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Phosphate sorption desorption characteristics of some ferruginous soils of tropical region in Eastern India

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Abstract Phosphate sorption and desorption experiments were conducted with four ferruginous soils (alfisols) of Eastern India, in view of the low native phosphate concentrations in tropical Indian soils. From the P-isotherm curve, standard P requirement (SPR) of the soils was determined. Phosphate sorption data were fitted to both Langmuir and Freundlich equations and mean sorption maximum values obtained for the different soil series were in the decreasing order as Matimahal > Anandapur > Mrigindih > Kashipur. The fraction of added P sorbed followed the same trend as SPR, P sorption maximum (P_{max}), phosphate affinity constant (K), maximum phosphate buffering capacity (MPBC), Freundlich constant K' and phosphate desorption values. Phosphate sorption maximum was significantly correlated with MPBC, Freundlich $1/n$, SPR, clay and different forms of Fe and Al. The value of K (bonding energy) was significantly correlated with MPBC, Freundlich K' and pyrophosphate extractable Fe and Al. The MPBC was significantly correlated with Freundlich K', Freundlich constant $1/n$, clay, oxalate and dithionite extractable, amorphous and crystalline form of Fe and Al. Freundlich K' was significantly correlated with Freundlich $1/n$, pH_{water}, clay, dithionite extractable and crystalline form of Fe and Al. The results suggested that the soils having higher amount of extractable and reactive Fe and Al shared higher P sorbtion capacity and such soils may need higher levels of P application

Keywords Phosphorous sorption–desorption · Phosphorous sorption maximum · Phosphorous affinity constant · Maximum phosphorous buffering capacity · Standard phosphorous requirement · Alfisols

Introduction

Ferruginous soils (alfisols) are the dominant soils of the semi-arid tropics where crop yield is often limited due to low native soil P concentration (Dolui and Dasgupta 1998). The problem of low soil P increases with the lowering of soil pH, since in acid soil the applied soluble phosphate fertilizer gets fixed through adsorption and precipitation, although the former appears to be dominant over a short reaction period (Mehadi and Taylor 1988; Sanyal and De Dutta 1991). Sorption and desorption reactions have a large impact on P availability to plants. Applied P is sorbed on the surface of inorganic constituents mainly by ligand exchange mechanism that provided its concentration in the soil solution which is not very high. Appreciable desorption of this P is possible if the negative charge on the surface is increased by raising the solution pH, or by introducing a competitive anion which could be specifically adsorbed by increasing the negative charge of the soil in the presence of P (Dolui et al. 1991). The P sorption by soil is important because sorbed P equilibrates with soil solution P, which in turn is the immediate source of P for plants. Phosphate sorption isotherms integrate P intensity, capacity and quantity parameters of soil. These factors play key roles in controlling P flux to the root of growing plants. The ability of the soil to replenish soil solution P, i.e., the desorption capacity; intensity and rate are important factors influencing uptake of P by plants and their growth. These factors are all interdependent and P availability can be expressed by a combination of two or more factors.

Soil factors influencing P sorption desorption include amount and type of clay, amounts of iron and aluminum oxides, organic matter content, pH and calcium carbonate content (Mehadi and Taylor 1988; Solis and Torrent 1989; Tsadilas et al. 1996; Chand et al. 1995; Saha et al. 1999) Phosphate sorption by the soils can be described by many equations, with Langmuir and Freundlich equations being the most commonly used. Using these equations, a number of P-sorption indices can be determined that describe the P-sorption capacity of soils. Phosphorus sorption–desorption phenomenon has been widely studied on Indian soils. Alfisols from different parent materials differ in their properties, which in turn significantly influence P sorption–desorption in the soils. The present investigation was carried out with the following objectives: (i) to determine the ability of representative Alfisols to adsorb P under laboratory conditions and to compare sorption isotherms among soil series; (ii) to determine the effects of the P sorption capacity and P affinity constant (K') on the quantity of added P, recovered with Bray's 1 extractant and (iii) to develop regression equations and use existing soil characteristics to predict relative P sorption potentials in some Alfisols.

Materials and methods

Four soil profiles of Alfisols under hot, dry, sub humid agro ecological sub region (12.3) from Puruliya district of West Bengal, India, were selected. Major site characteristics and land use pattern were given in Table 1. The samples were air dried and passed through 2-mm sieve.

Soil pH was determined in 1:2.5 soil:water suspensions. Electrical conductivity was determined in 1:5 soil:water suspension. Particle size distribution was determined by conventional international pipette analysis following destruction of organic matter with hydrogen peroxide; and organic carbon by the standard Walkey and Black method as cited by Piper (1966). Cation exchange capacity (CEC) was determined by 1 M ammonium acetate (pH 7.0).

Available P was extracted using Bray's 1 extractant (soil and extractant ratio 1:10) and determined following the methodology of Jackson (1973). Free Fe and Al fractions (Table 2) were determined by separate (not sequential) extraction with (1) 0.1 M sodium pyrophosphate (Agriculture Canada 1984), (2) 0.2 M ammonium oxalate adjusted to pH 3.0 (Agriculture Canada 1984) and (3) dithionate-citrate-bicarbonate reagent (CSSC Subcommittee on methods of analysis 1978), according to standard soil survey methods (USDA 1972). It is generally believed that extraction (1) removes organically bound Fe and Al (Fe_p, Al_p), (2) removes organically bound plus inorganic amorphous (Fe_o, Al_o) and (3) removes organically bound, inorganic amorphous and crystalline (Fe_d, Al_d) (Parafitt and Childs 1988; Borggaard 1988). Amorphous Fe and Al were designated as Fe_o–Fe_p and Al_o–Al_p, crystalline Fe and Al as Fe_d–Fe_o and Al_d–Al_o and active Fe and Al ratios as Fe_o:Fe_d and Al_o:Al_d, respectively.

Sorption experiment

The sorption isotherm was determined by equilibrating (at 25 ± 1°C) 3 g soil samples with 30 ml of 0.01 M $CaCl_2$ containing 0, 10, 20, 30, 40, 50 and 80 mg P L^{-1}. Two drops of toluene were added to arrest microbial growth. The suspensions were shaken horizontally for 30 min (180+ oscillations/min) each day, for 60 days. After equilibration, the suspension was centrifuged at 8,000 rpm for 20 min and the P content in the clear supernatant solution was determined by depletion technique (Olsen and Watanabe 1957). The amount of P sorbed was calculated by subtracting the amount of P in the extract from amount of P initially added (Fox and Kamprath 1970). Phosphorus sorbed (mg kg^{-1}) versus P remaining in solution (mg L^{-1}) was plotted to determine the sorption isotherm. The sorption values of each soil were plotted according to the Langmuir isotherm:

$$C/(x/m) = (1/Kb) + (C/b). \tag{1}$$

where C is equilibrium P concentration (mg L^{-1}), x/m is the amount of sorbed P (mg kg^{-1}), m, b are the constants related to P sorption maximum (mg kg^{-1}) and K is the bonding energy (L mg^{-1}), respectively. The plot of $C/(x/m)$ versus C should give a straight line from which b^{-1} (slope) and K (slope or intercept) can be calculated.

Maximum P buffering capacity (MPBC) is the product of P sorption capacity (or monolayer coverage in mol P Kg^{-1} of soil) and phosphate affinity constant related to the binding strength (Dalal and Hallsworth 1976) and regulates the partition of P between solution and solid phase.

The Freundlich equation takes the form:

$$x/m = K'C^{1/n}. \tag{2}$$

where x/m is the phosphorus sorption in mg kg^{-1} of soil, C is the equilibrium concentration in mg L^{-1}, K' and n

Table 1 Major site characteristics and land use pattern of selected soil series

Soil series	Geomorphology	Parent materials	Topography	Slope (%)	Drainage class	Rainfall (mm)	Present land use
Anandapur	Undulating upland	Granite-gneiss	Moderately gently sloping	3–5	Well	1,283	Paddy–pulses
Kasipur	Platue upland	Granite-gneiss	Level to nearly level	0–1	Moderate	1,185	Kharif paddy
Matimahal	Undulating upland	Granite-gneiss	Moderately gently sloping	3–5	Well	1,200	Kharif paddy
Mrigindih	Undulating plain	Old alluvium	Moderately gently sloping	3–5	Well	1,141	Pasture land

are two constants where *n* is always greater than unity. By taking the logarithm, Eq. (2) changes into $\log x/m = \log K' + 1/n \log c$. The log equation gives a straight line, or linear curve where $\log K'$ is the intercept and $1/n$ represents the slope of the curve or the regression coefficient.

Desorption experiment

The soil from the sorption run (after the supernatant solution was decanted off) was washed with alcohol to free the soil of soluble P. The washed soil was stirred continuously with 30 ml of Bray's 1 extractant for 5 min (180+ oscillations/min) and then centrifuged at 8,000 rpm for 20 min. The percentage of P desorbed was then calculated.

Result and discussion

Phosphate sorption characteristics

P sorbed at various equilibrating P concentrations and that remaining in solution at equilibrium is shown in Table 3. The P sorption in soil increased with increasing levels of P added to the soil. At low concentration the relationship was essentially linear while higher concentration showed some evidence of deviation from linearity. The linear relationship at lower P concentrations

Table 2 Extractable Fe and Al oxides, forms and degree of activation of Fe and Al oxides of the experimental soils

Depth (cm)	Extractable Fe_2O_3 (g kg^{-1})			Extractable Al_2O_3 (g kg^{-1})			Amorphous (g kg^{-1})		Crystalline (g kg^{-1})	
	Fe_p	Fe_o	Fe_d	Al_p	Al_o	Al_d	Fe_o–Fe_p	Al_o–Al_p	Fe_d–Fe_o	Al_d–Al_o
Pedon A (Anandapur series)										
0–10	0.14	0.28	0.82	0.17	0.33	1.02	0.14	0.16	0.54	0.69
10–26	0.12	0.32	0.90	0.15	0.38	1.12	0.20	0.24	0.58	0.73
26–51	0.12	0.64	1.66	0.15	0.78	2.05	0.52	0.63	1.02	1.27
51–89	0.09	0.72	1.84	0.11	0.88	2.27	0.63	0.76	1.12	1.40
89–120	0.08	0.68	1.76	0.10	0.83	2.18	0.60	0.73	1.08	1.34
Pedon B (Kasipur series)										
0–14	0.08	0.15	0.56	0.10	0.18	0.70	0.07	0.08	0.41	0.52
14–51	0.09	0.36	0.82	0.11	0.44	1.02	0.27	0.33	0.46	0.58
51–87	0.06	0.53	1.42	0.08	0.65	1.76	0.47	0.58	0.89	1.11
87–141	0.06	0.53	1.46	0.07	0.65	1.80	0.47	0.58	0.93	1.15
141–150	0.05	0.51	1.38	0.06	0.63	1.71	0.46	0.57	0.87	1.09
Pedon C (Matimahal series)										
0–11	0.13	0.28	0.72	0.16	0.34	0.90	0.15	0.18	0.44	0.56
11–26	0.14	0.46	1.24	0.17	0.56	1.54	0.32	0.39	0.78	0.98
26–52	0.12	0.59	1.64	0.15	0.72	2.03	0.47	0.57	1.05	1.31
52–88	0.10	0.65	1.66	0.12	0.80	2.05	0.55	0.67	1.01	1.25
88–120	0.09	0.68	1.76	0.11	0.84	2.18	0.59	0.73	1.08	1.34
Pedon D (Mrigindih series)										
0–9	0.09	0.37	0.92	0.11	0.45	1.14	0.28	0.34	0.55	0.69
9–26	0.08	0.38	0.94	0.10	0.46	1.17	0.30	0.36	0.56	0.71
26–59	0.08	0.57	1.36	0.10	0.71	1.68	0.49	0.61	0.79	0.97
59–86	0.06	0.62	1.54	0.07	0.76	1.90	0.56	0.69	0.92	1.14
86–144+	0.05	0.63	1.58	0.06	0.77	1.95	0.58	0.71	0.95	1.18

Table 3 Phosphorus sorption (mg P L^{-1}) in four experimental soils

Depth (cm)	Equilibrium P concentration (C) (mg L^{-1})							Sorbed P (x/m) (mg kg^{-1})						
	10	20	30	40	50	60	80	10	20	30	40	50	60	80
Pedon A (Anandapur series)														
0–10	0.43	1.54	3.32	8.51	15.65	26.01	34.45	98.2	184	282	369	457	517	633
10–26	0.38	1.41	3.12	7.1	14.12	21.78	30.44	96.8	176	272	357	449	497	621
26–51	0.28	1.02	2.16	5.55	10.21	16.92	22.43	99.1	198	291	387	495	587	752
51–89	0.22	0.78	1.89	4.36	8.11	13.29	17.63	97.4	182	276	262	481	567	747
89–120	0.18	0.65	1.39	4.56	7.56	10.88	14.42	98.8	192	288	381	488	571	749
PedonB (Kasipur series)														
0–14	0.76	3.01	6.02	15.33	27.87	46.23	61.33	81.6	147	223	249	285	337	374
14–51	0.67	2.47	4.28	11.52	19.56	30.77	47.08	84.2	152	239	287	331	348	428
51–87	0.41	1.53	3.25	8.28	15.02	24.93	33.08	84.8	156	244	306	397	430	475
87–141	0.33	1.24	2.62	7.66	12.11	20.11	26.63	82.1	149	231	273	352	428	478
141–150	0.32	1.38	2.54	6.43	12.73	21.47	25.81	80.6	144	219	247	308	349	370
Pedon C (Matimahal series)														
0–11	0.68	2.45	5.3	13.53	24.81	41.21	54.62	98.3	188	280	367	427	509	631
11–26	0.57	2.07	4.44	10.32	19.73	34.54	45.79	99.1	197	294	391	452	545	721
26–52	0.42	1.66	3.6	9.14	16.78	27.85	36.96	99.5	199	297	395	485	552	724
52–88	0.46	1.15	3.5	8.37	15.7	19.38	25.71	98	189	280	362	488	551	720
88–120	0.40	1.45	3.34	7.96	14.6	23.14	24.09	99.1	198	292	388	491	557	735
Pedon D (Mrigindih series)														
0–9	0.87	3.35	7.13	17.75	32.00	53.30	69.75	98.6	190	286	384	327	351	441
9–26	0.83	3.41	6.18	15.84	28.17	48.61	65.52	94.4	165	261	324	309	367	407
26–59	0.57	2.21	4.66	11.62	20.97	34.95	45.71	95.1	172	267	337	402	459	519
59–86	0.51	1.97	4.19	10.41	18.77	31.24	40.91	94.1	163	256	312	417	461	512
86–144 +	0.42	1.63	3.44	8.56	19.46	30.73	40.62	94.3	165	259	317	418	462	514

was probably due to the large intermolecular distance between P molecules, which resulted in negligible mutual repulsion. Deviation from the straight line indicated that the bonding energy is a decreasing function of increasing surface—saturation (Barrow 1978).

The results revealed that at all concentrations mean sorbed P was highest in the Matimahal soil series followed by Anandapur, Mrigindih and Kasipur series. The higher P sorption capacity of the Matimahal series could be attributed to the specific clay surface and amorphous and crystalline form of iron and aluminum oxide present in these soils. Lower sorption observed in the Kasipur soil series as compared to the other series might be due to comparatively low clay content and amorphous and crystalline from of iron and aluminum oxides (Kaistha et al. 1997) along with relatively higher pH (Hinga 1973) of these soils. Moderately weathered crystalline oxides, desilicated amorphous materials and various forms of sesquioxides adsorb high amount of P (Fox 1981).

Phosphate sorption parameters

The P sorption data of the soils from the four soil series were plotted according to the conventional Langmuir equation. The Langmuir isotherm was used only as a means of deriving a characteristic sorption maximum indicative of the soil capacity to sorb P. The amount of P sorbed at 0.2 mg P L^{-1} equilibrium concentration is considered to be adequate for most field crops and is widely accepted as the standard P requirement (SPR) of soils (Fox 1981). In the four soil series considered here the SPR of the soils varied from 11 to 25 mg kg^{-1} with an average of 18.9 mg kg^{-1} (Table 4). The highest SPR was observed in Matimahal (23.8 mg kg^{-1}) soils followed by the Anandapur (21.0 mg kg^{-1}), Mrigindih (18.8 mg kg^{-1}) and Kasipur (12.0 mg kg^{-1}) series. However, no specific trend of SPR was observed with depth.

Phosphate sorption maximum and bonding energy

Phosphate sorption maximum of the soil based on the first linear portion of the isotherms varied widely and ranged from 385 mg to 833 mg kg^{-1} (Table 4). Phosphate sorption maxima were highest in Anandapur series followed by Matimahal, Mrigindih and Kasipur series. The SPR, Frendulich K' and $1/n$ values were highest in Matimahal series, but bonding energy and MPBC were highest in Anandapur series.

The bonding energy K calculated from the Langmuir equation followed the similar trend as P sorption

Table 4 Phosphorus sorption parameters of four experimental soils

Depth (cm)	SPR (mg kg^{-1})	Langmuir constants		Maximum phosphate buffering capacity (bK) (L kg^{-1})	Freundlich	
		Phosphate sorption maxima (b) (mg kg^{-1})	Bonding energy (K) (L mg^{-1})		K' (mg kg^{-1})	$1/n$
Pedon A (Anandapur series)						
0–10	21	666.67	0.21	138.89	151.18	0.40
10–26	20	666.67	0.22	147.06	153.21	0.41
26–51	22	769.23	0.26	200.00	186.55	0.43
51–89	21	833.33	0.23	188.68	187.59	0.39
89–120	21	769.23	0.37	285.71	133.41	0.39
PedonB (Kasipur series)						
0–14	11	384.62	0.18	67.57	128.85	0.26
14–51	12	434.78	0.21	90.90	146.69	0.27
51–87	13	500.00	0.28	138.89	131.98	0.39
87–141	12	526.32	0.26	136.99	177.54	0.41
141–150	12	384.62	0.43	163.93	219.28	0.42
Pedon C (Matimahal seris)						
0–11	22	416.67	0.63	263.16	134.37	0.33
11–26	24	714.29	0.14	101.01	140.31	0.42
26–52	25	769.23	0.17	129.87	155.06	0.41
52–88	23	769.23	0.18	136.99	153.14	0.45
88–120	25	714.29	0.22	153.85	158.71	0.44
Pedon D (Mrigindih series)						
0–9	22	416.67	0.23	96.15	125.37	0.30
9–26	17	416.67	0.20	84.03	115.03	0.32
26–59	18	555.56	0.19	105.26	128.14	0.38
59–86	18	555.56	0.20	109.89	129.96	0.37
86–144+	19	526.31	0.25	133.30	140.64	0.36

maximum (P_{max}). Small K values indicated loose bonding (Mehadi and Taylor 1988), which might suggest that the Anadapur and Matimahal series could probably retain P better than Mringindih and Kasipur series and could possibly be the better P sink at similar P adding rates. Higher P retention characteristics of the Matimahal and Anadapur series could be attributed to the higher clay and organic carbon, higher Fe and Al concentration (Mallikarjuna et al. 2003) compared with Mrigindih and Kasipur series (Tables 2, 5). The parameter K of the Langmuir equation varied from 14 to 0.63 L mg^{-1} with a mean of 0.20 L mg^{-1}. These values were lower as compared to those reported by Solis and Torrent (1989) for calcareous Vertisol and Inceptisols from Spain but in the same order as those reported by Choudhuary et al. (1993) for semi-arid soils of Punjab. Higher value of phosphate sorption and bonding energy could be attributed to low CEC, which indicated the dominance of kaolinite, which played an active role in P sorbtion (Tomar 2000).

Maximum P buffering capacity

Maximum P buffering capacity (MPBC) is an inherent characteristic of soils, which unlike P buffering capacity does not vary with solution P concentration and its use was advocated by Holford and Mattingly (1976). The MPBC ranged from 67.6 to 286 L kg^{-1} with a mean of 116.8 L kg^{-1}. Anandapur series showed the highest MPBC (average 178.58 L kg^{-1}) followed by the other soil series. MPBC generally increased with depth in the different soil series with some irregular trends in few horizons. These variations in the buffering capacity of soils of the same soil series were due to variation in clay percent and Fe and Al oxides (Dhillon et al. 2004), which were generally increased down the profile. Buffering capacity values were assessed from changes in P quantity and intensity produced by cropping, i.e., the ratio between change in labile P and change in the solution P concentration (Δ labile P/Δ P concentration) (Dolui et al.1998). Thus, sorption isotherms can provide a rough estimate of the field P buffering capacity in the soils studied, as also found in other soils (Bowman and Olsen 1985). Management practices viz soil conservation measure, application of manure, lime, etc. also influences MPBC (Majumdar et al. 2004) and difference in MPBC in four soil series can be explained by different land use pattern of these soil series. Mrigindih soil series, which is a pasture land, received lowest level of management practices showed lowest MPBC value.

Table 5 Physico-chemical properties of four experimental soils

Horizon (depth in cm)	pH H_2O	Organic carbon (g kg^{-1})	Particle size distribution (g kg^{-1})			Texture	CEC (cmol (p+) kg^{-1})	Available P (mg kg^{-1})
			Sand	Silt	Clay			
Pedon A: Anandapur Series (fine, mixed, hyperthermic Ultic Paleustalfs)								
Ap (0–10)	5.25	5.39	263	493	244	l	4.9	24
BA (10–26)	5.42	2.36	220	528	252	sil	5.2	22
Bt1 (26–51)	5.71	1.01	315	232	453	c	9.4	27
Bt2 (51–89)	6.20	0.60	294	241	465	c	10.2	21
Bt3 (89–120)	5.94	0.60	283	262	455	c	9.8	25
Pedon B: Kasipur series (fine loamy, mixed, hyperthermic Typic hapustalfs)								
Ap (0–14)	5.83	2.16	728	152	120	sl	4.7	11
Bt1 (14–51)	6.32	1.08	541	243	216	scl	6.7	13
Bt2 (51–87)	6.36	0.46	477	227	296	scl	8.4	14
Bt3 (87–141)	6.51	0.41	471	221	308	scl	8.4	12
Bt L_1(141–150)	6.74	0.30	481	232	287	scl	8.2	10
Pedon C: Matimahal series (fine, mixed, hyperthermic Typic Paleustalfs)								
Ap (0–11)	5.70	2.30	286	492	231	l	4.8	24
BA (11–26)	6.00	1.60	329	284	387	cl	7.5	27
Bt1 (26–52)	6.42	1.10	267	291	442	c	8.8	28
Bt2 (52–88)	6.64	0.80	255	292	453	c	9.4	29
Bt3 (88–120)	6.51	0.60	243	294	463	c	9.4	24
Pedon D: Mrigindih series (fine loamy, mixed, hyperhermic Ultic Paleustalfs)								
Ap (0–9)	4.88	1.40	536	305	159	sl	8.2	24
BA (9–26)	5.26	1.20	501	332	161	sl	8.3	21
Bt1 (26–59)	5.42	0.80	530	181	289	scl	10.1	22
Bt2 (59–86)	6.40	0.30	468	194	338	scl	14.6	21
Bt3 (86–144+)	6.00	0.20	456	238	306	scl	13.2	22

Freundlich sorption isotherm

Freundlich equation gave a better fit of the equilibrium P sorption data than did the Langmuir equations. This is because the Freundlich equations although originally empirical, implies that affinity for sorption decreases exponentially with increasing saturation of the surface, which is closer to reality than the assumption of a constant bonding energy inherent in the Langmuir equations (Sposito 1981; Kuo and McNeal 1984; Sanyal and De Dutta 1991). Such behavior is supported by the findings of Polyzopoulos et al. (1985) and Saha et al. (1999). The Freundlich constant varied from 115 to 219 mg kg^{-1} with an average of 142 mg kg^{-1}. The coefficient $1/n$ (Table 4) values were in the same order as that observed by Tsadilas et al. (1996). However, no systematic depth wise trend was observed.

Desorption of sorbed P

Desorption percent of sorbed P from the surface and sub-surface soil by Bray's 1 extractant is shown in Figs. 1 and 2. The amount of sorbed P extracted varied considerably among the soil series, which suggested that some additional soil factors also affected the amount desorbed by the extractant. The mean desorption of sorbed P was highest in the Anandapur soil series, followed by the Mrigindih, Matimahal series and Kasipur series.

The maximum recovery was determined for each soil as ratio of the total amount of P extracted to the total amount of P sorbed. The range of P desorbed and mean maximum recovery followed the order: Mrigindih (12.8–17.7%, mean 14.9%) > Kasipur (13.2 m–16.6%, mean

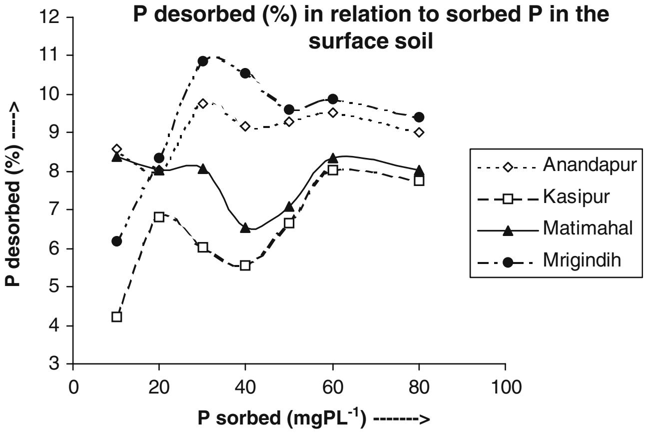

Fig. 1 P desorption characteristics in the surface soils

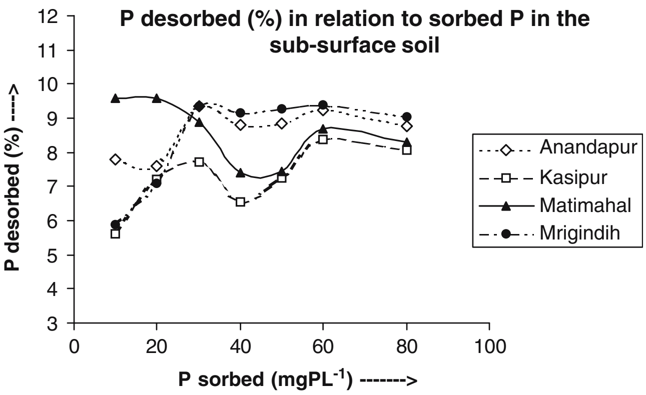

Fig. 2 P desorption characteristics in the sub-surface soils

14.9%) > Anandapur (10.0–11.4%, mean 10.9%) > Matimahal (8.9–11.7%, mean 10.2%), which followed the decreasing trend of P desorption. The amount of P desorbed increased with the amount of P originally sorbed, but the relationship was not described by any simple function. In accordance with the results obtained by other workers (Shailaja and Sahrawat 1990), the present results also indicated that applied P was not all irreversibly fixed; however, further study is required for determination of the factors affecting P desorption using different extractants.

Relationships among the P sorption parameters and soil properties

The relationship among the P sorption parameters and soil properties are presented in Table 6. Phosphate sorption maximum was significantly related to MPBC, Freundlich 1/*n*, SPR, clay and different form of Fe and Al. Since the sorption maximum (*b*) is a component of the buffering capacity, a relationship between P sorption maximum and bonding energy with MPBC may be expected. The SPR was correlated with sorption maximum showing that both parameters could be used in evaluating the P sorption characteristic of the soils (Osodeke et al. 1993). Murthy et al. (1996) reported that sorption maximum was significantly associated with Freundlich *K*′. The result supported the suggestion by Hinga (1973) and Dolui and Dasgupta (1998) who concluded that different forms of Fe and Al components are very active in the sorption of P added to soils.

The value of *K* (bonding energy) correlated significantly with MPBC was expected, as affinity constant (*K*) is a component of the buffering capacity. The significant association of Freundlich *K*′ with sorption maximum and bonding energy constant showed their interdependence. The surface site assumed to have constant affinity and the electrostatic interaction was

Table 6 Correlation coefficient among the sorption parameters of P and related soil properties

Y	X																	
	K	MPBC	Freundlich		SPR	pH water	Organic carbon	Clay	Fe_p	Fe_o	Fe_d	Al_p	Al_o	Al_d	Crystalline		Amorphous	
			K′	1/*n*											Fe_c	Al_c	Fe_a	Al_a
P_{max}	−0.19	0.57**	0.21	0.67**	0.88**	0.12	0.01	0.84**	0.62**	0.52**	0.56**	0.63**	0.51**	0.56**	0.58**	0.58**	0.38	0.37
K		0.66**	0.51**	0.09	−0.37	0.23	−0.01	0.11	−0.53**	0.29	0.33	−0.53**	0.30	0.33	0.34	0.34	0.37	0.37
MPBC			0.43*	0.44*	0.34	0.17	−0.04	0.67**	−0.01	0.61**	0.65**	−0.01	0.60**	0.65**	0.67**	0.68**	0.57**	0.57**
Freundlich *K*′				0.53**	−0.04	0.49*	−0.17	0.42*	−0.05	0.34	0.41	−0.05	0.33	0.41*	0.44*	0.45*	0.33	0.32
1/*n*					0.61**	0.36	−0.13	0.72**	0.30	0.54**	0.60**	0.30	0.54**	0.60**	0.62**	0.63**	0.46*	0.45*
SPR						−0.04	0.17	0.70**	0.66**	0.43*	0.44*	0.66**	0.43*	0.44*	0.43*	0.44*	0.29	0.29

Degrees of freedom (*n*): 19

* and ** is the significant at 5% & 1% level significantly

separated from the chemical components. The breakdown of sorption energy into chemical and electrostatic components was arbitrary (Sparks 1984) due to the lack of knowledge about the activity coefficient surface species (Sposito 1984).

Maximum P buffering capacity was significantly correlated with sorption parameters and soil properties, viz., Freundlich *K′*, $1/n$, clay and different forms of Fe and Al. The value of Freundlich *K′* was significantly correlated clay content attributed to the high surface area of clay particles, which provides for P sorption (Tsadilas et al. 1996). It indicates that, in the present contest abundance of amorphous and crystalline oxide of Fe and Al in alfisols reduces the leaching loss of phosphorus from the soil (Agbenin 2003), whereas comparatively low clay content in Mrigindih soil series increase the risk of phosphorus loss through leaching. The correlation coefficient of Freundlich *K′* with oxalate and dithionite soluble Fe and Al and crystalline Fe and Al were similar in magnitude as the values obtained for the different group of soils in the Mediterranean areas (Borrero et al. 1988), which indicated the important role of Fe and Al oxides in P sorption.

Conclusions

Phosphate fertilizers have immense contributions toward crop yield and play significant role in maintaining the soil physical properties. Low to medium available phosphorus in the soils was mainly due to acidic pH and presence of Fe and Al oxides. Using the standard value of 0.2 mg P L^{-1} in the equilibrium solution as that adequate for normal growth of most crops, the amount of P-fertilizers required to give this value for the studied soils ranged from 11 mg to 25 mg P L^{-1}. In the studied soils, moderate slope associated with high rainfall and low organic carbon status increased the risk of phosphate runoff. But acidic soil condition associated with dominance of kaolinite clay materials, low to medium status of available phosphorus and higher amount of Fe and Al oxide increased the phosphate adsorption capacity of the soil. This restricted the movement of phosphate and regulated the leaching loss. Therefore, broadcasting of phosphate fertilizer should be avoided in the area and slow releasing phosphate fertilizer should be applied in smaller, more frequent dozes for higher crop response.

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