All India Coordinated Research Project for Dryland Agriculture. The fertilizer treatments could be statistically evaluated and ranked for sustainability based on the procedure discussed by Vittal *et al.* (2003). The statistical models discussed by Draper and Smith (1973) and Maruthi Sankar (1986) could be used for optimizing fertilizer requirement of crops based on soil fertility and moisture parameters. An attempt is made in this paper to develop efficient prediction models of sorghum yield and optimize fertilizer N at varying levels of soil N and moisture at sowing based on experiments conducted in a permanent site under semi-arid Vertisols.

Materials and Methods

The permanent manurial experiments on sorghum (*Sorghum bicolor* L.) with 'M-35-1' variety were conducted in the same site in a Vertisol at Solapur (semi-arid) during 20 *rabi* seasons from 1985 to 2004 under receding soil moisture conditions. Solapur is located at a latitude of 17.7° North and a longitude of 75.9° East under scarce rainfall zone of Maharashtra. The earliest date of sowing of sorghum was on 11th September in 1993, while the farthest was on 27th October in 1998. Similarly, the earliest date of harvest of the crop was on 21st January in 1986, while the farthest was on 16th February in 1989. The crop had a minimum of 100 days growing period in 1998 and a maximum of 141 days in 1986 with a mean of 127 days and variation of 8.1%.

Eight fertilizer treatment combinations of nitrogen, farm yard manure (FYM), loppings of *Leucaena* and crop residue were tested in each season. The treatments were 25 kg N ha^{-1}; 50 kg N ha^{-1}; 25 kg N ha^{-1} (crop residue); 25 kg N ha^{-1} (FYM); 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1}; 25 kg N ha^{-1} (FYM) + 25 kg N ha^{-1}; 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1} (*Leucaena*) and an unfertilized treatment (control). The composted crop residue, FYM and *Leucaena* had 0.426%, 0.624% and 3.566% N respectively. Similarly, P content was 0.218, 0.571 and 0.215% and K content was 2.026, 1.033 and 1.718% in composted crop residue, FYM and *Leucaena* sources respectively. Freshly pruned leaves and small twigs of *Leucaena* were used as a source of N. A recommended P dose @ 25 kg ha^{-1} was applied in all treatments every year. The experiments were conducted in a net plot size of 9.9 m x 8.2 m with row spacing of 45 cm. The treatments were randomized and superimposed to plots in a Randomized Block Design with 3 replications.

The observations were recorded on available soil moisture (mm) from 0–30 cm depth at the time of sowing, 30, 60, 90 days after sowing (DAS) and harvest of the crop. Initial soil samples were collected from 0–30 cm depth and analyzed for available soil N with alkaline permanganate method (Subbaiah and Asija 1956) and soil P with Olsen's method (Olsen *et al.* 1954). The experiment was conducted on a Vertisol (Fine, smectitic, hyperthermic Typic Haplusterts) with field capacity of 304 mm and permanent wilting point of 155 mm per m depth of soil moisture. The crop attained a maximum root depth of 60 cm at 65 DAS in different years. Solapur receives a normal annual rainfall of 723 mm. The actual rainfall during South–West monsoon (June to September) ranged from 257 to 1212 mm with a mean of 552 mm and variation of 51.3%. The post-monsoon (October to February) rainfall ranged from 5 to 323 mm with a mean of 132 mm and variation of 86.1% during 1985 to 2004.

Results and Discussion

Distribution of soil moisture, soil test values and sorghum yield

The analysis of variance indicated a significant difference among treatments in both individual years and also over years for soil nutrients, soil moisture on different days after sowing and yield attained in different seasons. The treatment-wise mean, variation, standard error of mean and critical difference at $p < 0.05$ and $p < 0.01$ for assessing treatment differences for soil N and P, soil moisture at sowing, 30, 60, 90 DAS and harvest and yield are given in table 1. Soil-N ranged from 107 kg ha^{-1} in control during 2000 to 205 kg ha^{-1} in 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1} (*Leucaena*) during 1989 with mean of 148 kg ha^{-1} and variation of 11.2%. Soil-P ranged from 5.6 kg ha^{-1} in control during 1993 to 37.4 kg ha^{-1} in 25 kg N ha^{-1} (FYM)+25 kg N ha^{-1} treatment during 1989 with mean of 16 kg ha^{-1} and variation of 42.7%.

The mean soil moisture at sowing ranged from 210 mm with variation of 37.5% under control to 236 mm with variation of 31.8% under 25 kg N (crop residue) + 25 kg N (*Leucaena*). Similarly, it ranged from 210 mm with variation of 32.9% under control to 264 mm with variation of 34.1% under 25 kg N (crop residue) + 25 kg N ha^{-1} at 30 DAS; 186 mm with variation of 37.0% under control to 203 mm with variation of 33.2% under 25 kg N ha^{-1} (crop residue) at 60 DAS; 160 mm with variation of 39.7% under control to 183 mm with variation of 24.8% under 25 kg N ha^{-1} (crop residue) at 90 DAS; and 134 mm with variation of 38.9% under control to 167 mm with variation of 12.7% under 25 kg N ha^{-1} (crop residue) at harvest. A maximum mean yield of 1109 kg ha^{-1} with variation of 36.4% was attained by 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1} (*Leucaena*), while a minimum of 649 kg ha^{-1} with variation of 40.6% was attained by control.

Table 1. Effect of fertilizer treatments on soil nutrients, soil moisture and sorghum yield

Treatment	Soil nutrients (kg ha^{-1})		Soil moisture (mm) in 0–30 cm depth on different days after sowing					Grain yield (kg ha^{-1})
	N	P	Sowing	30	60	90	Harvest	
Control	128	12.9	210	210	186	160	134	649
	(8.8)*	(54.6)	(37.5)	(32.9)	(37.0)	(39.7)	(38.9)	(40.6)
25 kg N ha^{-1}	138	15.5	215	224	193	176	160	905
	(8.9)	(44.9)	(37.0)	(29.2)	(35.0)	(27.5)	(12.2)	(36.1)
50 kg N ha^{-1}	143	14.9	216	226	193	174	154	1049
	(8.4)	(44.4)	(36.8)	(28.3)	(36.0)	(27.6)	(15.1)	(36.8)
25 kg N ha^{-1} (CR)	142	16.5	217	227	203	183	167	820
	(6.3)	(37.1)	(36.7)	(27.1)	(33.2)	(24.8)	(12.7)	(42.1)
25 kg N ha^{-1} (FYM)	155	17.4	214	222	193	171	158	939
	(9.0)	(41.8)	(36.2)	(27.4)	(36.0)	(28.5)	(14.3)	(35.9)
25 kg N (CR) + 25 kg N	150	14.8	231	264	201	178	158	1047
ha^{-1}	(7.1)	(43.7)	(30.4)	(34.1)	(33.1)	(25.3)	(13.0)	(37.2)
25 kg N (FYM) + 25 kg	160	17.9	214	227	193	175	158	1052
N ha^{-1}	(9.0)	(38.9)	(36.1)	(29.2)	(34.8)	(26.2)	(12.3)	(38.7)
25 kg N (CR) + 25 kg N	163	18.4	236	227	200	178	160	1109
ha^{-1} (*Leucaena*)	(10.2)	(36.3)	(31.8)	(27.4)	(33.5)	(26.0)	(15.2)	(36.4)
Pooled	148	16.0	219	228	195	175	156	946
	(11.2)	(42.7)	(34.7)	(29.8)	(34.1)	(27.8)	(18.1)	(40.2)
F-test	**	**	**	**	**	**	**	**
Sem	2.3	0.5	3.9	5.9	2.1	3.8	4.1	35.6
CD ($p < 0.05$)	6.4	1.4	11.0	16.5	5.9	10.6	11.4	99.7
CD ($p < 0.01$)	8.4	1.9	14.5	21.8	7.8	14.0	15.1	131.6

* *Values in parentheses are coefficient of variation (%) CR: Crop residue CD: Critical difference*

Regression model of yield through soil moisture and soil fertility variables

The estimates of correlation between pairs of variables of rainfall received in *kharif* and *rabi* seasons, available soil moisture at sowing and on different DAS, available soil N and P, crop growing period, applied fertilizer N and grain yield are determined to assess type of relationship, magnitude and its significance for inclusion of variables in a model. Treatment-wise regression models could be calibrated to assess superiority of a treatment based on coefficient of determination (R^2) and prediction error (Φ). A regression model of yield is postulated as

$$Y = \pm \alpha \pm \beta_1 (SMS) \pm \beta_2 (SM30) \pm \beta_3 (SM60) \pm \beta_4 (SM90) \pm \beta_5 (SMH) \pm \beta_6 (SN) \pm \beta_7 (SN)^2 \pm \beta_8 (SP) \pm \beta_9 (SP)^2 \quad ..... (4)$$

In equation (4), α is intercept and β_1 to β_9 are regression coefficients of different variables considered in the model. The regression coefficient of an independent variable will indicate its contribution to dependent variable 'yield'. A pooled model of yield over years is calibrated as

$$Y = \pm \alpha \pm \beta_1 (SMS) \pm \beta_2 (SM30) \pm \beta_3 (SM60) \pm \beta_4 (SM90) \pm \beta_5 (SMH) \pm \beta_6 (SN) \pm \beta_7 (SN)^2 \pm \beta_8 (SP) \pm \beta_9 (SP)^2 \pm \beta_{10} (FN) \pm \beta_{11} (FN)^2 \pm \beta_{12} (FN)(SN) \pm \beta_{13} (FN)(SMS) \quad ..... (5)$$

In (5), α is intercept and β_1 to β_{13} are regression coefficients of different variables considered in the model and are tested for significance based on t-test. The estimates of regression coefficients, coefficient of determination (R^2) and prediction error (Φ) are examined for assessing sustainability of fertilizer treatments and optimizing fertilizer N at varying levels of soil N and soil moisture for attaining sustainable yield.

The superiority of organic, inorganic and INM treatments could be assessed based on a sustainable yield index as described by Vittal *et al.* (2003). Using mean yield of a treatment 'i' ($\bar{A}_i$) over 20 years; prediction error (Φ) based on the model calibrated for the treatment as postulated in (4); and maximum sorghum yield (Y_{max}) of 1708 kg ha^{-1} attained with an application of 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1} during 1996, the sustainable yield index (η_i) of treatment 'i' can be derived as

$$\eta_i = [(\bar{A}_i - \Phi) / (Y_{max})] * 100 \quad ..... (6)$$

A fertilizer treatment having maximum sustainable yield index could be identified and used for prescribing an optimum fertilizer dose in an efficient combination of organic and inorganic sources for attaining a sustainable yield. Based on the procedure out lined by Maruthi Sankar (1986), regression coefficients of linear fertilizer N (β_{10}), quadratic fertilizer N (β_{11}), interaction of fertilizer N and soil N (β_{12}), and interaction of fertilizer N and soil moisture at sowing (β_{13}) in (5) are used for deriving fertilizer N ($\tilde{N}$) adjustment equation as a function of soil N (SN) and soil moisture at sowing (SMS) as

$$\tilde{N} = [\beta_{10}/(2*\beta_{11})] - [\beta_{12}/(2*\beta_{11})] * SN - [\beta_{13}/(2*\beta_{11})] * SMS \quad .....(7)$$

A ready reckoner of optimum fertilizer N at varying soil N and moisture at sowing could be developed by using (7) and used for attaining sustainable sorghum yield under semi-arid vertisols.

Based on critical difference at $p < 0.05$ and $p < 0.01$ levels of significance, 25 kg N (crop residue) + 25 kg N ha^{-1} (*Leucaena*) was superior to all treatments for all variables except soil moisture on 30 DAS. 25 kg N (FYM) + 25 kg N ha^{-1} was 2nd best for all variables except soil moisture at sowing, 30 and 60 DAS. 25 kg N (crop residue) + 25 kg N ha^{-1} was superior for soil moisture at 30 DAS, 2nd best for soil moisture at sowing and 60 DAS, 3rd best for all other variables except soil P. Out of 224 pairs of comparison, a maximum of 105 (46.9 %) cases indicated a parity of treatments followed by 96 (42.9 %) cases of significance of treatments at $p < 0.01$ level and 23 (10.3 %) cases of significance at $p < 0.05$ level. Maximum number of treatments were superior for soil N, soil P and grain yield at $p < 0.01$ level, while were at par for soil moisture on different days except 60 DAS and are given in table 2.

Table 2. Superiority of treatments for soil nutrients, soil moisture and sorghum yield

Variable	Treatments 'at par'	Treatments significant at $p < 0.01$	Treatments significant at $p (< 0.05)$	Total
Soil N	T8 = T7	T8 > T6, T4, T3, T2, T1	T8 > T5	7 (25.0)
	T7 = T5	T7 > T6, T4, T3, T2, T1		6 (21.4)
	T6 = T5	T6 > T2, T1	T6 > T4, T3	5 (15.9)
		T5 > T4, T3, T2, T1		4 (14.3)
	T4 = T3, T2	T4 > T1		3 (10.7)
	T3 = T2	T3 > T1		2 (7.1)
		T2 > T1		1 (3.6)
Total	6 (21.4)*	19 (67.9)	3 (10.7)	28
Soil P	T8 = T7, T5	T8 > T6, T4, T3, T2, T1		7 (25.0)
	T7 = T5	T7 > T6, T3, T2, T1	T7 > T4	6 (21.4)
	T6 = T3, T2	T6 > T2		3 (10.7)
	T5 = T4	T5 > T6, T3, T2, T1		5 (17.9)
	T4 = T2	T4 > T1	T4 > T6, T3	4 (14.3)
	T3 = T2	T3 > T1		2 (7.1)
		T2 > T1		1 (3.6)
Total	8 (28.6)	17 (60.7)	3 (10.7)	28
SMS	T8 = T6	T8 > T7, T5, T4, T3, T2, T1		7 (25.0)
	T7 = T5, T4, T3, T2, T1			5 (17.9)
		T6 > T7, T5, T3, T2, T1	T6 > T4	6 (21.4)
	T5 = T4, T3, T2, T1			4 (14.3)
	T4 = T3, T2, T1			3 (10.7)
	T3 = T2, T1			2 (7.1)
	T2 = T1			1 (3.6)
Total	16 (57.1)	11 (39.3)	1 (3.6)	28
SM30	T8 = T7, T5, T4, T3, T2		T8 > T1	6 (21.4)
	T7 = T5, T4, T3, T2		T7 > T1	5 (17.9)
		T6 > T8, T7, T5, T4, T3, T2, T1		7 (25.0)
	T5 = T4, T3, T2, T1			4 (14.3)
	T4 = T3, T2		T4 > T1	3 (10.7)
	T3 = T2, T1			2 (7.1)
	T2 = T1			1 (3.6)
Total	18 (64.3)	7 (25.0)	3 (10.7)	28
SM60	T8 = T6, T4	T8 > T1	T8 > T7, T5, T3, T2	7 (25.0)
	T7 = T5, T3, T2		T7 > T1	4 (14.3)
	T6 = T4	T6 > T7, T5, T3, T2, T1		6 (21.4)
	T5 = T3, T2		T5 > T1	3 (10.7)
		T4 > T7, T5, T3, T2, T1		5 (17.9)
	T3 = T2		T3 > T1	2 (7.1)
			T2 > T1	1 (3.6)
Total	9 (32.1)	11 (39.3)	8 (28.6)	28
SM90	T8 = T7, T6, T5, T4, T3, T2	T8 > T1		7 (25.0)
	T7 = T6, T5, T4, T3, T2	T7 > T1		6 (21.4)
	T6 = T5, T4, T3, T2	T6 > T1		5 (17.9)
	T5 = T3, T2		T5 > T1	3 (10.7)
	T4 = T3, T2	T4 > T5, T1		4 (14.3)
	T3 = T2	T3 > T1		2 (7.1)
		T2 > T1		1 (3.6)
Total	20 (71.4)	7 (25.0)	1 (3.6)	28

contd ...

Variable	Treatments 'at par'	Treatments significant at p (< 0.01)	Treatments significant at p (< 0.05)	Total
SMH	T8 = T7, T6, T5, T4, T3, T2	T8 > T1		7 (25.0)
	T7 = T6, T5, T4, T3, T2	T7 > T1		6 (21.4)
	T6 = T5, T4, T3, T2	T6 > T1		5 (17.9)
	T5 = T4, T3, T2	T5 > T1		4 (14.3)
	T4 = T2	T4 > T1	T4 > T3	3 (10.7)
	T3 = T2	T3 > T1		2 (7.1)
		T2 > T1		1 (3.6)
Total	20 (71.4)	7 (25.0)	1 (3.6)	28
GY	T8 = T7, T6, T3	T8 > T5, T4, T2, T1		7 (25.0)
	T7 = T6, T3	T7 > T5, T4, T2, T1		6 (21.4)
	T6 = T3	T6 > T4, T2, T1	T6 > T5	5 (17.9)
	T5 = T2	T5 > T1	T5 > T4	3 (10.7)
	T4 = T2	T4 > T1		2 (7.1)
		T3 > T4, T2, T1	T3 > T5	4 (14.3)
		T2 > T1		1 (3.6)
Total	8 (28.6)	17 (60.7)	3 (10.7)	28
Overall	105 (46.9)	96 (42.9)	23 (10.3)	224

Values in parentheses indicate percentage of total number of cases T1 : Control T2 : 25 kg N ha^{-1} T3 : 50 kg N ha^{-1}
T4 : 25 kg N ha^{-1} (crop residue) T5 : 25 kg N ha^{-1} (FYM) T6 : 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1}
T7 : 25 kg N ha^{-1} (FYM) + 25 kg N ha^{-1} T8 : 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1} (Leucaena)

Relation between sorghum yield, soil moisture and soil fertility variables

Treatment-wise estimates of correlation between yield, soil moisture at sowing, 30, 60, 90 DAS and harvest, soil N and P nutrients where relation is significant for at least one treatment are given in table 3. The grain yield had a positive correlation with soil moisture at sowing, 30 and 60 DAS under 25 kg N ha^{-1}. The soil moisture at 30, 60 and 90 DAS had a positive relation with moisture at sowing for all treatments, while soil moisture at harvest had a positive relation with soil moisture at sowing, 30 and 60 DAS only for control. The soil moisture at 60 and 90 DAS had a positive correlation with moisture at 30 DAS, while moisture at 90 DAS had a positive correlation with moisture at 60 DAS for all treatments. The soil moisture at harvest was positively related with the moisture at 90 DAS for all treatments except 50 kg N ha^{-1}. *Rabi* rainfall had a positive relation with moisture at 60 DAS under 25 kg N ha^{-1} (crop residue) and 25 kg N (crop residue) + 25 kg N ha^{-1} (*Leucaena*), while it had a positive relation with moisture at 90 DAS in control, 25 kg N (FYM) + 25 kg N ha^{-1} and 25 kg N (crop residue) + 25 kg N ha^{-1} (*Leucaena*).

The soil-N was positively related with soil moisture at sowing under 25 kg N ha^{-1} (FYM) and 25 kg N (crop residue) + 25 kg N ha^{-1} (*Leucaena*), while it was negatively related with soil moisture at 60 DAS under 25 kg N (FYM) + 25 kg N ha^{-1}. It had a negative correlation with soil moisture at 90 DAS under 25 kg N ha^{-1} (crop residue), 25 kg N (crop residue) + 25 kg N ha^{-1} and 25 kg N (FYM) + 25 kg N ha^{-1} and harvest under 50 kg N ha^{-1}. The significant correlations are useful for modeling sorghum yield to assess the influence of soil moisture and soil fertility variables and assess their influence over a period (Vittal *et al.* 2003).

Table 3. Significant correlation of sorghum yield with rainfall, soil moisture and fertility

Var1	Var2	T1	T2	T3	T4	T5	T6	T7	T8
Yield	SMS	0.13	0.51*	0.30	-0.01	0.28	0.18	0.24	0.26
Yield	SM30	0.06	0.55**	0.28	-0.26	0.28	-0.15	0.23	0.10
Yield	SM60	-0.05	0.45*	0.21	-0.31	0.16	-0.01	0.17	0.07
Var1	Var2	T1	T2	T3	T4	T5	T6	T7	T8
SMS	SM30	0.79**	0.77**	0.77**	0.75**	0.76**	0.61**	0.74**	0.90**
SMS	SM60	0.83**	0.85**	0.81**	0.77**	0.78**	0.90**	0.82**	0.87**
SMS	SM90	0.85**	0.54**	0.58**	0.61**	0.56**	0.60**	0.54**	0.56**
SMS	SMH	0.81**	0.35	0.41	0.23	0.26	0.23	0.26	0.12
SMS	Soil N	0.25	0.04	-0.31	-0.37	0.49*	-0.03	-0.18	0.46*
SM30	SM60	0.95**	0.93**	0.94**	0.94**	0.93**	0.61**	0.95**	0.94**
SM30	SM90	0.91**	0.68**	0.66*	0.69**	0.71**	0.49*	0.70**	0.66**
SM30	SMH	0.89**	0.34	0.32	0.30	0.35	0.27	0.41	0.30
SM60	SM90	0.98**	0.73**	0.76**	0.70**	0.75**	0.71**	0.77**	0.72**
SM60	SMH	0.95**	0.37	0.32	0.39	0.38	0.30	0.41	0.37
SM60	Soil N	0.16	-0.03	-0.03	-0.18	0.39	-0.14	-0.43*	0.30
SM60	RRF	0.41	0.35	0.39	0.45*	0.43	0.42	0.41	0.45*
SM90	SMH	0.98**	0.46*	0.32	0.48*	0.50*	0.44*	0.49*	0.53**
SM90	Soil N	0.25	0.05	-0.07	-0.47*	0.25	-0.45*	-0.62**	0.22
SM90	RRF	0.44*	0.42	0.34	0.39	0.41	0.43	0.46*	0.45*
SMH	Soil N	0.24	-0.35	-0.57**	-0.29	-0.20	-0.34	-0.40	-0.28
SMH	Soil P	-0.07	-0.38	-0.47*	-0.35	-0.21	-0.26	-0.39	-0.33

** & ** indicate significance at $p < 0.05$ & $p < 0.01$ level* RRF : *Rabi rainfall*
SMS & SMH : Soil moisture at sowing & harvest SM30, SM60 & SM90: *Soil moisture at 30, 60 & 90 DAS*
T1 : Control T2 : 25 kg N ha^{-1} T3 : 50 kg N ha^{-1} *T4 : 25 kg N ha^{-1} (crop residue) T5 : 25 kg N ha^{-1} (FYM)*
T6 : 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1} *T7 : 25 kg N ha^{-1} (FYM) + 25 kg N ha^{-1}*
T8 : 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1} (Leucaena)

Regression model of sorghum yield through soil moisture and soil fertility variables

Treatment-wise regression models of sorghum yield were calibrated as a function of soil moisture at sowing, 30, 60, 90 DAS and harvest, soil N and P over seasons. The regression coefficients (β), coefficient of determination (R^2) and prediction error (Φ) are given in table 4. The models of all treatments except 25 kg N ha^{-1} (FYM) and 25 kg N (FYM) + 25 kg N ha^{-1} gave a significant R^2 based on the analysis. A maximum R^2 (0.85**) was observed for the model of 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1} (*Leucaena*), followed by R^2(0.82*) for 25 kg N (crop residue) + 25 kg N ha^{-1}, while the model of 25 kg N (FYM) + 25 kg N ha^{-1} had lowest R^2 (0.46). Maximum prediction error of 353 kg ha^{-1} was observed with the model of 25 kg N (FYM) + 25 kg N ha^{-1}, while minimum of 170 kg ha^{-1} was observed for control.

Based on the models, soil moisture available at sowing and harvest and soil P under control; 30 DAS under 25 kg N ha^{-1} and 25 kg N ha^{-1} (FYM); 60 DAS under 50 kg N ha^{-1} and 25 kg N ha^{-1} (crop residue); sowing and 60 DAS under 25 kg N (crop residue) + 25 kg N ha^{-1}; harvest under 25 kg N (FYM) + 25 kg N ha^{-1}; sowing, 60 DAS, harvest and soil P under 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1} (*Leucaena*) had a significant influence on yield. The coefficients indicated a positive effect of soil moisture at sowing, 30 DAS and harvest, and negative effect on 60 and 90 DAS. The soil N and P had a positive linear effect and negative quadratic effect on yield of all treatments. However, linear coefficients of soil P in control and soil N and P in 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1} (*Leucaena*) were significant for predicting yield.

Table 4. Regression models of sorghum yield through soil moisture and fertility variables

Treatment	Regression model	R^2	Φ	η
Control	Y = 3994 + 2.94 * (SMS) + 2.23 (SM30) – 2.17 (SM60) – 12.01 (SM90) + 9.57 * (SMH) – 45.54 (SN) + 0.18 (SN^2) – 86.92 * (SP) + 2.29 (SP^2)	0.75*	170	0.28
25 kg N ha^{-1}	Y = 4754 + 2.17 (SMS) + 7.96 * (SM30) – 5.60 (SM60) – 2.56 (SM90) + 1.81 (SMH) – 64.18 (SN) + 0.21 (SN^2) – 1.42 (SP) – 0.09 (SP^2)	0.79*	245	0.39
50 kg N ha^{-1}	Y = – 4535 + 0.21 (SMS) + 8.76 (SM30) – 9.44 * (SM60) – 2.51 (SM90) + 3.93 (SMH) + 54.90 (SN) – 0.17 (SN^2) – 7.64 (SP) + 0.29 (SP^2)	0.72*	301	0.44
25 kg N ha^{-1} (crop residue)	Y = 17096 + 1.91 (SMS) + 1.49 (SM30) – 6.01 * (SM60) – 0.91 (SM90) + 3.19 (SMH) – 236.79 (SN) + 0.84 (SN^2) + 14.47 (SP) – 0.38 (SP^2)	0.70*	213	0.36
25 kg N ha^{-1} (FYM)	Y = 9666 + 0.56 (SMS) + 6.51 * (SM30) – 4.92 (SM60) – 1.21 (SM90) + 1.17 (SMH) – 116.31 (SN) + 0.34 (SN^2) + 7.70 (SP) – 0.23 (SP^2)	0.62	219	0.42
25 kg N (crop residue) + 25 kg N ha^{-1}	Y = – 14784 + 12.82 ** (SMS) + 0.62 (SM30) – 14.07 ** (SM60) – 2.18 (SM90) + 3.91 (SMH) + 233.80 (SN) – 0.79 (SN^2) – 179.88 (SP) + 3.53 (SP^2)	0.82**	217	0.49
25 kg N (FYM) + 25 kg N ha^{-1}	Y = – 4922 + 1.74 (SMS) + 3.02 (SM30) – 3.73 (SM60) – 0.36 (SM90) + 9.61 * (SMH) + 48.77 (SN) – 0.15 (SN^2) + 18.34 (SP) – 0.29 (SP^2)	0.46	353	0.41
25 kg N (crop residue) + 25 kg N ha^{-1} *(Leucaena)*	Y = 4350 + 10.12 ** (SMS) + 1.93 (SM30) – 11.06 ** (SM60) – 1.06 (SM90) + 9.15 ** (SMH) – 76.12 (SN) + 0.21 (SN^2) + 144.85 * (SP) – 3.28 * (SP^2)	0.85**	193	0.54

** & ** indicate significance at $p < 0.05$ & $p < 0.01$ η : Sustainable yield index Φ : Prediction error (kg ha^{-1})*

Sustainability of fertilizer treatments over different years

Based on (6), sustainable yield index of fertilizer treatments were derived and are given in table 4. Application of 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1} (*Leucaena*) was superior with maximum sustainability of 0.54 and provided a maximum mean sorghum yield of 1109 kg ha^{-1} with variation of 36.4%. This was followed by 25 kg N (crop residue) + 25 kg N ha^{-1} with sustainability of 0.49 with mean yield of 1047 kg ha^{-1} and variation of 37.2%. Application of 50 kg N ha^{-1}, 25 kg N ha^{-1} (FYM) and 25 kg N (FYM) + 25 kg N ha^{-1} were next best treatments with sustainability of 0.44, 0.42 and 0.41; mean yield of 1049, 939 and 1109 kg ha^{-1} and variation of 36.8, 35.9 and 36.4% respectively.

Pooled regression model for sorghum yield prediction and fertilizer optimization

A pooled regression model of yield attained by all treatments over years was calibrated as a function of soil moisture at sowing, 30, 60, 90 DAS and harvest, linear and quadratic variables of soil N, soil P and fertilizer N,

Table 5. Optimum fertilizer N at varying soil N and soil moisture for sorghum

Soil moisture at sowing (mm)	Optimum fertilizer N (kg ha⁻¹) at a soil N (kg ha⁻¹) of 100	120	140	160	180	200	220
100	39	26	14	1			
120	44	31	19	6			
140	49	36	24	11			
160	54	41	29	16	4		
180	59	46	34	21	9		
200	64	51	39	26	14	1	
220	69	56	44	31	19	6	
240	74	61	49	36	24	11	
260	79	66	54	41	29	16	3
280	84	71	59	46	34	21	8
300	89	76	64	51	39	26	13

interactions of fertilizer N and soil N and fertilizer N and soil moisture at sowing as postulated in (5). The model gave a significant coefficient of determination (0.38**) with prediction error of 282 kg ha^{-1}. The regression coefficients of soil moisture at 30, 60 DAS and harvest, soil N and soil P and interaction of fertilizer N and soil moisture at sowing were significant for yield predictability based on pooled model. The soil moisture at sowing, 30 DAS and harvest had a positive effect, while 60 and 90 DAS had a negative effect on yield. The linear terms of soil N, soil P and fertilizer N had a positive effect, while the effects were declining and negative at higher levels of variables as indicated by negative coefficients of quadratic terms of variables. Fertilizer N had a positive interaction with soil moisture at sowing, while it had a negative interaction with soil N based on the model.

$$Y = 384 + 0.73\ (SMS) + 1.91^{**}\ (SM30) - 3.95^{**}\ (SM60) - 0.24\ (SM90) + 3.35^{**}\ (SMH) + 0.48^{*}\ (SN) - 0.02\ (SN^2) + 27.84^{*}\ (SP) - 0.67\ (SP^2) + 12.33^{*}\ (FN) - 0.08\ (FN^2) - 0.10\ (FNSN) + 0.04^{*}\ (FN\ SMS) \quad ..... (8)$$

Optimization of fertilizer N at varying levels of soil N and soil moisture at sowing

Using pooled regression model given in (8), fertilizer N (FN) equation was derived as a function of soil moisture at sowing (SMS) and soil N (SN) and is given as

$$FN = 77 - 0.63\ SN + 0.25\ SMS \quad ..... (9)$$

Based on (9), optimal fertilizer N was derived at varying levels of soil N ranging from 107 to 205 kg ha^{-1} and soil moisture ranging from 197 to 295 mm and are given in table 5. The optimum N increased with increase in soil moisture at sowing, while it decreased with increase in soil N. This would minimize risk and reduce cost of cultivation in situations of low available soil moisture at sowing. At a soil N of 100 kg ha^{-1}, fertilizer N of 39, 64 and 89 kg ha^{-1} was optimum at available soil moisture of 100, 200 and 300 mm at sowing. At a soil N of 180 kg ha^{-1}, there was no N requirement at soil moisture of 100 mm, while application of 14 kg ha^{-1} at 200 mm and 39 kg ha^{-1} at 300 mm was optimum for attaining sustainable yield. Since application of 50% N (crop residue) + 50% N (*Leaucaena*) has maximum sustainability of 0.54 with mean yield of 1109 kg ha^{-1}, R^2 of (0.85**) and minimum prediction error of 193 kg ha^{-1}, the optimum N is desired to be applied through crop residue and *Leaucaena* sources. Thus the study has indicated the superiority of this nutrient management practice for attaining sustainable sorghum yield in a Vertisol at Solapur.

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