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Screening of groundnut genotypes for phosphorus efficiency under field conditions

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Abstract

Groundnut is an important legume of tropical world where phosphorus (P) deficiency is one of the limiting factors affecting productivity and use of P-efficient genotype is the solution. Thus P-efficiency among seventy groundnut genotypes was studied under P-deficit (-P) and adequate-P (+P) condition by recording yield and its attributes and calculating various P-efficiency indices. Significant differences among groundnut genotypes, P levels and their interactions were observed for all the traits and the range of pod yield was 3.4-10.5 g plant^{-1} under -P and 4.1-12.8 g plant^{-1} at +P, 100 seed mass was 23-68 g. The range of phosphorus stress factor (PSF) was -40 to 39 in pod (PSF_p) and -142 to 45 in haulm (PSF_h), P efficiency (PE) was 0.61-1.40 in pod (PE_p) and 0.55-2.42 in haulm (PE_h) and agronomic P use efficiency was 14 to 29. Genotypes were divided into efficient, inefficient and moderate based on the P-efficiency index (PEI), but into efficient and inefficient, responder and non-responder, using PEI and pod yielding potential. The efficient responders genotypes GG 5, PBS 11037, PBS 11046, PBS 13007, PBS 20505 and SP 250A with low PSF, high PEI and, PE close to unity were identified for P-deficit soils.

Key words: Groundnut, Phosphorus efficiency, Screening methodologies, P-efficient genotypes

Introduction

Groundnut (*Arachis hypogaea* L.) is an important legume crop of tropical and subtropical region of the world grown on about 25 million ha area with a production of 41 million tonne pod (FAOSTAT 2014). It requires warm growing season with well distributed rainfall in the range of 500-1000 mm and cultivated mainly in semi-arid regions of India, China, Nigeria, USA, Myanmar, Senegal, Sudan, Indonesia, Argentina and Vietnam. Though an energy rich crop, groundnut is predominantly grown on light texture soil by resource poor farmers across wide range of environment where frequent drought and soil infertility limit its productivity (Singh 2011). Though the world average groundnut yield is around 1650 kg ha^{-1}, it is less than 1000 kg ha^{-1} in more than 30% of the groundnut growing countries of the world (FAOSTAT 2014) where P deficiency is common occurrence (Ajay et al. 2015; Singh 2004 2014).

Application of P fertilizer and increasing its efficiency economise its cultivation. However, the response of groundnut crop to P is not consistent as the P uptake depends greatly on the soil types, genotypes used, mode of application, form of P in the soil, and presence of arbuscular mycorrhizae and phosphorus solubilising microorganisms in soil (Singh 1999; Singh and Chaudhari 1996; Singh et al. 2004). Thus P, a key nutrient for groundnut, needs efficient management and as in the long run it is even necessary to avoid the depletion of soil-P by genotypes with the higher ability to mine soil-P reserves. As the plant-available P is generally a small fraction of the total P of the soil, the second option is to make use of nutrient efficient genotypes, which allows the resource poor farmers to harvest reasonable yield without any extra inputs (Singh and Basu 2005a).

Development of P-efficient genotypes with an ability to grow and yield in P-deficient soil is an important goal in plant breeding (Singh 1999; Singh et al. 2004; Wissuwa et al. 2002; Yan et al. 2004). Knowledge about extent of genetic variation among the existing genotypes is a primary step and there are

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only a few reports in groundnut (Singh 2004; Singh and Basu 2005a). As there is no well-defined selection criterion (Ajay et al. 2015; Singh 2004), work was initiated in many laboratories worldwide to understand the mechanism and to develop screening methodologies for the search of nutrient efficient genotypes in various crops (Blair 1993; Hammond et al. 2009; Pan et al. 2008; Randal 1995; Sepehr et al. 2009; Yaseen and Malhi 2009).

Several definitions have been proposed for nutrient use efficiency and hence criterions used by these definitions vary (Ajay et al. 2015; Singh and Basu 2005a; Singh et al. 2004; Hammond et al. 2009; Pan et al. 2008; Sepehr et al. 2009; Yaseen and Malhi 2009). Gourley et al. (1994) suggested comparisons of crop genotypes at non-limiting nutrient supply levels as well as under low-nutrient conditions. Screening and selection of P-efficient groundnut genotypes having superior yield at both low and high levels of P availabilities in field are of practical significance (Singh 2004; Singh and Basu 2005a). However, recently, multiple-parameter screening of P efficiency has been proposed for identifying P-efficient genotype (Pan et al. 2008). As enough genotypic differences exist in groundnut, it was felt essential to identify suitable traits and P-efficient genotypes using multiple-parameters for P-deficit conditions.

Material and methods

In-situ field screening, was conducted at the research farm of the Directorate of Groundnut Research, Junagadh (lat 21°31'N, long 70°36'E altitude 83 m above msl), India during rainy season, in a medium black calcareous (17 % $CaCO_3$) clayey, Vertic Ustochrept soil having low available phosphorus (6 ppm P), 7.5 pH, 0.70% organic C, 600 ppm N, 11 ppm available S, and 3.5, 5.0, and 0.62 ppm DTPA extractable Fe, Mn and Zn, respectively. The field was ploughed, levelled and 10 cm deep furrows were opened at 45 cm spacing. Seventy groundnut genotypes (comprising of 26 varieties, 15 germplasm accessions and 29 advanced breeding lines), each in one row plots of 5 m length sown at 10 cm spacing, were grown under two treatments, P-unfertilized (P-deficit) and P-fertilized (50 kg P_2O_5 ha^{-1} as single super phosphate) condition in three replicates. A common dose of ammonium sulphate at 40 kg N ha^{-1} and muriate of potash at 40 kg K_2O ha^{-1} were mixed in the soil before sowing and 500 kg ha^{-1} gypsum mixed in the soil at flowering. The crop was grown under recommended package of practices with proper plant protection during the cropping season, harvested at maturity, dried in sun for a week and pod and haulm yields, shelling out turn and 100-seed mass were recorded. Five plants from each row were uprooted randomly at maturity and plant height and numbers of pods $plant^{-1}$ were recorded.

Statistical analysis

Differences amongst genotypes in response to P application were analyzed by two-way of ANOVA using DSAASTAT (Onofri 2007). Various P-efficiency indices such as phosphorous stress factor (PSF), P efficiency (PE), P-efficiency index (PEI) and Agronomic P use efficiency (APE) in groundnut genotypes were calculated as per modified formula given in Table 1. Correlations were worked out to study the association of various P-efficiency indices with yield related traits. Correlation, PCA and cluster analysis were performed using statistical software PAST (Hammer et al. 2001). Phosphorus efficiency in groundnut genotypes was determined using phosphorus efficiency index (PEI) (Pan et al. 2008) calculated through the principal component analysis of values of various parameters at –P and +P. The principal components with eigen values more than one were retained. The relative weight of each principal component was weighed by the corresponding contribution rate accounting for variations of all traits. Consequently, PEI of different genotypes was calculated according to the retained principal components and their relative weight. Finally, groundnut genotypes were divided into 3 categories of P efficiency using PEI and intangible cluster analysis (Fig. 1). However into 4 categories using P efficiency in combination with yield potentials (pod yield at –P) (Fig. 2).

Results

Yield and yield attributes

The pod and haulm yields, shelling per cent, 100 seed mass, seed length and width among groundnut genotypes varied significantly with contrast genotypic differences (Tables 2 and 3). The effect of P treatments and their interaction with genotype were also significant for these parameters as well plant height and number of pods $plant^{-1}$. Pod yield showed maximum variation among genotypes ranging from 3.4 to 10.5 g $plant^{-1}$ under P-unfertilised condition (–P) and 4.1 to 12.8 g $plant^{-1}$ with P-fertilised condition (+P). The 100 seed mass ranged from 23.3 to 60.6 g at –P and 24 to 68 g a++ P.

Table 1. Phosphorous efficiency parameters and their modifications for groundnut

Parameters	Plant parts	Abbreviation	Calculation	Reference
Phosphorous stress factor, %	Grain	PSF_g	$100*(GY_{adeq} - GY_{def})/ GY_{adeq}$	Yaseen and Malhi 2009
	Pod	PSF_p	$100*(PY_{adeq} - PY_{def})/ PY_{adeq}$	Modified for this study
	Haulm	PSF_h	$100*(HY_{adeq} - HY_{def})/HY_{adeq}$	
Agronomic P use efficiency	Grain	APE	$(Y_{high} - Y_{low})/ ÄP_{app}$	Hammond et al. 2009
	Pod	APE	$(PY_{high} - PY_{low})/ ÄP_{app}$	Modified for this study
P efficiency	Haulm	PE_h	HY_{low} / HY_{high}	Sepehr et al. 2009
	Pod	PE_p	PY_{low}/ PY_{high}	Modified for this study
	Haulm	PE_h	HY_{low} /HY_{high}	
P-efficiency Index		PEI	$F\sum_{i=1}^{n} PC_i^* RW_1$	Pan et al. 2008

GY_{adeq} = Grain yield on high P/ fertilised soil (adequate P); GY_{def} = Grain yield on low P/ un-fertilised soil (deficient P); (modified as PY_{adeq} = Pod yield on high P/ fertilised soil; PY_{def} = Pod yield on low P/un-fertilised soil); HY_{adeq} = haulm yield on high P/ fertilised soil; HY_{def} = haulm yield on low P/ un-fertilised soil. PY_{high} = pod yield on high P/ fertilised soil; PY_{low} = Pod yield on low P/ un-fertilised soil; HY_{high} = haulm yield on high P/ fertilised soil; HY_{low} = haulm yield on low P/ un-fertilised soil; $ÄP_{app}$ = difference in amount of P applied as fertilizer between high and low P treatments. The composite parameter (F value) for evaluating P efficiency of different genotypes was obtained according to the retained PCs of different genotypes and their relative weights (RWs)

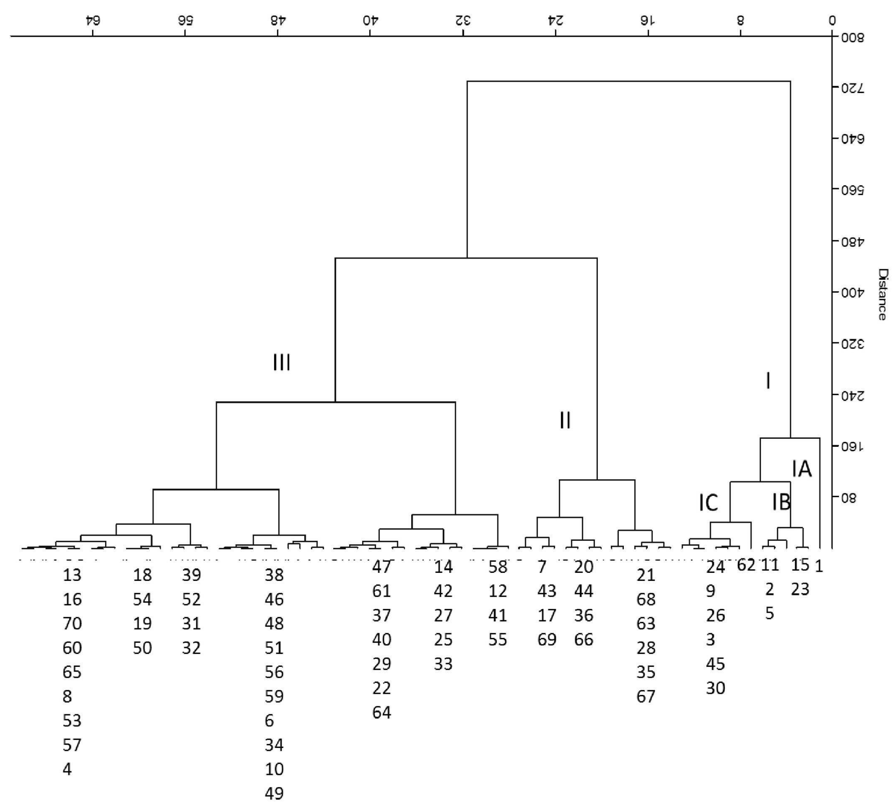

Fig. 1. Ward's cluster dendogram of 70 groundnut genotypes for P-efficiency using PEI of each genotype, obtained from principal component analysis. Clusters I, II and III represents P- efficient, P- inefficient and moderate genotypes, respectively (see Table 2 for genotype against serial number here)

P-efficiency indices

The P-efficiency indices i.e. phosphorus stress factor in pod (PSF_p), phosphorus stress factor in haulm (PSF_h), agronomic P use efficiency (APE), phosphorus efficiency in pod (PE_p) and haulm (PE_h), varied significantly among genotypes (Table 2 and 3). The PSF ranged from –40 to 39 in pod (PSF_p) and -142 to 45 in haulm (PSF_h). When the P efficiency indices values for efficient and responder (ER) and inefficient and non-responder (INR) were averaged the PSF_p value of ER was 4, however, it was 19 for the INR. Similarly the average PSF_h value was 14 in ER and 63 in INR indicating that efficient genotype showed very less value (Table 4). The PE_p and PE_h ranged from 0.61 to 1.40 and 0.55 to 2.42, respectively. The genotypes with PE value close to unity were grouped as efficient and the ER genotypes

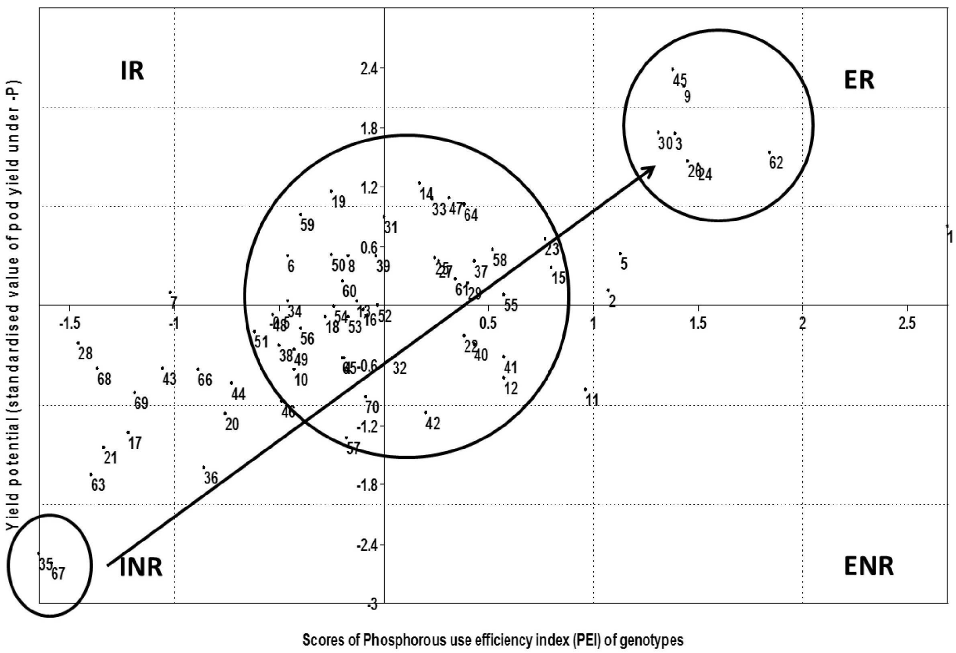

Fig. 2. Grouping of 70 groundnut genotypes according to P efficiency and standardised value of pod yield under –P conditions. P-efficiency is expressed as PEI which was calculated from principal component analysis. Standardised value of pod yield under –P was obtained using the function: Xs = (X-mean)/SD. A, B, C and D represents (i) high yield potential with high P-efficiency, (ii) high yield potential with low P efficiency, (iii) low yield potential with low P efficiency and (iv) low yield potential with high P-efficiency respectively

showed 0.96 as average PEp value as against 0.81 in INR genotype (Table 4). APE in genotypes ranged from –14.1 to 29.0.

Phosphorous efficiency index (PEI) was assessed using principal component analysis (Table 1). Eight parameters at -P along with eight parameters at +P were used for analysis. Principal components with eigen value more than 1 were considered as significant. Four principal components (PC) were found significant and together they explained 76% variation (data not show). The PCA scores of each genotype from four retained PC along with their relative weights (RW) were used for calculating PEI.

When the PEI values were used to develop cluster diagram by Ward's method it grouped 70 genotypes into three clusters (Fig. 1). Cluster 1 comprised of 13 genotypes PBS 11037, 11046, 13007, 20505, SP 250 A, B 95, CSMG 84-1, GG 5, ICGV 86590, NRCG 1308, 3498, 6155, 7599 which showed high yield either under –P, +P or both with > 0.77 PEI and hence were grouped as P-efficient. Cluster II had 14 genotypes with very low PEI < –0.62 and were categorised as P-inefficient. The Cluster III comprised of 43 genotypes with PEI values –0.62 to 0.76 and hence were moderately P-efficient genotypes.

Phosphorus responsiveness

There was huge variation in the responsiveness of the groundnut genotypes. Based on PEI and yield potential (standardised value) these genotypes were divided into four categories (Fig. 2), (i) high yield potential and high P efficiency (ER, efficient responders); (ii) high yield potential and low P efficiency (IR, In-efficient responders); (iii) low yield potential and low P-efficiency (INR, In-efficient non-responders) and (iv) low yield potential and high P-efficiency (ENR efficient non-responders).When 70 genotypes were compared for their responsiveness on the basis of pod yield potential and PEI (Fig. 2 and Table 2), 23 genotypes were categorized as ER, 11 genotypes as IR, 29 genotypes as INR and 7 genotypes were categorized as ENR. Finally the genotypes GG 5, NRCG 1308, PBS 11037, PBS 11046, PBS 13007, PBS 20505, SP 250 A were found most efficient responders (ER) as they produced high pod yield under both conditions. These seven highly efficient responders genotypes and two in-efficient non-responders (PBS 16003, SP 26 A) when compared with their mean values, the parameters varied differently in response to P supply between efficient and in-efficient genotypes (Table 4). Increasing P supply enhanced pod and haulm yields, number of pods, seed length and width in ER genotypes, whereas in case of INR genotypes though there was increase in pod yield, shelling per cent, plant height and seed width with addition of P, it did not increase the haulm yield, 100 SM, number of pods and seed length. The ER had high pod yield, 100 seed mass, increased plant height, seed length and seed width in comparison to INR. The ER also had low PSF_p and APE; PE_p and PE_h close to unity and high PEI compared to INR.

Table 2. Pod (PY) and haulm (HY) yields (g/plant) 100 SM (100 seed mass), shelling % (SHP) and P- efficiency parameters in 70 groundnut genotypes grown without (-P) and with P (+P) in field

S.No.	Genotype	PY		HY		100 SM		SHP		PSF_p	PSF_h	APE	PE_p	PE_h	PEI
		-P	+P	-P	+P	-P	+P	-P	+P						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1	B 95	8.2	9.7	8.7	11.2	60.6	67.8	68.6	70.0	14	22	11.0	0.9	0.8	2.7
2	CSMG 84-1	7.3	7.8	12.5	12.9	42.5	44.4	66.5	67.2	6	1	3.6	0.9	1.0	1.1
3	GG 5	9.5	9.9	7.1	9.6	45.8	43.0	79.4	79.7	3	26	2.4	1.0	0.7	1.4
4	I 2	6.3	7.0	6.9	7.0	38.5	37.2	77.8	78.7	9	1	5.0	0.9	1.0	-0.2
5	ICGV 86590	7.8	7.9	7.9	7.9	46.6	42.7	69.0	70.7	0	0	0.2	1.0	1.0	1.1
6	MOR 139	7.8	8.5	7.7	11.0	23.3	24.2	76.6	76.6	9	30	5.5	0.9	0.7	-0.5
7	MOR 161	7.3	7.7	3.7	3.5	39.4	43.8	73.6	74.7	5	-6	3.0	1.0	1.1	-1.0
8	MOR 204	7.8	8.9	5.5	5.5	41.0	40.1	76.0	75.4	12	-1	8.1	0.9	1.0	-0.2
9	NRCG 1308	10.2	9.6	8.3	10.2	47.1	47.5	78.1	78.0	-7	19	-5.0	1.1	0.8	1.4
10	NRCG 2588	6.2	8.3	7.8	5.8	35.6	37.8	75.1	78.4	26	-34	16.7	0.7	1.3	-0.4
11	NRCG 3498	5.9	9.7	6.0	10.3	45.2	46.6	77.2	77.5	39	41	29.0	0.6	0.6	1.0
12	NRCG 4659	6.1	8.1	8.3	7.9	45.5	46.9	69.7	70.0	26	-5	16.0	0.7	1.1	0.6
13	NRCG 5513	7.1	7.6	8.5	8.8	32.6	32.0	75.6	75.5	6	3	3.7	0.9	1.0	-0.1
14	NRCG 6131	8.8	7.8	6.9	6.5	37.2	39.7	77.4	77.4	-14	-8	-8.1	1.1	1.1	0.2
15	NRCG 6155	7.6	6.6	7.2	8.6	51.2	49.2	73.8	72.3	-17	15	-8.1	1.2	0.9	0.8
16	NRCG 6450	7.0	7.2	6.0	6.5	41.1	41.1	76.1	76.5	1	7	1.5	1.0	0.9	-0.1
17	NRCG 6820	5.3	6.6	4.6	5.1	31.3	31.9	77.0	78.4	20	11	10.0	0.8	0.9	-1.2
18	NRCG 6919	6.9	6.8	7.5	6.3	33.9	35.7	72.8	74.5	-1	-20	-0.4	1.0	1.2	-0.3
19	NRCG 7085-1	8.7	8.3	7.4	5.1	30.5	32.9	70.5	73.2	-5	-48	-2.9	1.1	1.5	-0.3
20	NRCG 7085-3	5.5	7.7	8.3	6.5	29.8	31.2	73.1	72.9	28	-28	16.4	0.7	1.3	-0.8
21	NRCG 7206	5.1	6.7	5.1	5.6	27.7	30.6	78.0	78.4	25	8	12.6	0.8	0.9	-1.3
22	NRCG 7472	6.6	8.4	8.4	7.5	38.5	39.6	75.0	77.9	21	-12	13.6	0.8	1.1	0.4
23	NRCG 7599	8.0	7.1	8.2	8.2	46.9	50.3	73.2	72.7	-14	-6	-7.3	1.1	1.1	0.8
24	PBS 11037	9.1	12.8	5.7	10.9	53.7	46.6	74.5	74.1	29	45	28.6	0.7	0.6	1.5
25	PBS 11038	7.8	8.8	7.1	7.7	38.2	41.1	74.6	74.9	12	7	8.1	0.9	0.9	0.2
26	PBS 11046	9.2	8.6	8.2	7.7	56.1	56.4	75.3	76.2	-9	-7	-4.0	1.1	1.1	1.5
27	PBS 12042	7.7	7.2	6.4	6.4	40.9	44.8	73.9	75.1	-7	-1	-3.8	1.1	1.0	0.3
28	PBS 12074	6.6	4.9	4.8	6.4	32.3	32.8	74.8	74.6	-32	25	-12.3	1.3	0.8	-1.5
29	PBS 13	7.4	9.2	6.5	7.7	32.8	39.1	74.4	76.1	20	15	13.8	0.8	0.9	0.4
30	PBS 13007	9.6	9.3	6.8	7.8	48.2	48.1	80.6	80.0	-4	13	-2.2	1.0	0.9	1.3
31	PBS 14011	8.4	7.2	4.6	6.0	45.6	41.8	76.7	76.9	-17	23	-9.1	1.2	0.8	0.0
32	PBS 14013	6.3	8.0	6.2	7.1	38.0	38.8	79.7	79.4	18	12	12.4	0.8	0.9	0.0
33	PBS 14014	8.6	8.5	6.3	7.5	32.9	34.6	77.9	78.7	-2	15	-0.7	1.0	0.9	0.2
34	PBS 14027	7.1	7.3	5.3	6.8	32.3	32.9	79.1	78.1	2	21	1.0	1.0	0.8	-0.5
35	PBS 16003	3.5	4.1	6.1	7.2	28.6	29.4	76.9	77.9	14	16	4.5	0.9	0.8	-1.7
36	PBS 18029	4.8	4.4	8.3	6.5	29.5	33.0	72.8	74.7	-8	-28	-2.7	1.1	1.3	-0.9
37	PBS 18057	7.7	8.7	7.2	8.5	40.3	41.8	73.8	73.1	12	14	7.8	0.9	0.9	0.4
38	PBS 20012	6.5	6.7	6.1	7.1	33.0	34.0	77.8	79.0	2	13	1.3	1.0	0.9	-0.5
39	PBS 20016	7.8	6.1	9.6	6.5	33.0	32.5	70.4	74.6	-31	-46	-13.2	1.3	1.5	0.0
40	PBS 20036	6.5	6.9	8.3	9.2	36.8	37.8	74.7	74.1	5	9	2.5	1.0	0.9	0.4
41	PBS 20047	6.3	5.9	10.9	12.6	34.3	30.7	73.1	72.1	-7	13	-3.1	1.1	0.9	0.6
42	PBS 20057	5.5	7.8	6.5	8.1	43.1	38.0	73.9	73.1	28	20	17.0	0.7	0.8	0.2
43	PBS 20503	6.2	6.1	6.0	5.2	34.9	31.8	76.4	78.5	-1	-16	-0.3	1.0	1.2	-1.1
44	PBS 20504	6.0	4.3	5.6	10.3	30.7	30.5	72.5	73.0	-40	45	-12.9	1.4	0.6	-0.7
45	PBS 20505	10.5	9.7	8.1	9.2	47.2	44.8	77.5	77.4	-8	9	-5.7	1.1	0.9	1.4
46	PBS 20507	5.7	4.9	5.1	5.6	44.4	43.1	72.4	67.5	-20	9	-6.4	1.2	0.9	-0.5
47	PBS 20511	8.6	6.9	7.5	7.1	35.7	33.7	79.0	78.9	-26	-6	-13.4	1.3	1.1	0.3
48	PBS 20517	6.9	7.1	5.1	4.6	40.7	42.1	75.6	75.7	3	-10	1.4	1.0	1.1	-0.5
49	PBS12056	6.4	8.3	6.4	4.6	35.0	33.7	77.7	80.1	22	-44	14.1	0.8	1.4	-0.4
50	PBS14017	7.8	7.4	4.3	6.7	40.4	40.4	75.8	75.9	-6	36	-3.3	1.1	0.6	-0.3
51	PBS14032	6.7	7.6	5.5	6.2	37.9	37.4	78.5	77.1	12	12	6.9	0.9	0.9	-0.6
52	PBS20509	7.1	7.1	9.1	8.0	35.7	32.6	71.9	72.8	1	-14	0.4	1.0	1.1	0.0

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
53	PKVG 8	6.9	8.5	6.3	7.4	33.8	36.3	79.6	78.7	17	15	11.9	0.8	0.9	-0.2
54	PM 20 A	7.1	8.1	7.4	7.9	28.3	29.1	75.9	76.4	12	6	7.5	0.9	0.9	-0.2
55	PM 20 C	7.2	9.4	8.9	11.1	35.7	38.6	71.0	72.1	23	20	16.6	0.8	0.8	0.6
56	PM 33 B-1	6.8	8.2	6.1	7.6	32.0	38.0	71.5	75.5	17	19	10.9	0.8	0.8	-0.4
57	PM 4	5.2	5.1	6.2	8.2	43.5	39.1	79.1	80.2	-1	24	-0.5	1.0	0.8	-0.2
58	PM 49	7.9	9.3	5.8	8.1	39.5	45.1	70.8	74.4	16	29	11.1	0.8	0.7	0.5
59	PM 79 A	8.4	8.4	4.2	4.4	44.5	43.6	75.3	74.8	0	4	0.2	1.0	1.0	-0.4
60	SG 84	7.4	7.3	4.8	7.9	39.8	40.4	75.3	77.3	-4	40	-1.2	1.0	0.6	-0.2
61	SP 144	7.5	7.8	6.7	8.8	40.6	39.2	67.6	67.3	5	24	2.7	1.0	0.8	0.3
62	SP 250 A	9.3	11.7	10.0	9.1	40.9	46.8	67.4	67.5	21	-10	18.5	0.8	1.1	1.8
63	SP 26 B	4.6	6.2	4.8	4.1	34.7	35.8	71.8	74.0	25	-23	11.6	0.8	1.2	-1.4
64	SP 61	8.5	6.7	8.0	8.8	40.7	37.5	73.3	73.4	-29	9	-14.1	1.3	0.9	0.4
65	SP 76 A	6.3	7.1	8.7	8.8	40.2	37.2	74.3	75.6	12	-1	6.3	0.9	1.0	-0.2
66	SP 94	6.2	6.6	8.0	7.6	29.6	32.7	69.4	72.4	6	-5	3.2	0.9	1.1	-0.9
67	SP26 A	3.4	4.4	8.7	3.6	33.1	32.1	74.7	76.0	23	-142	7.8	0.8	2.4	-1.6
68	TG 26	6.2	7.6	3.4	3.3	40.1	39.9	73.8	76.5	19	-3	11.0	0.8	1.0	-1.4
69	TSP 49 A	5.8	7.5	6.4	4.7	33.6	35.4	71.6	74.9	22	-38	12.7	0.8	1.4	-1.2
70	VRI 3	5.8	7.7	7.6	6.5	35.7	36.2	76.5	79.3	25.0	-17	15.0	0.8	1.2	-0.1
	Mean	7.1	7.6	6.9	7.4	38.4	38.9	74.6	75.3	5.2	2.4	4.1	0.9	1.0	0.0

Association among various P-efficiency indices

The correlation studies between P efficiency indices and yield related parameters indicated that PEI was positively correlated with pod and haulm yields, plant height, seed length and seed width under both –P and +P conditions, but it showed negative correlation with pods plant^{-1} and PE_h under –P condition (Table 5). However, the PE_h was negatively correlated with pod yield, haulm yield (except in -P) and seed length and width under both high and low P conditions. Association of PE_p with pod yield was positive under P-deficient (–P) and negative under adequate (+P) P, whereas APE and PSF_p had negative association with pod yield under –P and positive under +P. The APE had positive correlation with PSF_p (r = 0.96**) and negative association with PE_p (r = –0.96**) under –P condition. The PSF_h showed positive association with pod yield and seed width under both –P and +P and haulm yield and seed length under +P condition and 100 seed mass (SM) under -P but showed negative association with haulm yield under –P. The P efficiency indices PSF, APE and PE did not show any significant association with most of the traits, whereas PEI had significant association with most of the traits and hence was most useful parameter.

Discussion

The P is essential for growth and availability of P by leaves lead to further growth of pod (Singh 2004; Singh and Chaudhari 2006; 2007). P efficiency is a complex trait which involves differences in growth, P uptake (Singh and Basu 2005a; Pan et al. 2008). As per definition, a 'nutrient efficient' genotype is the one that better converts nutrient inputs into desired outputs than other genotypes, which by comparison are 'nutrient inefficient'. Substantial genotypic variations in response to P deficiency are common in groundnut (Singh and Basu 2005a; Singh et al. 2004), soybean (Pan et al. 2008) and common bean (Mourice and Tryphone 2012). Under P sufficient condition the groundnut expand growth and accumulate more biomass resulting in high pod yield (Singh and Chaudhari 2006). The P-efficient genotypes had high pod yield, high P uptake by pods and plants both at low and high levels of P and high relative pod yield (Singh and Basu 2005b). In general, the P content less than 0.18 % in leaves falls under deficiency range (Singh et al. 2004), however, this value varied with genotypes and was very common in the genotypes grown without P fertilizer (Singh and Basu 2005a).

The relative P-efficiency indices like relative pod weight and relative shoot weight, takes into account both the acquisition and P utilisation efficiencies (Singh and Basu 2005a). In Cotton, the varieties showing smaller PSF values were selected as P-efficient because of lesser yield decrease at low nutrient supply (Iqbal et al. 2001). The P efficiency indices used in this study are PEI, $PSF_{p,}$ PSF_h, $PE_{p,}$ PE_h and APE. The PSF measures the relative reduction (%) in biomass of a plant due to P deficiency compared to its biomass production at adequate P supply level and also determines the responsive and nonresponsive

Table 3. Analysis of variance for yield related traits and P-efficiency parameters among 70 groundnut genotypes grown in the field under P-deficient (-P) and adequate P (+P) conditions in calcareous soil

	P	G	P × G	Range	
				-P	+P
PY	**	**	**	3.37-10.46	4.10-12.84
HY	**	**	**	3.40-12.47	3.31-12.88
SHP	**	**	**	66.53-80.57	67.20-80.20
100SM	**	**	**	23.30-60.60	24.20-67.83
PHt	*	**	n.s	31.13-54.20	31.87-55.27
PPP	*	**	n.s	6.40-12.73	6.40-14.27
SL	**	**	**	0.98-1.86	1.00-1.85
SW	**	**	**	0.59-0.88	0.63-0.91
PSF_p	na	**	na	-0.40-0.39	
PSF_h	na	**	na	-1.42-0.45	
APE	na	**	na	-14.12-28.98	
PE_p	na	**	na	0.61-1.40	
PE_h	na	**	na	0.53-2.47	

Where P represent P levels, G is Genotypes and PxG is interactions, 100 SM=100 seed mass, SHP= Shelling (%) percent, PHt = Plant height, PPP= Pods$^{plant-1}$, SL =Seed length and SW= Seed width. *P < 0.05, ** P < 0.01, ^{ns} non-significant; ^{na} not applicable

behaviour of a genotype to P. Here, 70 groundnut genotypes were tested in the field under similar input and environment where variation in yield was observed mainly due to their capabilities of utilizing P from the soil.

The APE is an increase in yield per unit of added P fertilizer which account for both the P acquisition and utilisation efficiencies. Thus in P-efficient genotypes reduction in yield per unit of P applied under P deficit conditions among genotypes should be low (Hammond et al. 2009). Here in the present study also the ER genotypes showed average APE value of 4.67 as against 6.12 in INR. Considering PEI, the genotypes GG 5, NRCG 1308, PBS 11037, PBS 11046, PBS 13007, PBS 20505 and SP 250A were the best for P-deficient soil and were also categorized as the P-efficient, due to responsiveness to increased P availability. The PEI in combination with P responsiveness has also been used to identify efficient genotypes in soybean (Pan et al. 2008) and maize (Bayuelo-jiménez 2011). The P-efficient genotypes identified in this study had high pod yield potential, low PSF_p, low APE, high PEI and PE_p and PE_h close to unity and PEI value > 0.77.

The PEI was positively correlated with pod and haulm yields, plant height, seed length and seed width under both -P and +P conditions. Association of PE_p with pod yield was positive under P-deficient and negative under adequate P. Whereas APE and PSF_p showed negative association with pod yield under -P and positive association under +P. The PSF should be low (Akhtar et al. 2007; Iqbal et al. 2001) and PE should be close to unity (Hammond et al. 2009). The PEI had significant association with most of the traits in this study and hence was most useful parameter. This may be due to PEI being composite parameter which includes all morphological and physiological parameters (Pan et al. 2008).

Yield related traits and P efficiency indices of seven highly P efficient genotypes and two P in-efficient genotypes when compared, there was much variation in pod yield between ER and INR. This was attributed to reduction in plant height, 100 SM, seed length and seed width in P-inefficient genotype over the P efficient one which is supported by our earlier studies (Singh and Basu 2005a, 2005b; Singh et al. 2004), biomass accumulation in P efficient genotypes was better than P in-efficient genotypes (Osborne and Rengel 2002; Sui et al. 2005). In our earlier field study the average and range of pod yield of groundnut genotypes were 195 and 65-295 g m^{-2}, respectively without P fertilizer, which increased to 230 and 90-340 g m^{-2}, respectively with addition of 50 kg ha^{-1} P

Table 4. Mean values of yield related parameters and P-efficiency indices in P-efficient and P responder (ER) and P-inefficient and P non responder (INR) groundnut genotypes grown in field with (+P) and without (-P) P

Genotypes		PY	HY	SHP	100SM	PHt	PPP	SL	SW	PSF_p	PSF_h	APE	PE_p	PE_h	PEI
ER	-P	9.61	7.75	76.12	48.43	46.04	9.26	1.33	0.79	4	14	4.67	0.96	0.86	1.47
	+P	10.23	9.22	76.11	47.58	47.68	10.96	1.36	0.82						
INR	-P	3.44	7.38	75.77	30.87	36.87	9.47	1.09	0.67	19	-63	6.12	0.81	1.63	-1.62
	+P	4.24	5.43	76.95	30.77	40.57	9.07	1.08	0.76						

Table 5. Correlation between various P efficiency indices and yield parameters in 70 groundnut genotypes grown in calcareous soil with (+P) and without (-P) P

	PSF_p		PSF_h		APE		PE_p		PE_h		PEI	
	-P	+P	-P	+P	-P	+P	-P	+P	-P	+P	-P	+P
PY	-0.36**	0.43**	0.31**	0.27*	-0.30**	0.51**	0.36**	-0.43**	-0.31**	-0.27*	0.72**	0.68**
HY			-0.29**	0.54**					0.29**	-0.54**	0.48**	0.68**
SHP												-0.26*
100SM			0.25*						-0.25*			
PHt											0.47**	0.47**
PPP											-0.37**	
SL				0.28*						-0.28*	0.67**	0.65**
SW			0.26*	0.25*					-0.26*	-0.25*	0.54**	0.38**
PSF_p					0.96							
PSF_h											0.33**	
APE							-0.96					
PE_p												
PE_h											-0.33**	

fertilizer (Singh and Basu 2005a). As in plant breeding all traits correlated with P efficiency may not be helpful, the pod yield is easily measurable and recommended.

The difference in 100 SM, seed length and seed width in this study indicated that there is wide variation in sink strength between ER and INR. Increasing sink strength (seed size) would impart tolerance to P deficiency. Seed size closely related to P efficiency in legumes mainly by affecting leaf growth and expansion (Liao and Yan 1999) as early growth of a seedling depends on P reserves in the seed (White and Veneklaas 2012). Effort on identification of the P-efficient genotypes is useful for early establishment of seedlings. The P uptake in groundnut increased with various levels of P supply, however the yield increase was up to certain level only (Singh and Chaudhari 2007). The average yields of P-efficient and P-inefficient genotypes were 275 and 102 g m^{-2} pod respectively (Singh and Basu 2005a). Here in this study also clear cut differences were noticed and hence it is recommended to grow P efficient genotypes.

Phosphorous is one of the nutrients whose availability is very limited for plant growth in calcareous soils where most of the P applied is fixed with very low recovery rate. Efficient cultivars grow better in the absence of fertilization, as well as are more responsive to P where fixation of fertilizer-P is a problem (Singh et al. 2004). The P-efficient groundnut genotypes, with high yielding abilities under both high- and low-input systems, identified in this study would reduce the cultivation costs, and contribute to the maintenance of P resources.

The study concludes that the identified P-efficient genotypes GG 5, PBS 11037, PBS 11046, PBS 13007, PBS 20505 and SP 250A are best suited for low P soil and hence recommended for their direct cultivation and could be used in breeding programme. The traits identified for P-efficiency are easily measured and hence could be efficiently employed in breeding programme to develop P-efficient groundnut genotypes for P-deficient soils.

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