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□ *The productivity of sorghum, an important staple food crops in semi-arid tropics of the world, is low due to scarcity of moisture and poor soil fertility. Response of crops to phosphorus (P) application in these soils is erratic and tricky, which depends upon the available P status in soils, distribution of rainfall, adsorption and desorption capacity of soil, and overall P sink created by crop depending upon its vigor. Delineation of optimum P level for higher productivity and to avoid wastage of precious P fertilizer thus becomes inevitable. Hence, an experiment was conducted at Hayathnagar Research Farm of Central Research Institute for Dryland Agriculture, Hyderabad to i) study the external (relative grain yields, agronomic efficiency, harvest index) and internal response (fertilizer P use efficiency, P uptake harvest index) indicators of sorghum to various levels of P application, ii) development of prediction functions to arrive at optimum P dose and iii) P use - removal balance for grain sorghum for these rainfed semi-arid tropical Alfisols. Results of the study indicated that P application to sorghum in these Alfisol soils beyond 23 kg ha^{-1} might not be much economical and desirable. It was observed that the maximum grain yield of 87% could be achieved at a leaf P concentration of 0.39% at boot leaf or flag leaf stage and 0.30% at 50% flowering stage. The prediction functions were developed to understand the quantitative relationship between external and internal response indicators. The zero P balance (neither depletion nor excessive build up) obtained at 20 kg ha^{-1} level (per se near 23 kg P ha^{-1}) indicates that this level is sufficient for sorghum crop to perform with an agronomic efficiency of 19.42 kg grain kg^{-1} P. The findings of this study would help in efficient use of P fertilizer for achieving desirable yield levels and will in turn reduce the expenditure on P fertilizers that are mostly imported by India and majority of other developing countries.*

Keywords: P use efficiency, agronomic P efficiency, optimum P level, P uptake, P harvest index, balance, prediction functions, India

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INTRODUCTION

Phosphorus (P), which was discovered first in 1669 by Hannig Barandit of Hamburg, Germany, is indispensable of all life forms. During 1839, C. Sprengel established its essentiality for plants. It plays an important role in plant growth and development by virtue of being a major component of biochemical compounds essentially required in photosynthesis, energy transformations, protein synthesis, genetic inheritance, etc., in plants (Kanwar and Damodar Reddy, 2003). Phosphorus is a major building block of deoxyribonucleic acid (DNA) molecules, which is responsible for the storage of energy in the form of adenosine diphosphate (ADP) and adenosine triphosphate (ATP). The energy stored in these phosphate compounds allows for the transportation of nutrients across the cell wall and the synthesis of nucleic acid and proteins. The addition of phosphorus fertilizers ensure that crops will reach their full potential by using the additional phosphorus to encourage root growth and stalk strength while promoting resistance to root rot diseases. Further, phosphorus has been associated with early maturity of crops, particularly in grain crops. The quality of certain fruits, forages, and vegetable and grain crops is said to be improved and disease resistance increased when these crops have satisfactory phosphorus nutrition. In the process of uptake, phosphorus is readily mobilized in plants and when a deficiency occurs, the element contained in the older tissues is transferred to the active meristematic regions (Tisdale et al., 1985).

Phosphorus has been termed the bottleneck of world hunger (Rorty, 1946) and it is indeed, frequently the limiting plant nutrient in small scale farming systems (Ayaga et al., 2006). The role of phosphorus in soil plant continuum has been a central topic of research for many years. Further, in both natural and agricultural ecosystems, the quantity of P available for plants uptake is generally low due to the low solubility of P compounds present in soils (Sharpley et al, 2003). The soils vary widely in their capacities to supply P to growing plants because only a small fraction of total P in soil is in plant available form. Thus, unless the soil contains adequate level of plant available P, or is supplied with readily available P sources (fertilizers, manures, etc.), crop growth suffers resulting in serious yield losses. The low availability of native soil P and poor recovery or use efficiency of applied fertilizer P (approximately 18–20%) are mainly due to sorption and precipitation reactions of P in soils, commonly referred as phosphate fixation phenomenon. The P fixation reactions are triggered by the activity of calcium-based minerals in Vertisols and iron (Fe) and aluminum (Al) based active compounds in Alfisol soils having acidic pH range.

Alfisols are the third most important soil order in the world, covering 13.1% area. In the semi-arid tropics, Alfisols cover a much larger area of potentially arable and grazable lands than Vertisols and about 62% of the world's Alfisols are located in West Africa and India (ICRISAT, 1987). These soils are not only low in organic matter and plant available nitrogen, but are also extensively deficient in P, one of the most important factors limiting crop productivity. In the Indian subcontinent, the use of fertilizer in general, during the 70s was very limited and there has been a connotation that rainfed lands are hungry as well as thirsty. But during 80s the connotation changed to the fact that these lands are stated to be even hungrier than thirsty (Venkateswarlu, 1986). The small farmers (<2 ha) who can only afford few kg of nitrogen fertilizer, do not go for P application and at the same time, medium (2–4 ha) and large (>4 ha) farmers apply substantially higher doses of P especially to coarse cereals such as sorghum and corn (maize). This ultimately leads to low crop yields and poor available-P status in small and marginal farms, and stagnated yield levels and high available P build up and consequent wastage of precious P fertilizer in medium and large farms in rainfed semiarid tropical Alfisols. Developing countries, including India, who import phosphatic fertilizers, lose huge amounts of money on account of import costs and the subsidies provided to the farmers on P fertilizers.

Sorghum is one of the important staple food crops in semi-arid tropics of the world. It is the fifth most important cereal crop grown for human consumption in the world being surpassed only by rice, wheat, barley and corn (Akram et al., 2007). Its productivity is low due to scarcity of moisture and poor soil fertility. This crop responds tremendously to nitrogen application in Alfisol soils, which are miserably low in organic carbon and available nitrogen (N) [alkaline potassium permanganate ($KMnO_4$) oxidizable nitrogen] (Sharma et al., 2005). Response of crops to P application in these soils is erratic and tricky, which depends upon the available P status in soils, distribution of rainfall, adsorption and desorption capacity of soil, and overall P sink created by crop depending upon its vigor. However, according to Vance et al. (2003), the P availability in soil is regulated by several factors such as chemical (soil mineralogy, pH organic matter, adsorption capacity, interactions with other chemicals), physical (texture, impedances, temperature, aeration, soil moisture), and biological (presence of roots, residues, bacteria, and fungi). In addition, plant factors such as root architecture, rhizosphere alterations, and mycorrhizal symbiosis may increase the accessibility to soil P sources.(Vance et al., 2003). Ciampitti et al. (2009) reported that nutrient, (specially P) response, balance and budgeting using long term rotations are very effective and can aid the growers in managing nutrients more efficiently. Delineation of optimum P level for higher productivity and to avoid wastage of precious P fertilizer thus becomes inevitable. Considerable work on response and phosphorus requirement of sorghum and its residual effects has been done in semi-arid tropical Vertisols (Sahrawat, 1999, 2000; Sahrawat et al., 1999). In case of semi-arid tropical rainfed Alfisols, few studies have been carried out on the internal and external response of applied P (Rao and Das, 1982; Ravinder Singh et al., 1996; Das et al., 1996). Ragwaa et al. (2001) have emphasized that in areas where soils are deficient in P, like those in semi-arid tropics of Africa, access and affordability of P fertilizer limits the quantities that farmers apply to their fields. This in turn leads to poor seedling emergence, which results in poor stand establishment and low yields in many semi-arid regions. While emphasizing the role of P in other rainfed crops, Rebafka et al. (1993) reported that P deficiency is one of the major constraints that limit crop yield in pearl millet and research is needed to optimize the scarce P fertilizer that is available. Uptake of P by plants is very sensitive to its concentration in the soil solution (Barber, 1982; Marschner, 1985; Holford, 1997). Though soil solution concentration is usually low but is buffered by various P fractions in the solid phase through complex desorption-adsorption, dissolution-precipitation and mineralization and immobilization process. Reijneveld et al (2010) reported that reckless use of organic manures and fertilizers tremendously build up the soil P and its excessive enrichment increases the risk of losses to the aquatic environment through erosion, overland flow, and subsurface leaching (Pautler and Sims, 2000; Sims et al., 2000; Schoumans and Chardon, 2003), hence its optimum application and judicious management is must. Some of the studies have been restricted to pot culture conditions only. Keeping this background insight in mind, we were inspired to study i) external response of sorghum to P application (crop yields, agronomic efficiency, harvest index), ii) internal response (influence on third leaf P concentration at different phenological stages, P concentration in different plant parts and its total uptake, P use efficiency, P harvest index), iii) P balance and iv) computation of prediction functions to arrive at optimum P dose for grain sorghum in these semi-arid tropical rainfed Alfisol soils.

MATERIALS AND METHODS

Experimental Site

The field experiment was conducted at Hayathnagar Research Farm of Central Research Institute for Dryland Agriculture, Hyderabad situated at 17°18′ N latitude, 78°36′ E longitude and an elevation of 515 m above mean sea level. The farm represents a semi-arid tropical region with hot summers and mild winters and a mean annual temperature of 25.7°C. Mean annual rainfall is 746 mm and accounts for approximately 42% of annual potential evapotranspiration (1754 mm). Nearly 70% of the total precipitation is received during the southwest monsoon season (June to September). Soils of the experimental field were fine, loamy mixed hyperthermic, udic haplustalfs and belong to Hayathnagar soil series (Typic Haplustalf) with a sandy surface layer and increasing clay content in the sub soil. The particle size distribution of these soils consisted of 68% sand, 13.8% silt and 18.2% clay composing a sandy loam texture. Some of the initial characteristics of the experimental site were: soil pH (6.4), electrical conductivity (0.48 dSm^{-1}), organic carbon (4.70 g kg^{-1}), calcium carbonate ($CaCO_3$; 4.3%), diethylenetriaminepentaacetic acid (DTPA)- Fe (9.8 μg g^{-1}) and exchangeable Al (36.8 g g^{-1}).

The experiment was laid out in a randomized block design with five treatments in four replications using sorghum ('CSH-6') as the test crop. The treatments included different phosphorus levels viz., 0 (P_0), 10 (P_{10}), 20 (P_{20}), 40 (P_{40}) and 80 (P_{80}) kg P ha^{-1}. The Experimental field was ploughed every year carefully with bullock drawn plough and leveled using a wooden plank. The treatments were imposed as per the layout. Sorghum crop ('CSH-6') was sown in a recommended spacing of 45 cm × 30cm with 2 seedlings per hill in *Kharif* season and the field was left fallow in *Rabi* and summer. The fertilizers were applied in bands at 5 cm from seed rows. The recommended dose of N at 40 kg N ha^{-1} was applied through urea in two equal splits, one as basal dose and other as top dressing at 25-30 days after sowing (DAS). The phosphorus was applied through single super phosphate (SSP) at different levels as per the treatments. Two hand weedings were done on 20th and 40th DAS in all the treatments. Carbaryl 50% WP was sprayed to control shoot fly incidence at seedling stage. During each of the years of experimentation, leaf samples (3rd leaf from the top of the plant) were collected at two stages viz., flag leaf or boot leaf stage at 40 DAS, and during 50% flowering stage at 70 DAS. The leaf samples were dried in an oven at 65°C till constant weight was obtained. Harvesting of the crop was done at physiological maturity when drying up of the leaves was observed. The border rows were harvested first and collected as bulk. The plants in the net plot were harvested and dried separately. The sorghum ear heads were separated from the stover. The dried leaves and plant samples and grain and husk samples at harvest were ground into fine powder. The 0.5g of the fine ground material was digested in a triacid mixture [10 nitric acid (HNO_3): 1 sulfuric acid (H_2SO_4): 4 perchloric acid ($HClO_4$)] and made up to a suitable volume. The P content in triacid digest was determined by developing yellow color employing Barton's reagent as suggested by Piper (1942) using. The intensity of the yellow color was measured by using spectrophotometer (model Spectronic 20; Bausch & Lomb, Rochester, NY, USA) at 470 mm wavelength. The data on grain yield and dry matter produce was recorded as per the treatments and was expressed in kg ha^{-1}. The uptake of phosphorus by crop at the time of physiological maturity was computed by multiplying the P concentration with the respective yields. Soil available P initially and at the end of the experiment was extracted using 0.5 M sodium bicarbonate ($NaHCO_3$) (pH 8.5) reagent as per the procedure suggested by Olsen et al. (1954), and the P in aliquot was determined by using ascorbic acid method (Olsen and Sommers, 1982).

The data obtained from the field experiment for all five years was statistically analyzed using randomized block design. The data was subjected to regression analysis to determine the relationships between P levels and leaf P content, P levels and root P content, grain yield and total P uptake. In order to arrive at the optimum P level, a quadratic function was fitted between the average yield data and the applied phosphorus levels. Further, monetary output and monetary input ratio (P_{output}/ P_{input}) per kg of applied P was also estimated. In order to obtain the monetary output (P_{output}), the unit response of P i.e. kg grain produced per kg P were calculated by dividing the predicted sorghum grain yield with the respective applied P levels. The values so obtained were multiplied with the unit cost of sorghum grain (Rs. 8.40/- per kg of sorghum grain which is approximately equivalent to US$ 168 per ton). The price of one kg of P (source: single super phosphate at Rs. 48.66/- per kg P approximately equivalent to US$ 973 per ton P) was considered as the monetary input (P_{input}). The Cate and Nelson (1971) method of graphic presentation of relationship between leaf P and relative sorghum grain yield was used to arrive at a critical limit for leaf P. Besides these, the other response parameters viz., relative grain yields, agronomic efficiency, harvest index and fertilizer P use efficiency were also computed using the following relationships.

Relative grain yields were computed using the following relationship:

$$\text{Relative grain yield } (\%) = Y/Y_{max} \times 100$$

Where Y is the yield (kg ha^{-1}) obtained at any P level and Y_{max} is the maximum yield obtained throughout the experiment.

Agronomic efficiency (AE) was computed by using the relationship as follows:

$$\text{AE (kg grain kg}^{-1}\text{P applied)} = Y_P - Y_0/\text{P applied}$$

Where Y_P is the yield (kg ha^{-1}) obtained in P treated plots; Y_0 is the yield obtained in the control plot; P is the level of phosphorus applied (kg ha^{-1}) through fertilizer.

Harvest index (HI) was computed by using the relationship:

$$\text{HI} = \text{Grain yield/Total plant yield}$$

Fertilizer P use efficiency (FPUE) was also computed using the following relationship:

$$\text{PUE}(\%) = \text{TPU}_P - \text{TPU}_0/\text{P applied} \times 100$$

Where TPU_P is the Total P uptake in P treated plots while TPU_0 is the Total P uptake in control plot. Here total P uptake refers to the summation of P uptake by grain, stover and husk.

RESULTS

External P Response

The average sorghum grain yields varied from 963 to 1352 kg ha^{-1} across the P levels studied (Table 1). Out of the five years of experimentation, the grain yields were significantly influenced by the P levels only for three years. Based on the average of five years yield data, the highest sorghum grain yields were obtained with application of P at 20 kg ha^{-1}, which was at par with the yield obtained with 40 and 80 kg P ha^{-1} levels. From a predictive quadratic function fitted between the average yield data and the applied phosphorus levels (Figure 1), a maximum yield of 1403.8 kg ha^{-1} was obtained with an applied P level of 55 kg ha^{-1} after which a decreasing trend in yield was observed. With the assumption that producing maximum yield by adding 55 kg P ha^{-1} may not be a desirable optimum level, one more additional parameter viz monetary output and monetary input ratio (P_{output}/P_{input}) was used. Since the cost of crop production involves substantial other costs than on P fertilizer alone, it was felt to be economical to enhance the fertilizer P level up to the point as long as the P_{output}/P_{input} ratio is ≥ 2.0.

Besides the above two external response indicators, harvest index (HI), which is also a one of the important indicators of external response to

TABLE 1 Effect of varying phosphorus levels on sorghum grain and biomass yields

Phosphorus level (P kg ha^{-1})	1990	1991	1992	1993	1994	Mean of 5 years
			Grain yields (kg ha^{-1})			
0	789	344	1408	1284	992	963
10	1014	435	1678	1342	1195	1133
20	1250	626	1954	1580	1349	1352
40	1167	705	1896	1417	1283	1294
80	1403	613	1854	1481	1310	1332
LSD ($P = 0.05$)	256.7	72.2	NS	NS	123.2	129.7
			Stover yields (kg ha^{-1})			
0	3855	2332	1868	5183	1824	3012
10	4283	2615	2293	5790	2388	3474
20	4582	3425	2691	5858	2840	3879
40	4349	3117	2673	5160	2535	3567
80	4685	3390	2926	5243	2566	3762
LSD ($P = 0.05$)	NS	455.2	639.5	NS	205.1	
			Husk yields (kg ha^{-1})			
0	770	393	709	890	685	634
10	855	500	590	979	779	740
20	1120	720	704	982	880	881
40	973	840	561	1062	837	870
80	1150	700	649	1018	842	872
LSD ($P = 0.05$)	NS	78.2	NS	NS	61.8	

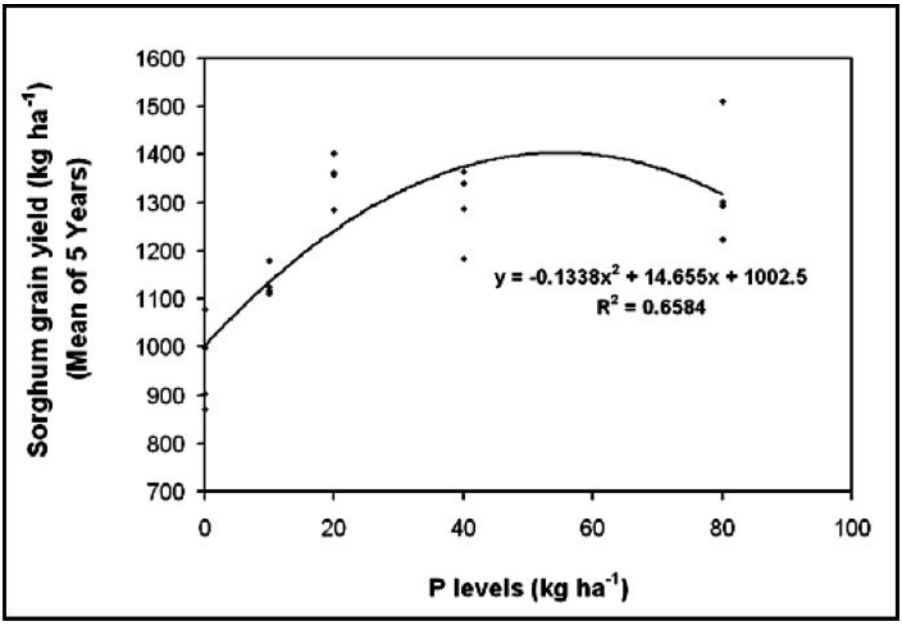

FIGURE 1 Quadratic function predicting the sorghum grain yields as influenced by varying P levels in semi-arid tropical rainfed Alfisol.

nutrient application, was considered. The HI values revealed a very narrow variability ranging from 0.21 to 0.23 across the P levels (Figure 2). Hence, harvest indices could not be used to determine the optimum P levels. To explore further, another important parameter of external response viz. agronomic efficiency (AE) was also studied which varied from 4.61 to 19.42 kg grain kg^{-1} P across the various P levels applied. From the data presented in Figure 2, AE was found highest with application of 20 kg P ha^{-1} (19.42 kg grain kg^{-1} P) followed by 10 kg P ha^{-1} (16.95 kg grain kg^{-1} P).

Internal Response

The internal response of the applied P fertilizer was studied in terms of the P content in third leaves at different phenological stages i.e. at flag leaf or boot leaf stage (40 DAS) and at 50% flowering stage (70 DAS) (Table 2). From the perusal of these data, on an average, during boot leaf stage, the highest P concentration was observed with 80 kg ha^{-1} P level followed by 40 kg P ha^{-1}. Similarly, during 50% flowering stage, highest leaf P content was observed with 80 and 40 kg ha^{-1} of P levels applied. The regression coefficients worked out between the P levels and the P content in the third leaves were found to have significant quadratic relationship during both boot leaf stage (R^2 = 0.818) as well as 50% flowering stage (R^2 = 0.743) (Figure 3). From the graphical relationship worked out between relative yield and

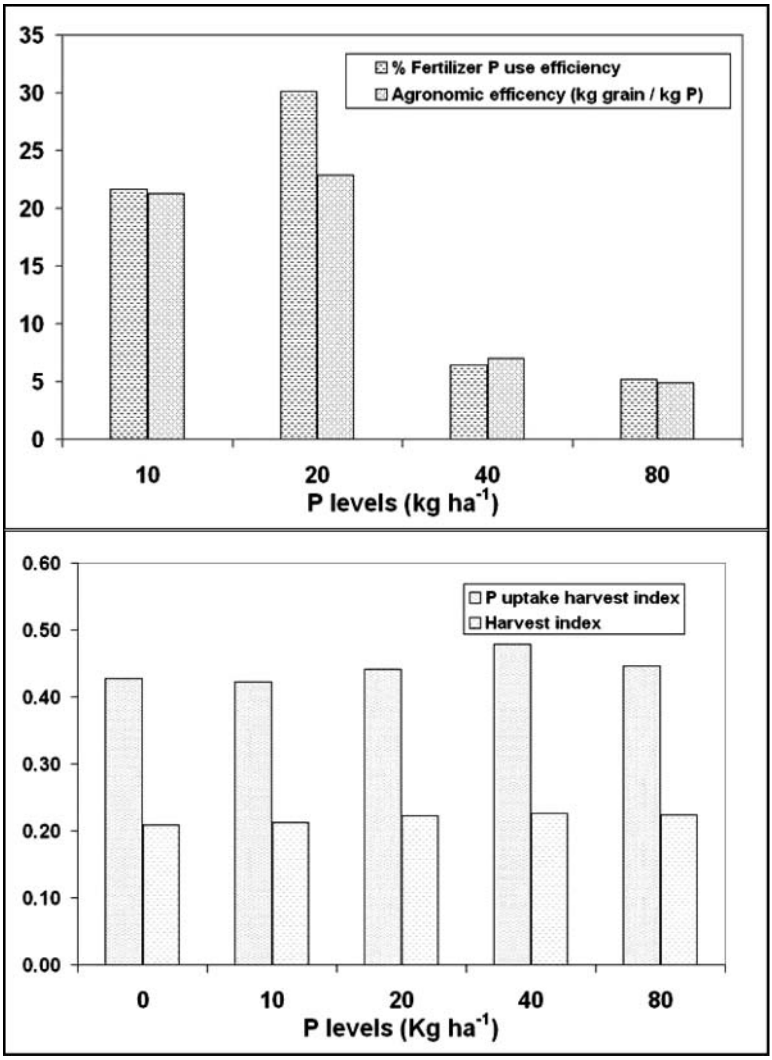

FIGURE 2 Influence of phosphorus levels on fertilizer P use efficiency, agronomic efficiency, P uptake harvest indices and harvest index (yield) in sorghum crop.

percent P concentration in third leaf at different phenological stages, it was observed that the maximum grain yield of 87% could be achieved at a leaf P concentration of 0.39% at boot leaf or flag leaf stage and 0.30% at 50% flowering stage (Figure 4). Similarly, the response between the fertilizer P applied and the P content in the roots was also studied which showed a significant quadratic relationship at 40 DAS ($r^2 = 0.752$) and at 70 DAS ($r^2 = 0.975$) (Figure 5).

TABLE 2 Influence of P levels on P concentration in third leaves at different phenological stages of sorghum

Phosphorus level (P kg ha^{-1})	1990	1991	1992	1993	1994	Mean of 5 years
			P content in 3rd leaf at 40 DAS (g kg^{-1})			
0	0.22	0.33	0.39	0.22	0.31	0.29
10	0.25	0.36	0.41	0.29	0.33	0.32
20	0.25	0.35	0.43	0.35	0.36	0.35
40	0.29	0.35	0.48	0.30	0.36	0.36
80	0.28	0.37	0.49	0.41	0.37	0.38
LSD ($P = 0.05$)	NS	NS	0.07	0.10	0.03	
			P content in 3rd leaf at 70 DAS (g kg^{-1})			
0	0.18	0.24	0.23	0.27	0.23	0.23
10	0.23	0.24	0.26	0.31	0.25	0.26
20	0.24	0.26	0.26	0.30	0.25	0.26
40	0.24	0.26	0.28	0.35	0.27	0.28
80	0.24	0.25	0.28	0.35	0.28	0.28
LSD ($P = 0.05$)	0.04	NS	0.02	NS	0.02	

Phosphorus Content in Grain, Stover and Husk

The phosphorus contents in grain, stover and husk were estimated after harvest of the crop (Table 3). It was observed that out of the five years of experimentation, during two years, the P levels applied did not significantly influence the P content in grain but during the other three years, the response was quite significant. On an average, significantly highest grain P

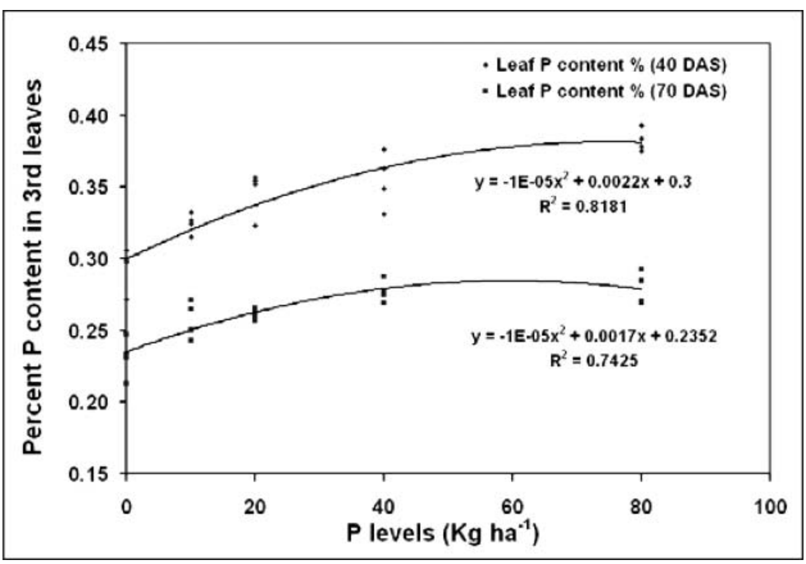

FIGURE 3 Quadratic relationship between percent P content in third leaves and fertilizer P levels in sorghum at two phenological stages.

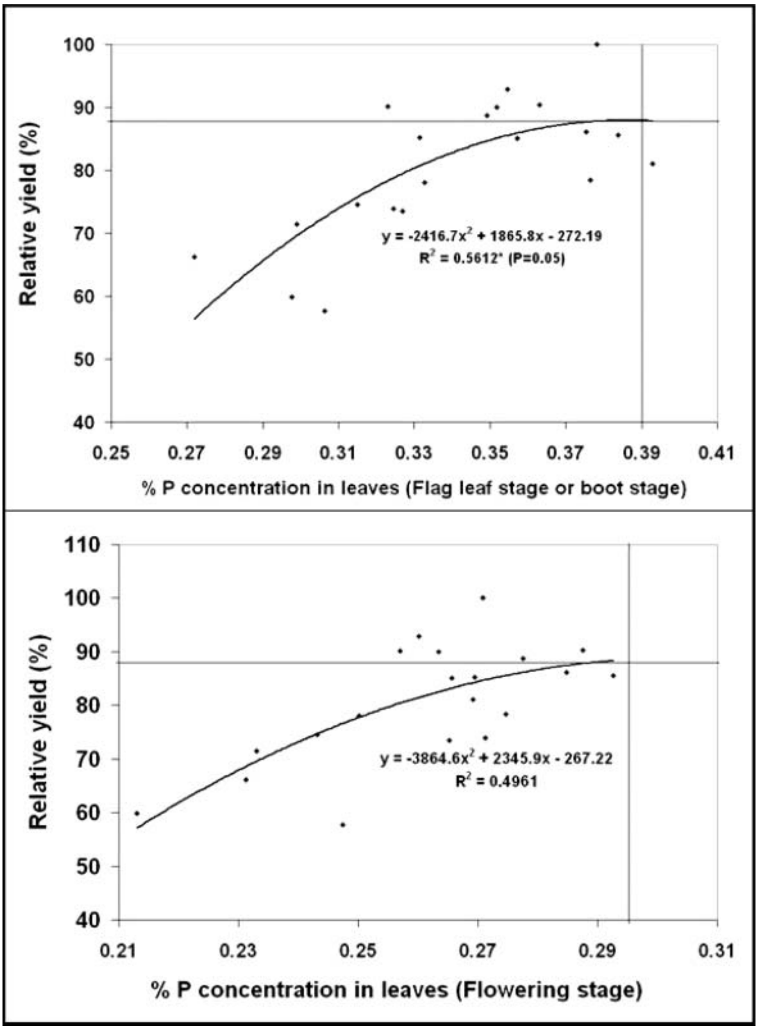

FIGURE 4 Prediction function for P content in third leaves at flag leaf stage or boot stage and flowering stage for achieving maximum possible grain yield.

content was observed at 20 kg P ha^{-1}, which was at par with 40 and 80 kg P ha^{-1}. Even in stover, on an average, application of 20 kg P ha^{-1} recorded the highest P content, while in husk, the significantly highest P (1.66 kg ha^{-1}) content was recorded at 10 kg P ha^{-1} followed by 20 kg P ha^{-1}.

Influence of P Levels on Plant Uptake

Based on the five-year data presented in Table 4, it was observed that the P uptake by grain, stover and husk were significant in almost all the years and

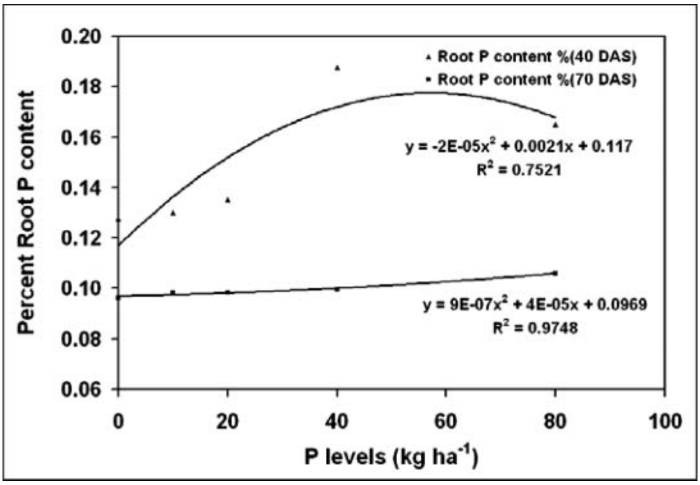

FIGURE 5 Prediction functions between percent P content in roots of sorghum plant and applied P levels.

on an average, the uptake was observed to be maximum at 20 kg P ha^{-1} and showed a slight decrease when P was applied at 40 kg P ha^{-1} and thereafter showed an increase with 80 kg P ha^{-1}. The relationships between sorghum grain yields (Y), P uptake by grain and P uptake by total plant were found to

TABLE 3 Effect of phosphorus levels on P content (g kg^{-1}) in grain, stover and husk over years

Phosphorus level (P kg ha^{-1})	1990	1991	1992	1993	1994	Mean of 5 years
			P content in grain (g kg^{-1})			
0	2.65	3.33	3.03	1.93	0.79	2.35
10	2.28	3.42	2.85	2.53	3.12	2.84
20	3.33	3.43	3.40	3.01	3.55	3.34
40	3.00	3.61	3.35	2.43	3.81	3.24
80	2.73	3.51	3.08	3.21	3.75	3.26
LSD ($P = 0.05$)	0.53	NS	0.26	NS	0.53	
			P content in stover (g kg^{-1})			
0	0.95	0.84	0.86	0.42	0.21	0.66
10	1.05	1.05	0.94	0.71	0.93	0.93
20	1.18	1.20	1.12	0.99	1.77	1.25
40	0.83	1.00	0.92	0.77	1.33	0.97
80	0.95	0.98	1.09	0.89	1.60	1.10
LSD ($P = 0.05$)	0.18	NS	NS	0.37	0.13	
			P content in husk (g kg^{-1})			
0	1.65	2.00	1.85	0.68	1.53	1.54
10	1.48	2.19	1.85	1.02	1.78	1.66
20	1.38	2.01	1.70	1.07	1.84	1.60
40	1.43	1.79	1.60	0.80	1.69	1.46
80	1.48	1.93	1.69	1.12	1.71	1.59
LSD ($P = 0.05$)	NS	NS	NS	0.32	0.13	

TABLE 4 Effect of phosphorus levels on P uptake by grain, stover, and husk over years

Phosphorus level ($P\ kg\ ha^{-1}$)	1990	1991	1992	1993	1994	Mean of 5 years
			Grain uptake ($kg\ ha^{-1}$)			
0	2.07	1.15	4.26	2.43	0.79	2.14
10	2.33	1.49	4.78	3.36	3.72	3.13
20	4.16	2.15	6.64	4.71	4.78	4.49
40	3.55	2.55	6.40	3.38	4.89	4.15
80	3.85	2.15	5.69	4.68	4.91	4.25
LSD ($P = 0.05$)	1.08	0.31	1.47	0.95	0.72	
			Stover uptake ($kg\ ha^{-1}$)			
0	3.63	1.94	1.64	2.17	0.39	1.95
10	4.43	2.73	2.15	4.13	2.21	3.13
20	5.18	4.12	3.04	4.43	5.02	4.36
40	3.66	3.15	2.47	4.05	3.37	3.33
80	4.41	3.33	3.21	4.63	4.12	3.94
LSD ($P = 0.05$)	0.83	0.79	1.09	NS	0.43	
			Husk uptake ($kg\ ha^{-1}$)			
0	1.27	0.78	0.86	0.59	1.01	0.90
10	1.26	1.10	1.10	1.01	1.39	1.17
20	1.52	1.44	1.21	1.01	1.61	1.36
40	1.35	1.51	0.90	0.86	1.42	1.20
80	1.64	1.34	1.08	1.14	1.44	1.33
LSD ($P = 0.05$)	NS	0.32	NS	0.33	0.19	
			Total uptake ($kg\ ha^{-1}$)			
0	6.97	3.87	6.75	5.19	2.18	4.99
10	8.01	5.31	8.02	8.50	7.32	7.43
20	10.9	7.69	10.9	10.2	11.4	10.2
40	8.55	7.15	9.77	8.28	9.68	8.69
80	9.90	6.82	9.98	10.5	10.5	9.52
CD at 0.05	2.26	0.82	2.28	2.72	0.88	

have a linear relationship and the regression equation are as follows:

$$Y(kg\,ha^{-1)} = 240.51 * P\,uptake\,by\,grain\,(kg\,ha^{-1}) + 340.92 (R^2 = 0.749)\,(n = 80)$$

$$Y(kg\,ha^{-1}) = 79.237 * P\,uptake\,by\,total\,plant\,(kg\,ha^{-1}) + 567.54 (R^2 = 0.864)\,(n = 20)$$

From these two equations, one can predict the P uptake/ removal at a given level of yield per unit land or vice versa which would be helpful in deciding the level of P application.

The prediction function between total plant P uptake and the applied P levels was quadratically significant and is predicted by the following equation:

$$Total\,P\,uptake\,by\,plant\,(kg\,ha^{-1}) = -0.0016\,x^2 + 0.1703\,x + 5.7302 (R^2 = 0.627),$$

where x is the P applied in kg ha^{-1}.

From this equation, one can predict the P uptake at a given level of P application.

Fertilizer P Use Efficiency and P Uptake Harvest Index

Some of the important parameters of internal response viz., percent fertilizer P use efficiency (FPUE) and P uptake harvest indices (PUHI) were also computed and the data are presented in Figure 2. Fertilizer P use efficiency at P level of 10 kg ha^{-1} was 24.4% while at 20 kg P ha^{-1}, it slightly increased to 26.0%. However, at higher levels of P i.e. at 40 and 80 kg P ha^{-1}, the FPUE was 9.20 and 5.70%, respectively. On the other hand, the P uptake harvest index for the various P levels, showed a very narrow variation ranging from 0.42 to 0.48 across the treatments. These observations indicate that percent P use efficiency can be a good internal response indicator for deciding the optimum P level for achieving best output from a given level of fertilizer.

Phosphorus Balance Sheet/Budget

A simple phosphorus balance sheet using the data on initially available soil P, P added through fertilizers during five years, P removed by the growing crops during five years and the final available P present in soil was prepared and the results are presented in Table 5. It was observed that, in the control plot, which received no phosphorus, the initial soil P available was 7.23 kg ha^{-1} and the final available P after a period of five years was estimated to be 5.56 kg ha^{-1}. But the total P removed by the crops over a period of five years was 25.0 kg ha^{-1}, leaving a negative balance of 25.5 kg ha^{-1} of P over a total accountable P of 30.5 kg ha^{-1}. Similarly, in the plots, which received 10 kg ha^{-1} of P for a period of five years, along with the initial P status of 7.23 kg ha^{-1}, the total P added amounted to 57.2 kg ha^{-1}. But the total P removed by the crops during these five years was 37.2 kg ha^{-1} while the final P was 47.1 kg ha^{-1} at the end of five years giving a total accountable P of 84.3 kg ha^{-1}. This accounts to a net negative balance of 27.1 kg ha^{-1} when compared to the total P input.

DISCUSSION

External Response

The response to P application to sorghum in this study followed a quadratic function with significant R^2 value (0.65). From the results, it was observed that P application to sorghum in these Alfisol soils beyond 23 kg P ha^{-1} might not be much economical and desirable. Our findings are in

TABLE 5 Phosphorus balance sheet (kg ha^{-1})

								P balance	
Sno	P levels	Initial soil available P	P added through fertilizer during (1990-94)	Total P input to soil (1990-94)	P removed by crops (1990-94)	Final soil available P (1994)	Total P outputs (accountable) P	Probable P released (gain)	Probable P adsorbed (loss)
	(1)	(2)	(3)	2+3 = (4)	(5)	(6)	5+6 = (7)	7–4 = (8)	7–4 = (9)
1	0	7.23	0	7.23	25.0	5.56	30.5	23.3	
2	10	7.23	50	57.2	37.2	47.1	84.3	27.1	
3	20	7.23	100	107.2	51.0	56.2	107.2		(−)0.00
4	40	7.23	200	207.2	43.4	64.8	108.2		(−)99.0
5	80	7.23	400	407.2	47.6	80.1	127.7		(−)279.5

corroboration with those reported earlier by Sahrawat (2000) for sorghum in Vertisol soils in semi arid tropical region. He observed that ninety percent of relative grain yield was achieved at about 20 kg ha^{-1} of fresh P. It was interesting to note that in the present study, agronomic efficiency (AE) declined at higher P levels of 40 (8.26 kg grain kg^{-1} P) and 80 kg P (4.61 kg grain kg^{-1} P). This observation again confirmed that rainfed sorghum crop in these Alfisol soils receiving annual average rainfall of 750 mm could capitalize the benefit of P application only up to 20 kg P ha^{-1}. Earlier Ryan et al. (2008) demonstrated the highly variable nature of crop response to fertilizer P under semi arid field conditions over several years, with soil moisture from seasonal rainfall being the dominant influence on overall yields. Further, they concluded that while crop responses may not occur in any given year, especially if available P is near or above critical threshold levels, dryland cropping without P fertilizer is unsustainable in the long run. Kanwar (1986) reported that response to P application to sorghum was in the order of: Alfisol > Cambisol > Vertisol. Based on P sorption isotherms of 200 soils, Warren (1992) concluded that fertilizer P requirements tend to follow the order: Andisols > Oxisols > Ultisols >Alfisols > Entisols. This is probably the reason that the response in the present study in Alfisol soils to P application could be noticed only up to 20 kg P ha^{-1}, which is a considerably lower P dose. The third indicator of external response studied was HI. As the variation in HI values was narrow, hence, this indicator could not be employed to interpret the external response of sorghum to P application in the present study.

Internal Response

In case of internal response, it was observed that the maximum grain yield of 87% could be achieved at a leaf P concentration of 0.39% at boot leaf or flag leaf stage and 0.30% at 50% flowering stage. In another study conducted in Vertisols earlier (Sahrawat et al., 1999), it was reported that sorghum grain yield and leaf P concentration increased in response to P application up to 40 kg P ha^{-1} and the leaf P concentration was linearly related to grain yield. The critical leaf P concentration at 90% of the maximum grain yield was found to be about 0.25% P. In the present study, 0.30% P concentration in the third leaf of sorghum could be considered as critical concentration for attaining 87% of maximum grain yield, hence, our results are in close proximity to the trends of earlier findings. When the internal response was studied in terms of P concentration in grain, husk and stover, on an average, a significantly highest grain P content was observed at 20 kg P ha^{-1} (3.34 g kg^{-1}), which was at par with 40 and 80 kg P ha^{-1}. Even in stover, on an average, application of 20 kg P ha^{-1} recorded the highest P content, while in husk, significantly highest P (1.66 kg ha^{-1}) content was recorded at 10 kg P ha^{-1} followed by 20 kg P. These observations are indicative of the fact that increase in P concentration in grain could be realized only up to certain levels of P (say 20 kg P in this case). Application of P at higher levels did not enrich the grains in P. The total P uptake by sorghum crop (grain + husk + stover) in the present study varied from 4.99 to 10.2 kg P ha^{-1}, the range of uptake in the individual components was 2.14 to 4.49 in grain, 0.90 to 1.36 in husk and 1.95 to 4.36 kg P ha^{-1} in stover. The amount of total P uptake in the present study was comparatively lower than the values earlier reported under Vertisols soils by Latha and Durai Singh (2003) for sorghum crop. The relatively lower level of P removal in this study under rainfed conditions could be attributed to the lower levels of sorghum grain yield obtained under Alfisol soils. When another important parameter of internal response viz., percent fertilizer P use efficiency (FPUE) was examined, it was clearly understood that fertilizer P use efficiency increased with increase in P level but tapered off at 20 kg P ha^{-1}, (26.0%). Evidently, at higher levels of P, i.e. at 40, and 80 kg P ha^{-1}, the FPUE declined significantly to 9.20 and 5.70%, respectively. Similar observations were earlier recorded by Tang et al. (2008) in the case of maize in China and reported the value of FPUE up to 29%. However, because of the narrow range (0.42 to 0.48) of P uptake harvest indices (PUHI) values, this indicator of internal response could not be used for arriving at the optimum level of P for attaining maximum possible internal and external response of sorghum to P application.

Phosphorus Balance Sheet / Budget

After addition of varying levels of P every year to sorghum crop for five years, our interest was to study the P inputs and outputs (amount) relationship, i.e., balance (gain and loss) .The higher amount of P outputs (P removed by crops + the final soil available P at harvest of last crop) compared to P inputs (initial P status + P added through fertilizers during five years) at both the 0 and 10 kg ha^{-1} levels observed after the five-year period might have been due to the release of P from different organic and inorganic P pools from the soil. In the subsequent P levels, i.e., at 20, 40 and 80 kg ha^{-1} levels, the P outputs were lower compared to their respective P inputs showing a negative balance. At P level applied at 20 kg ha^{-1}, the difference between the P outputs and total P inputs was zero, while it increased with further increase in P application rates. At a P level of 40 kg P ha^{-1}, the negative P balance was (−) 99.0 kg ha^{-1} while at 80 kg ha^{-1}, the balance was (−) 279.5 kg ha^{-1} indicating that higher rate of P application though helped in considerable P build up in soil but also substantially contributed towards adsorbed/non-labile P. The zero output-input balance of P (0.00 kg ha^{-1}) obtained at 20 kg ha^{-1} level indicates no release of P from non-labile P to available P and no adsorption of P. This level was just sufficient for sorghum crop to perform with an agronomic efficiency of 19.42 kg grain kg^{-1} P without creating any difference between P output and P input, while improving the soil P value from the existing 7.3 to 56.2 mg kg^{-1}. Finally, it was understood that this 20 kg P ha^{-1} level looks to be quite desirable from the view point of response pattern, economics, as well as affordability by the resource poor small and marginal farmers.

CONCLUSIONS

The response of grain sorghum to P application in rainfed Alfisol is erratic and is largely determined by available P status in soils, distribution of rainfall, adsorption and desorption capacity of soil, and overall P sink created by crop depending upon its vigor and yield levels. Some farmers being resource poor cannot invest on costly fertilizer inputs. Some other group of farmers who can invest on fertilizer, blindly dump fertilizer P inadvertently through fertilizer such as diammonium phosphate rich in P. Consequently, some of the rainfed sorghum and corn growing areas have build up a lot of available soil P. This situation not only creates imbalance in plant nutrition but also leads to wastage of fertilizer, which is being imported by spending thousands of crore rupees. Thus, it was felt essential to conduct a holistic study covering external and internal P response indicators. From this study, it has been clearly understood that P application to sorghum in rainfed Alfisol soils beyond 23 kg ha^{-1} might not be much economical and desirable. Further, it was established that the maximum grain yield of 87% could be achieved at a leaf P concentration of 0.39% at boot leaf or flag leaf stage and with 0.30% at 50% flowering stage. The prediction functions developed with high degree of statistical reliability between i) grain yields and P levels, ii) grain yields and P uptake by grain and total plant and iii) total plant P uptake and the applied P levels using five year data would be quite useful to predict yield at a given level of fertilizer and to understand the quantitative relationship between external and internal response. The minimum P balance of 0.05 kg ha^{-1} (neither depletion nor excessive build up) obtained at 20 kg ha^{-1} level (per se near 23 kg P ha^{-1}) indicates that this level is sufficient for sorghum crop to perform with an agronomic efficiency of 19.42 kg grain kg^{-1} P. Thus, the findings of this study would help in efficient use of P fertilizer for achieving desirable yield levels and will in turn reduce the expenditure on P fertilizers. The analogy followed in this study can also be used for similar rainfed Alfisol soils of tropics and subtropics with required modification depending upon the situation.

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