

Characterization of acid piedmont rice soils for phosphorus sorption and phosphorus saturation

M. A. Islam¹⁾, M. A. Saleque²⁾, A. J. M. S. Karim³⁾,
A. R. M. Solaiman³⁾ and M. M. Masud⁴⁾*

Abstract

The maximum phosphorus adsorption (S_{\max}) and Phosphorous saturation index (P_{sat}) of a soil provide information for the proper management of the P fertilizer of the soil. The objective of this investigation was to determine S_{\max} and develop a P_{sat} for 14 rice soils. Soil samples were analyzed for pH, clay content, dithionite extractable Fe (Fe_D), Mehlich-3 (M3) extractable P (PM3), and Fe (FeM3). The S_{\max} value and P_{sat} based on M3 extractions were determined. The S_{\max} value ranged from 110 to 625 mg kg^{-1} , and correlated with sand ($r = -0.70$, $P > 0.01$), silt ($r = 0.70$, $P > 0.01$), clay ($r = 0.59$, $P > 0.05$) and Fe_D ($r = 0.71$, $P > 0.01$). Soil $\text{pH}_{\text{H}_2\text{O}}$ and organic carbon content were not correlated ($P > 0.05$) with S_{\max} , while pH_{KCl} was negatively correlated ($r = -0.64$, $P > 0.05$) with S_{\max} . Multiple regression found that the combination of pH_{KCl} and Fe_D were the two most important soil properties related to the S_{\max} of the soils studied. Conventional adsorption equations, such as the Langmuir, Freundlich and Temkin equations, satisfactorily described the P sorption of the soils. The P sorption capacity of the studied soils varied from 80 to 316 mg kg^{-1} . The calculated energy of adsorption of the soils ranged from 0.18 to 1.56 mg L^{-1} , and there was apparently a negative correlation between the energy of adsorption (k) and the observed S_{\max} values. Buffering capacity ranged from 14 to 69. Phosphorus saturation indices (P_{sat}) of the tested soils varied from 1.82 to 28.21%, and were correlated with sand ($r = 0.56$, $P > 0.05$) and silt ($r = -0.59$, $P > 0.05$), but not with the other soil properties we studied.

Keywords: Maximum adsorption capacity, phosphorus buffering capacity, energy of adsorption, Langmuir equation.

Introduction

Phosphate adsorption by soils is important, because adsorbed phosphate equilibrates with P in the soil solution and this P, in turn, is the immediate source of P for plants. Phosphate adsorption isotherm inte-

1) Principal Scientific Officer, Bangladesh Rice Research Institute, Regional Station-Sonagazi, Feni, Bangladesh.

2) Principal Scientific Officer, Bangladesh Rice Research Institute Regional Station, Rupaloli Housing, Barisal 8200, Bangladesh.

3) Professor, Soil Science Department, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Salna, Gazipur 1706, Bangladesh

4) Scientific Officer, Soil Science Division, Bangladesh Agricultural Research Institute, Gazipur 1701, Bangladesh.

*Corresponding author

E-mail: mzaman76@yahoo.com

grates the P intensity, capacity and quantity parameters of the soil, and these factors play an important role in controlling the P-flux to the roots of growing plants (Chand *et al.*, 1995). When a material containing P is applied to a soil that initially has low levels of P, the soluble forms of P become increasingly less soluble with time (Holford *et al.*, 1997). From an agronomic point of view, this is a concern because P that is strongly retained by the soil is less available for plant uptake. But from an environmental point of view, strong retention of P by the soil may prevent losses of soluble P in runoff, as well as movement to ground water. Thus, sorption and desorption reactions involving P, as well as the P-buffering capacities of soils, may play an important role in both the agronomic and the environmental aspects of P management (Sui and Thompson, 2000). Many investigators have suggested that a phosphorus sorption isotherm be used to determine the amount of P that must be added in order to bring the concentration of P in the soil solution to a level optimum for maximum plant growth (Fox and Kampath, 1970; Fontes and Wilcox, 1983). Such a sorption isotherm takes into account both the intensity and capacity factors, which are considered to be important in estimating the amount of soil P required for maximum plant growth. If the critical solution level for plant growth (including rice) can be identified, P-sorption isotherms can be used for predicting the amount of fertilizer P needed to adjust the soil solution P to a level optimum for the crop. The phosphorus sorption capacity of rice-growing soils in Asian countries has so far received little attention, but the P availability of these soils changes tremendously with seasonal variations in temperature (Saleque *et al.*, 1995).

Phosphorus saturation in Asian rice soils has not been characterized thoroughly, although P run-off from rice fields, especially during the rainy season, is a potential source of eutrophication. The concept of P saturation is meaningful, as it estimates the degree to which P sorption sites have been filled and indicates the potential desorbability of soil P (Beauchemin and Simard, 1999). Sibbesen and Sharpley (1997) reported that phosphorus saturation has been highly correlated with P desorption such that P desorption increases with higher degrees of P saturation. Phosphorus saturation is viewed as an environmental indicator of soil P because it has been found to be a good indicator of the amount of P available as run-off and leachate (Kleinman and Sharpley, 2002). Phosphorus saturation can be measured as in Sharpley's study (1995),

$$P_{sat} = \frac{P_{M3}}{S_{max}} \quad (1)$$

where P_{sat} is the P saturation index, P_{M3} is the Mehlich 3 extractable P (Mehlich 1984) and S_{max} is the P Langmuir adsorption maximum (mg kg^{-1}). Zhang *et al.* (2005) compared three methods for P saturation and reported a very good correlation between this method and the other two. With the above considerations, the present study was therefore undertaken in order to determine the P adsorption characteristics, maximum adsorption capacity and energy of P adsorption, and P saturation of some acid piedmont soils that had been being cultivated with rice for a long time.

Materials and Methods

Fourteen soil samples used for this study were collected from cultivated rice fields after the harvest of wet-season rice (Transplanted Aman) from the Hobigonj and Moulvibazar districts of Bangladesh. In the FAO-Unesco legend, these soils are classified as Chromi-Dystric and Eutric Gleysols. According to the USDA Soil Taxonomy, these soils have been classified as Typic Haplaquepts and Aeric Haplaquepts. For the convenience of discussion, the 14 soils are referred to as soil 1 through soil 14, as shown in Table 1. These samples were collected from the surface horizon (a horizon or plow layer) of selected farmers' fields, air-dried and ground to pass through a 2.0-mm sieve, and then mixed to form a composite sample for each replication.

Table 1. Locations and descriptions of the Piedmont soil samples examined in this study.

Designation	Farmer and Village	Upazilla and District	FAO Soil Unit	USDA Soil Family	Soil series
Soil 1	Ajit Paul, Nischintapur	Sreemongal, Moulvibazar	Haplic Alisols	Plinthic Haplustult	Sreemongal loam
Soil 2	Abinash Deb, Nischintapur	Sreemongal, Moulvibazar	Haplic Alisols	Plinthic Haplustult	Sreemongal loam
Soil 3	Hemendra Datta, Nischintapur	Sreemongal, Moulvibazar	Haplic Alisols	Plinthic Haplustult	Sreemongal sandy loam1
Soil 4	Ranadhir Datta, Nischintapur	Sreemongal, Moulvibazar	Haplic Alisols	Plinthic Haplustult	Sreemongal sandy loam
Soil 5	Rabindra Deb, Nischintapur	Sreemongal, Moulvibazar	Haplic Alisols	Plinthic Haplustult	Sreemongal sandy loam
Soil 6	Abu Taher, Sirajnagar	Sreemongal, Moulvibazar	Chromi-Eutric Gleysols	Typic Haplaquept	Pritimpasa loam
Soil 7	Afroz Khan, Isobpur	Sreemongal, Moulvibazar.	Chromi-Eutric Gleysols	Typic Haplaquept	Pritimpasa loamy sand
Soil 8	Mahram Ali, Haturakandi	Chunarughat, Hobiganj.	Chromi-Eutric Gleysols	Typic Haplaquept	Bijipur silt loam
Soil 9	Poritosh Boidha, Debipur	Kamalgonj, Moulvibazar	Chromi-Eutric Gleysols	Typic Haplaquept	Bijipur silt loam
Soil 10	Monjulal Dhar, Madhabpur	Kamalgonj, Moulvibazar.	Chromi-Eutric Gleysols	Typic Haplaquept	Bijipur loam
Soil 11	Nanda Paul, Debipur	Kamalgonj, Moulvibazar.	Chromi-Eutric Gleysols	Aeric Haplaquept	Monu sandy loam
Soil 12	Yakut Mia, Gogaura	Chunarughat, Hobigonj.	Chromi-Eutric Gleysols	Typic Haplaquept	Bijipur loam
Soil 13	Kutub Ali, Fultoli	Kamalgonj, Moulvibazar.	Chromi-Eutric Gleysols	Typic Haplaquept	Bijipur sandy loam
Soil 14	Gopal Paul, Debipur	Kamalgonj, Moulvibazar.	Chromi-Eutric Gleysols	Typic Haplaquept	Bijipur loam

Soil Properties

The soil's sand, silt and clay contents were determined using the hydrometer method (Black *et al.*, 1965). Soil pH_{H_2O} was measured in a 1:2.5 soil water ratio, using the glass electrode method (Jackson, 1958), and the pH_{KCl} was also measured by using a 1.0 M KCl solution in a similar manner as in pH_{H_2O} determination. The soil's organic carbon content was determined by Walkley, and the Black wet digestion method (Nelson and Sommers, 1982). Dithionite extractable Fe (Fe_D) was determined using a sodium dithionate-citrate system buffered with sodium bicarbonate (Mehra and Jackson, 1960). Mehlich-3 (M3) extractable P (PM3), and Fe (Fe_{M3}) were determined using the Mehlich-3 extraction method (Mehlich, 1984). The initial soil properties are presented in Table 2.

Table 2. Selected properties of the experimental soil samples.

Soil no.	Sand (%)	Silt (%)	Clay (%)	pH_{KCl}	pH_{H_2O}	ΔpH	Org. C (%)	Fe_D (ppm)	Fe_M (ppm)
1	28	49	23	4.81	4.69	0.12	3.3	814	150
2	49	38	13	4.85	4.66	0.19	3.12	370	203
3	54	30	15	4.90	4.75	0.15	2.74	574	217
4	54	33	13	4.85	4.74	0.11	2.06	389	225
5	65	28	8	5.01	5.00	0.01	2.42	259	207
6	51	36	13	4.69	5.84	-1.15	3.38	407	207
7	80	15	5	5.10	5.12	-0.02	1.96	333	210
8	26	56	18	4.79	5.25	-0.46	0.96	1018	238
9	29	51	20	5.00	5.41	-0.41	1.62	315	220
10	48	44	8	4.90	6.05	-1.15	1.9	592	223
11	61	31	8	4.85	5.43	-0.58	0.59	444	231
12	40	43	17	5.25	5.83	-0.58	2.71	500	211
13	66	24	10	5.12	5.61	-0.49	0.7	241	204
14	47	38	15	4.77	5.35	-0.58	1.29	648	237

Adsorption Isotherms

Phosphorus sorption isotherms were constructed using the procedure delineated by Nair *et al.* (1984). Briefly, one gram of soil sample was placed in a 25-ml test-tube with a given amount of added P (0, 1, 3, 6, 12, 18, 24, 30, 37, 43, 55, 68 or 80 ppm) in 20 ml of 0.01M $CaCl_2$ solution. The resultant P contents were 0, 20, 60, 120, 240, 360, 480, 600, 740, 860, 1100, 1360, and 1600 $mg\ kg^{-1}$, respectively. Then, the test tubes were shaken for 24 hr on a horizontal shaker with low oscillation. After equilibration, the supernatant was passed through a piece of Whatman 42 filter paper, and the filtrate was analyzed for P using the following Murphy and Riley (1962) method. Sorbed P was inferred from the difference between the concentration of soluble P added to the initial solution and the concentration of P in the solution at equilibrium. The equilibrium P concentration data were interpreted by the Langmuir, Freundlich and Temkin equations as described below:

Langmuir equation

The Langmuir adsorption equation is given by:

$$\frac{C}{x/m} = \frac{1}{kb} + \frac{C}{b} \quad (2)$$

where C is the equilibrium P concentration (mg L^{-1}), x/m is milligrams of P sorbed per kilogram of soil, b (S_{max}) is the adsorption maximum (maximum adsorption capacity), and k is a constant related to the bonding energy of adsorption.

A plot of $C/(x/m)$ versus C gives a straight line. The constants b (S_{max}) and k were obtained from the slope and intercept.

Freundlich equation:

The Freundlich equation is described by:

$$x/m = aC^b \quad (3)$$

By taking the log of both sides, the equation becomes

$$\log(x/m) = \log a + b \log C \quad (4)$$

where x/m is milligrams of P sorbed per kilogram of soil, C is the equilibrium P concentration (mg L^{-1}), and a and b are constants. A linear plot of $\log x/m$ versus $\log C$ allows the calculation of a and b from the intercept and slope, respectively.

Temkin equation

The Tempkin equation is

$$x/m = a + b \ln C \quad (5)$$

where x/m is the amount of P adsorbed per unit mass of adsorbent (mg/kg), C is the equilibrium P concentration (mg L^{-1}), and a and b are constants. A plot of x/m against $\ln C$ gives a straight line. The constants a and b were obtained from the intercept and slope. The b of Eq. 5 is considered to be the P buffering capacity.

Calculation of S_{max} , Adsorption energy, P-buffering capacity and P_{sat}

The phosphorus adsorption maximum (S_{max}) was calculated using the Langmuir adsorption equation (Eq. 2). S_{max} was calculated by regressing $C/(x/m)$ versus C , where C is the equilibrium solution P concentration and (x/m) is adsorbed P. The reciprocal of the slope of the linear regression is S_{max} (Olsen and Watanabe, 1957; Syers *et al.*, 1973). The energy of adsorption for phosphorus (binding energy) was also calculated from the Langmuir adsorption equation, where k is a constant related to the bonding energy of adsorption. The P-buffering capacity of soils has been calculated from the Temkin equation (Eq. 5), where b is considered the P-buffering capacity. Phosphorus saturation (P_{sat}), proposed by Sharpley (1995), was estimated from the equation (Eq. 1) by Mehlich-3 (M3) P (Mehlich, 1984) and the adsorption maximum (S_{max}) from the P adsorption isotherms.

Statistical Analyses

All measurements of P were done in duplicate, and the data were analyzed by ANOVA using the statistical software IRRISTAT 4.1 (Windows version: Bartolome *et al.*, 1998). Backward-stepwise regression analysis was utilized to evaluate the effects of soil properties on S_{\max} . Backward-stepwise regression analysis was used to generate empirical models capable of predicting S_{\max} based on soil properties. Backward-stepwise regression was used to identify crucial soil properties, explaining most of the variation in S_{\max} . Soil properties that did not explain a significant part of the variation (i.e., $p > 0.05$) were not used as independent variables in the multiple regression equation.

Results and Discussions

Phosphorus adsorption

The mean phosphorus adsorption and solution P concentrations due to the effects of different soils and phosphorus concentrations are presented in Table 3. There was significant variation among soils in P sorption ($P < 0.001$), and the application of P largely increased P sorption ($P < 0.001$). Interaction between the soil and phosphorus was also significant ($P < 0.001$). The highest mean P sorption (316 ppm) was found in soil 1, the lowest (80 pp) in soil 7.

The mean solution P concentration (due to the high amount of P application) varied significantly ($P < 0.001$) in different soils. The highest P concentration value for a 2.5 ppm solution was observed in soil 7, while the lowest, 13 ppm, was observed in soil 1. The second highest value for a 22-ppm P concentration was observed in soil 13, followed by soil 5 (21 ppm). In terms of statistical variation, soils 2, 6, 11 and 12 were in the same group, which showed similar amounts (19 ppm) of solution P concentration. A concentration of 18 ppm of solution P was extracted from soils 4 and 9, whereas soils 3, 8 and 10 yielded 16-ppm P concentrations.

High P sorption was attributed to the pH of the soil. Soil pH greatly influenced the P sorption of soils (Lopez-Hernandez and Burnham, 1974; Mokwunye, 1975; White and Taylor, 1977). According to some, phosphate sorption decreases with increases in pH within the acidic pH range (Parfitt, 1977; Friesen *et al.*, 1980), while others have shown that phosphate sorption increases with increases in pH (Amarasiri and Olsen, 1973; Mokwunye and Chien, 1980). There is also some evidence to show that phosphate sorption decreases with increases in pH up to 5.0-6.0, beyond which it increases (Barrow, 1987; Sims and Ellis, 1983) due largely to the difference in the exchangeable Al values of the soils.

Langmuir adsorption isotherm

The Langmuir adsorption isotherm explains the phosphorus adsorption maxima (S_{\max}) and energy of the P-adsorption of a soil. The intercept, slope and R^2 values for the equation of Langmuir adsorption isotherms are presented in Table 4. Langmuir equations were found to well explain P adsorption in most of

Table 3. Phosphorus adsorption and solution P concentrations of the piedmont rice soils.

Variable	<i>n</i>	P adsorption (mg kg ⁻¹)	Solution P (mg L ⁻¹)
Soil			
Soil 1	26	316	13
Soil 2	26	195	19
Soil 3	26	256	16
Soil 4	26	223	18
Soil 5	26	168	21
Soil 6	26	206	19
Soil 7	26	80	25
Soil 8	26	266	16
Soil 9	26	213	18
Soil 10	26	264	16
Soil 11	26	202	19
Soil 12	26	207	19
Soil 13	26	133	22
Soil 14	26	296	14
LSD _{0.05}		9	1
Phosphorus (ppm)			
0	28	0.00	0.01
1	28	20	0.03
3	28	57	0.18
6	28	103	0.86
12	28	164	3.81
18	28	218	7.11
24	28	248	11.61
30	28	289	15.57
37	28	300	22.00
43	28	308	27.63
55	28	344	37.79
68	28	369	49.57
80	28	391	60.48
LSD _{0.05}		8.34	0.42
	df		
Replication	1	0.018	0.017
Soil (S)	13	P<0.001	P<0.001
Phosphorus (P)	12	P<0.001	P<0.001
S × P	156	P<0.001	P<0.001
Residual	181		

n = No. of observations
df = Degrees of freedom

Table 4. Intercept, slope and R² for Langmuir adsorption isotherms of different soils examined in this study.

Soil	Intercept	Slope	R ²
Soil 1	0.0053	0.0016	0.96
Soil 2	0.0141	0.0027	0.96
Soil 3	0.006	0.0022	0.99
Soil 4	0.0083	0.0025	0.98
Soil 5	0.0142	0.0034	0.98
Soil 6	0.0089	0.0028	0.98
Soil 7	0.0144	0.0091	0.99
Soil 8	0.0039	0.0022	0.99
Soil 9	0.0102	0.0026	0.97
Soil 10	0.0087	0.0019	0.95
Soil 11	0.0144	0.0026	0.96
Soil 12	0.0059	0.0031	0.97
Soil 13	0.0043	0.0067	0.96
Soil 14	0.0055	0.0018	0.97

the soils with R² values ranging from 0.95 to 0.99. The highest R² value (0.99) was observed in soil 7, the lowest (0.95) in soil 10. The intercept of the Langmuir equation varied from 0.0039 to 0.0144. The highest intercept (0.0144) was found in both soil 7 and soil 11, the lowest (0.0039) in soil 8.

Because of differences in their slopes, the Langmuir isotherms of the soils we studied were different. The slope of the Langmuir isotherm of soil 1 was 0.0016, the lowest from among the 14 soils. The slopes for soils 10 and 14 were slightly higher than that for soil 1. Soils 3 and 8 both had a slope of 0.0022, although their intercepts were quite different. Soils 4, 6, 9 and 11 had similar slopes (0.0025-0.0028), and their isotherms look almost identical. A greater slope of 0.0067 was found for soil 13, and the highest slope of 0.0091 was observed for soil 7.

The good fit of the Langmuir adsorption isotherm explains why the P sorption affinity of soils remains constant with increases in surface saturation (Mead, 1981). Mehadi and Taylor (1988) reported that P adsorbed basically with one adsorption energy, which might explain the good fit of the linear Langmuir equation. The Langmuir equation can be used to calculate parameters that are indices of the capacity for and the intensity of P sorption by the soil. Because the simple Langmuir model does not adequately describe P sorption of soil when the surfaces have more than one type of adsorption site (i.e. sites with different sorption energies), a two-surface Langmuir equation has been used in some P sorption studies (Holford *et al.*, 1974).

Freundlich adsorption isotherm

Intercept, slope, and R² values for the equation of Freundlich adsorption isotherms for the studied soils are presented in Table 5. The Freundlich adsorption isotherm fitted well in the studied soils. The R² value of the Freundlich equation was more than 0.84 for most of the soils (9 soils), whereas two soils ranged above 0.91 and three soils ranged from 0.73 to 0.79. The highest R² value (0.92) was observed

Table 5. Intercept, slope and R² for Freundlich adsorption isotherms of different soils examined in this study.

Soil	Intercept	Slope	R ²
Soil 1	2.04	0.55	0.84
Soil 2	1.74	0.53	0.85
Soil 3	2.04	0.42	0.85
Soil 4	1.96	0.41	0.85
Soil 5	1.73	0.47	0.92
Soil 6	1.82	0.50	0.85
Soil 7	1.36	0.47	0.84
Soil 8	1.99	0.50	0.78
Soil 9	1.88	0.45	0.79
Soil 10	1.95	0.50	0.87
Soil 11	1.77	0.50	0.88
Soil 12	1.85	0.48	0.85
Soil 13	1.70	0.40	0.73
Soil 14	2.04	0.51	0.92

in soil 5, the lowest (0.73) in soil 13. The intercepts of the equations for most of the soils did not vary considerably. The intercepts of 13 out of the 14 soils ranged from 1.70 to 2.04, whereas the lowest intercept value was 1.36 (soil 7). The highest value (2.04) was observed in soil 3, which was very similar to soils 1 (2.04) and 14 (2.04). The slope of the equation ranged from 0.40 to 0.55. The highest slope (0.55) was observed in soil 1 and the lowest (0.40) was observed in soil 13. The lower R² value in the Freundlich equation than in the Langmuir equation for the studied soils shows that the P sorption affinity of these soils did not decrease logarithmically with increasing surface saturation (Mead, 1981).

Temkin adsorption isotherm

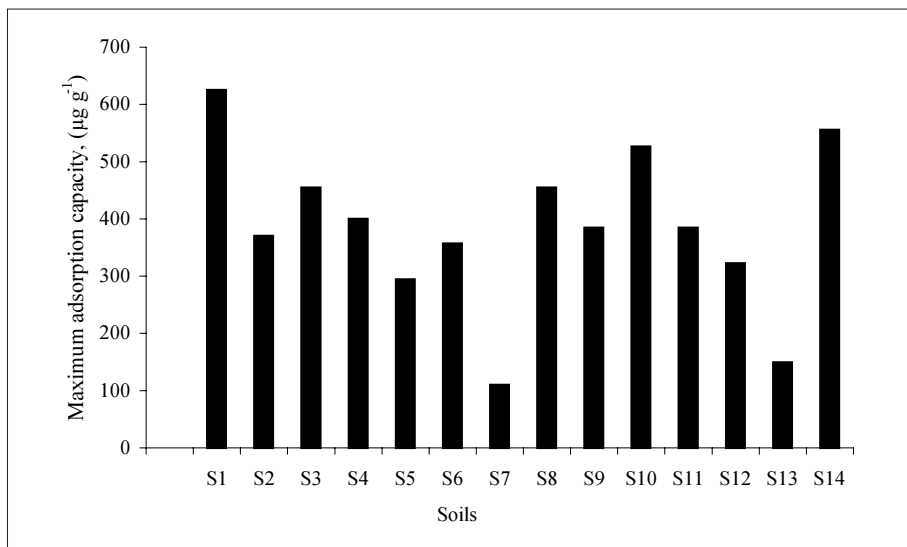
The Temkin adsorption isotherm was better fitted to the studied soils than the Freundlich adsorption isotherm (Table 6). With respect to the R² value of the equation, the Temkin adsorption isotherm was found to be better than the Freundlich adsorption isotherm. Among the fourteen soils, the R² values of five soils (soils 2, 6, 7, 8 and 9) ranged from 0.90 to 0.98, those of eight soils (soils 1, 3, 4, 5, 10, 11, 12 and 14) ranged from 0.84 to 0.90, and that of only one soil (soil 13) was outside these ranges, with an R² value of 0.67. The highest R² value (0.98) was observed in soil 8. The slope of the Temkin equation ranged from 14.03 (soil 7) to 68.79 (soil 1). The highest intercept value (267.31) was found in soil 1 and the lowest intercept value (53.48) was found in soil 7. Soil 13 was found to have the poorest fit for the Temkin adsorption isotherm, meaning that the adsorption capacity of the soil did not decrease linearly with increasing surface saturation.

Phosphorus adsorption maximum

The phosphorus adsorption maximum (S_{\max}) was calculated from the Langmuir adsorption isotherms, which showed that S_{\max} varied with the background P concentration of the soil (Fig. 1). The S_{\max} of

Table 6. Intercept, slope and R^2 for Temkin adsorption isotherms of different soils examined in this study.

Soil	Intercept	Slope	R^2
Soil 1	267.31	68.79	0.90
Soil 2	139.15	40.70	0.90
Soil 3	233.22	40.41	0.88
Soil 4	196.56	34.04	0.87
Soil 5	129.24	29.42	0.89
Soil 6	160.50	39.04	0.94
Soil 7	53.484	14.03	0.94
Soil 8	224.21	52.91	0.98
Soil 9	173.39	38.99	0.91
Soil 10	218.75	51.00	0.86
Soil 11	151.33	38.61	0.84
Soil 12	167.87	36.36	0.89
Soil 13	107.71	19.23	0.67
Soil 14	258.97	56.24	0.87

**Fig. 1.** Maximum phosphorus adsorption capacity (S_{max}) in fourteen northeastern acid piedmont rice soils of Bangladesh.

different soils varied from 110 to 625 $\mu\text{g g}^{-1}$. The highest S_{max} value (625 $\mu\text{g g}^{-1}$) was observed in soil 1, the lowest (110 $\mu\text{g g}^{-1}$) in soil 7. Due to the background P concentration, the maximum phosphorus adsorption capacities (S_{max}) of the different soils fell in the following descending order of soils number 1 (625 $\mu\text{g g}^{-1}$), 14 (556 $\mu\text{g g}^{-1}$), 10 (526 $\mu\text{g g}^{-1}$), 3 and 8 (455 $\mu\text{g g}^{-1}$), 4 (400 $\mu\text{g g}^{-1}$), 9 and 11 (385 $\mu\text{g g}^{-1}$), 2 (370 $\mu\text{g g}^{-1}$), 6 (357 $\mu\text{g g}^{-1}$), 12 (323 $\mu\text{g g}^{-1}$), 5 (294 $\mu\text{g g}^{-1}$), 13 (149 $\mu\text{g g}^{-1}$) and 7

($110 \mu\text{g g}^{-1}$).

Abedin and Saleque (1998) reported a P adsorption maximum of 450 mg kg^{-1} for BRRRI farm soil. Shil (2002) reported a lower P adsorption maximum (240 mg kg^{-1}) for the same soil because he limited the P sorption to 300 ppm of added P, compared to 1600 ppm in the present study. Harter (1984) has shown that the sorption maxima estimated by the Langmuir equation could be in error by more than 50% if the entire isotherm is not used in calculating the sorption parameters. Mehadi and Taylor (1988) obtained adsorption maxima of 233 mg kg^{-1} for virgin soil and 250 mg kg^{-1} for cultivated soil in the USA. Correlation analysis showed that soil reaction, organic carbon, and clay concentration did not significantly influence soil S_{max} . Masud (2003) found that S_{max} varied from 617 to $1481 \mu\text{g g}^{-1}$ for his 15 soils.

Adsorption energy

The energy of adsorption for phosphorus (binding energy) was calculated from the Langmuir adsorption isotherm (Eq. 2). The energy of adsorption was highest in soil 13 ($1.56 \mu\text{g ml}^{-1}$) and lowest in soil 11 ($0.18 \mu\text{g ml}^{-1}$) (Fig. 2). In fact, there was apparently a negative correlation between the energy of adsorption (k) and the S_{max} (b) values, which was observed in most of the soils we studied. A similar relationship between k and b values was also observed by Rao *et al.*, (1983), Abedin and Saleque (1998), and Islam (2003). Their studies revealed that the value of b decreases with increases in the value of k . Energy of adsorption expresses the binding energy required to adsorb phosphorus. Thus, a soil with greater energy of adsorption would have less P adsorption than a soil with low energy adsorption. In other words, the energy of adsorption is negatively correlated with the phosphorus adsorption maximum (S_{max}).

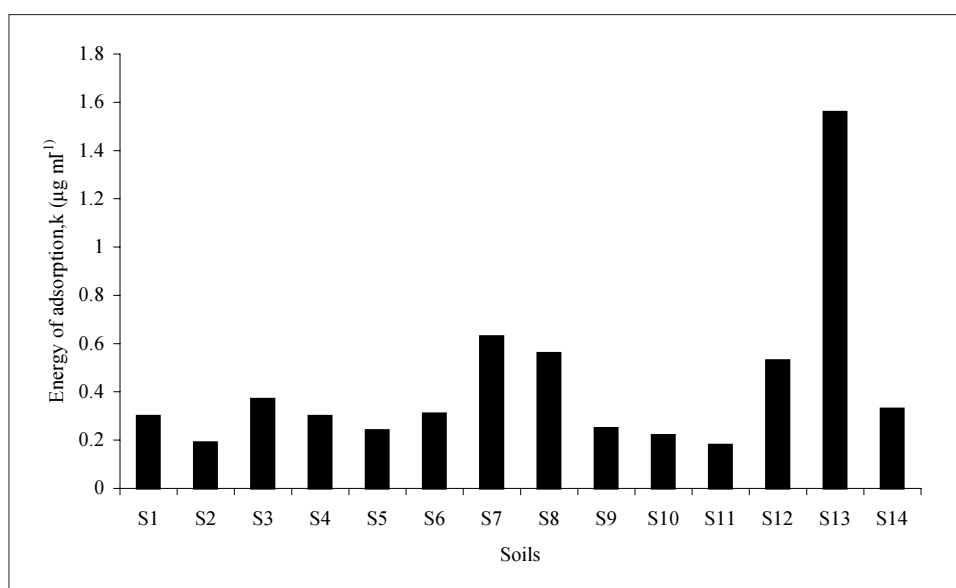


Fig. 2. Energy of P adsorption in fourteen northeastern acid piedmont rice soils of Bangladesh.

Buffering capacity

The P-buffering capacity of a soil is its capacity to resist a change in the P concentration of the solution phase (Sui and Thompson, 2000). The buffering capacities of the soils were calculated from the Temkin adsorption isotherms at a $1 \mu\text{g ml}^{-1}$ level of solution P. Buffering capacities ranged from 14.03 to 68.79 (Fig. 3). The highest buffering capacity was 68.79 (soil 1), the lowest 14.03 (soil 7). In most of the cases, the trend was almost identical to that observed for the maximum phosphorus adsorption capacity (S_{max}). The buffering capacity values of the tested soils differed greatly from one another. Only one soil (soil 1) was found with a value above 60 (68.79). Three soils with a buffering capacity between 50 and 60 were identified (Soils 8, 10, and 14). Five soils (Soils 2, 3, 6, 9, and 11) were very similar in buffering capacity, with values ranging from 38.61 to 40.70. The buffering capacity of two soils (Soils 12 and 4) ranged from 34.04 to 36.36. The buffering capacity of soil 5 was 29.42, while those of the other two soils (Soils 7 and 13) ranged below 20, relatively very low. The rate of P diffusion was related to buffering capacity. For soils in which the buffering capacity was higher, the diffusion rate of P would be lower.

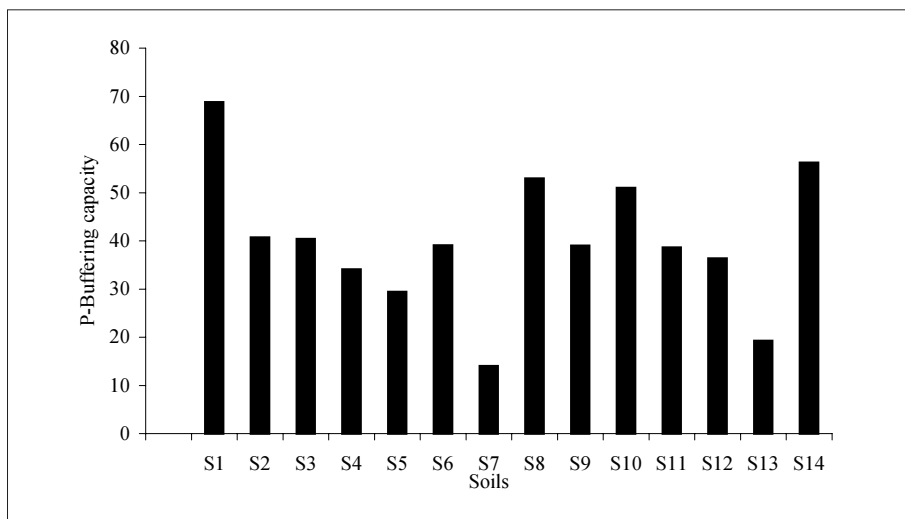


Fig. 3. Buffering capacity of phosphorus in fourteen northeastern acid piedmont rice soils of Bangladesh.

Phosphorus saturation indices

Phosphorus saturation (P_{sat}) was calculated from Mehlich-3 (M3) extractable P and maximum phosphorus adsorption capacity (S_{max}) (Sharpley, 1995). The P_{sat} values of different soils varied from 1.82 to 28.21% (Fig. 4). The highest P_{sat} value (28.21%) was observed in soil 7, the lowest (1.82%) in soil 9. Due to the concentration of Mehlich-3 extractable P and the maximum phosphorus adsorption capacity (S_{max}), the P_{sat} (%) values of the different soils descended in the following order: soil 7 (28.21), 2 (7.56), 11 (6.76), 14 (6.66), 3 (6.60), 1 (5.76), 12 (5.58), 4 (4.50), 6 (4.20), 5 (4.08), 8 (3.30), 10 (2.09), 13 (2.01) and 9 (1.82).

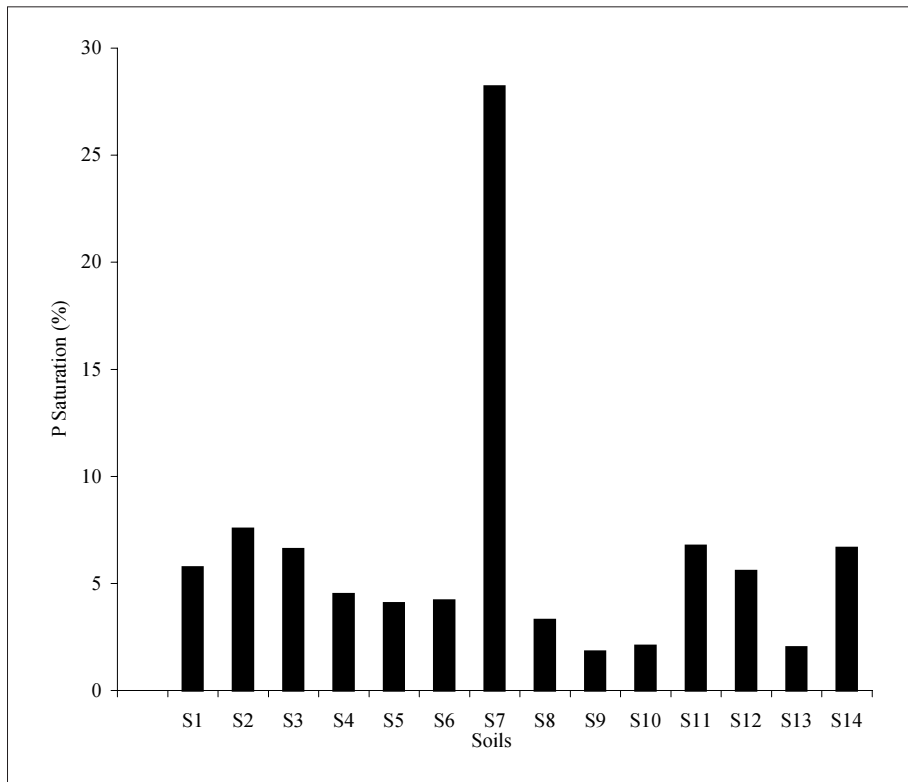


Fig. 4. Phosphorus saturation (%) in fourteen northeastern acid piedmont rice soils of Bangladesh.

A critical DPS (degree of P saturation) of 25% has been established for Dutch soils (Sharpley *et al.*, 1996). Above this limit, the risk of P losses via leaching and surface run-off becomes unacceptable to the Dutch government and further applications of manure may be prohibited. However, this method may not be applicable to high-pH soils, especially calcareous soils, because the carbonates in calcareous soils tend to neutralize the acidic extracting solution (Loeppert and Inskeep, 1996; Kleinman and Sharpley, 2002). Furthermore, Al and Fe oxides are less significant for P sorption in high pH soils than in acidic soils (Lindsay, 1979). In our tested samples, only soil 7 seems to have a P saturation above the critical level of 25%. The rest of the soils have much lower P saturations, where the application of P fertilizer or manure is safe from an environmental point of view.

Relationship between adsorption parameters and some soil parameters

The correlation between adsorption parameters and some soil properties is summarized in Table 7. The correlation study shows that sand correlates well with maximum adsorption capacity (S_{max}), buffering capacity, the intercept of the Freundlich adsorption isotherm, and phosphorus saturation (P_{sat}). Sand was negatively correlated with S_{max} ($r = -0.70$, $P < 0.01$), buffering capacity ($r = -0.78$, $P < 0.01$) and the intercept of the Freundlich adsorption isotherm (A) value ($r = -0.73$, $P < 0.01$). However, sand was positively

Table 7. Correlation coefficient (r) of adsorption parameters with soil properties.

	S_{\max}^1	K^2	BP^3	A^4	P_{sat}^5
Sand	-0.70**	0.29	-0.78**	-0.73**	0.56*
Silt	0.70**	-0.34	0.78**	0.70**	-0.59*
Clay	0.59*	-0.15	0.67**	0.68**	-0.42
pH _{KCl}	-0.64*	0.49	-0.62*	-0.50	0.24
pH _{H2O}	-0.14	0.22	-0.09	-0.06	-0.23
Δ pH	-0.08	-0.06	-0.12	-0.11	0.32
O.C	0.19	-0.41	0.20	0.09	0.07
Fe (D)	0.71**	-0.19	0.79**	0.63*	-0.16
Fe (M3)	-0.09	-0.07	-0.19	0.06	-0.07
S_{\max}	1.00	-0.58*	0.96**	0.88**	-0.46
k		1.00	-0.48	-0.32	0.04
BP			1.00	0.81**	-0.43
A				1.00	-0.70**
P_{sat}					1.00

¹Maximum adsorption capacity ($\mu\text{g g}^{-1}$), ²Energy of adsorption (g ml^{-1}),

³Buffering capacity, ⁴Intercept of Freundlich equation, ⁵P saturation (%)

* Significant at 5% level, ** Significant at 1% level.

correlated with P saturation ($r=0.56$, $P<0.05$). We found a good positive correlation of silt with S_{\max} ($r=0.70$, $P<0.01$), buffering capacity ($r=0.78$, $P<0.01$) and the intercept of the Freundlich adsorption isotherm ($r=0.70$, $P<0.01$), but a negative correlation with P_{sat} ($r=-0.59$, $P<0.05$). We also found a good positive correlation between clay content and S_{\max} ($r=0.59$, $P<0.05$), buffering capacity ($r=0.67$, $P<0.01$) and A value ($r=0.68$, $P<0.01$). We found pH_{KCl} to have a negative relationship with S_{\max} ($r=-0.64$, $P<0.05$) and buffering capacity ($r=-0.62$, $P<0.05$). pH_{H2O} and soil organic carbon did not show any linear correlation with the any of the adsorption parameters ($r<0.50$). Our results are similar to those of other researchers who reported nonsignificant relationships between soil pH and S_{\max} (Zhang *et al.*, 2005; Donor and Oya, 2000). The Fe_D concentration of soil showed a positive correlation with S_{\max} ($r=0.71$, $P<0.01$), buffering capacity ($r=0.79$, $P<0.01$), and with A ($r=0.63$, $P<0.05$), but Fe_{M3} did not show any linear relationship with P adsorption parameters or with P_{sat} ; this result was supported by Zhang *et al.*, 2005. Our results are similar to those of Tran *et al.* (1990), who did not find a relationship between Fe_{M3} and P adsorption in their study. Kleinman and Sharpley (2002) also reported an insignificant relationship between Fe_{M3} and S_{\max} .

The P adsorption parameters of the studied soils showed good relationships with one another. We found a negative correlation ($r=-0.58$, $P<0.05$) between the S_{\max} and k values observed for the studied soils. A similar relationship between maximum adsorption capacity and k value was also observed by Rao *et al.* (1983) and Abedin and Saleque (1998). In their study, they revealed that an increase in the value of k decreased the maximum adsorption capacity. The energy of adsorption expresses the binding energy required to adsorb phosphorus. Thus, a soil with high energy of adsorption would have less P adsorption than a soil with low energy of adsorption. Maximum adsorption capacity (S_{\max}) also showed a significant

positive relationship with buffering capacity ($r=0.96$, $P<0.01$) and the intercept of the Freundlich adsorption isotherm ($r=0.88$, $P<0.01$). The relationship between buffering capacity and the intercept of the Freundlich adsorption isotherm was also positive ($r=0.81$, $P<0.01$). Masud (2003) also observed a similar relationship between buffering capacity and the intercept of the Freundlich adsorption isotherm. A negative correlation between the intercept of the Freundlich adsorption isotherm and Phosphorus saturation indices (P_{sat}) was also found ($r=-0.70$, $P<0.01$).

Multiple relationship of P adsorption with soil properties

Mean maximum phosphorus adsorption capacity (S_{max}) was regressed with soil pH, sand, silt, clay, organic carbon (%) and $Fe_{(D)}$ stepwise, and multiple regression analysis was also done (Table 8). We can see from the table that the S_{max} of the tested soil samples had a good relationship with both pH_{KCl} and $Fe_{(D)}$, but not with the other soil properties. S_{max} decreased with increasing pH_{KCl} , and changes in pH_{KCl} explained about 41% of the change in S_{max} . The slope of the maximum phosphorus adsorption capacity decreased with increases in pH_{KCl} ; this relationship was statistically significant ($p<0.01$). A good relationship was found between S_{max} and $Fe_{(D)}$, one which indicated that S_{max} increases with increases in $Fe_{(D)}$. The R^2 value ($P<0.05$) of the equation was 0.50, indicating that $Fe_{(D)}$ predicts 50% of the variation in the maximum phosphorus adsorption capacity (S_{max}) of soil. The combined significant contribution of pH_{KCl} and $Fe_{(D)}$ to the maximum phosphorus adsorption capacity (S_{max}) was 63%, meaning that pH_{KCl} and $Fe_{(D)}$ together explain about 63% of the variation in S_{max} , and the remaining 37% of the variation may be accounted for by other soil variables.

Table 8. Stepwise multiple regression equations between maximum phosphorus adsorption capacity (S_{max}) and soil pH_{KCl} , dithionate extractant Fe

Variables	Regression equations	R^2	Prob.
pH_{KCl}	$S_{max} = 2673.6 - 583.7 pH_{KCl}$	0.41	0.013
Fe_D	$S_{max} = 160.5 + 0.46 Fe_D$	0.50	0.005
pH_{KCl} and Fe_D	$S_{max} = 1656.1 - 366.6 pH_{KCl}^* + 0.34 Fe_D^{**}$	0.63	0.05

* Significant at 5% level and ** Significant at 1% level of probability

Conclusion

Understanding the P sorption capacity of a soil can help to estimate the amount of P that a soil is capable of holding. Given the diversity in soil properties, the soils that we studied had differing P sorption capacities, energies of adsorption, and P buffering capacities. Soil properties (sand, silt and clay content), Fe_D , and pH_{KCl} were correlated with S_{max} , while soil pH_{H_2O} and organic carbon content were not ($p>0.05$). Multiple regression found that pH_{KCl} and Fe_D together were the two most important soil properties related to S_{max} in the soils we studied. The maximum P sorption capacity (S_{max}) varied from 110 mg g^{-1} to 625

mg g⁻¹ soil. The P buffering capacity of the soils varied from 14 to 68 at 1 ppm of the solution P. Similarly, the variation in the P adsorption energy of the soils ranged from 0.18 to 1.56 g mL⁻¹. These great variations in the P sorption characteristics of soils collected from the same region indicate that those in charge of P management ought to take a closer look at the soil rather than giving a general P management recommendation for crop production on a regional or AEZ basis. The soils that showed lower P buffering capacities may need more frequent application of P fertilizer than soils with relatively higher buffering capacities.

The phosphorus saturation indices (P_{sat}) of different soils varied from 1.82 to 28.21% and were significantly correlated with sand and silt, but not with the other soil properties soils we studied. Phosphorus saturation may prove useful in identifying soils with increased risk for P loss, and it provides useful information about the risk of run-off and P leaching. Therefore, the overapplication of P can be limited.

References

- Abedin, M. J. and M. A. Saleque. 1998. Effects of phosphorus fertilizer management on phosphorus sorption characteristics of lowland rice soil. *Thai. J. Agric. Sci.* **31**: 122-129.
- Amarasiri, S. L. and S. R. Olsen. 1973. Liming as related to solubility of P and plant growth in an acid tropical soil. *Soil Sci. Soc. Am. Proc.* **37**: 716-721.
- Barrow, N. J. 1987. Reaction with variable-charged soils. *Fert. Res.* **14**: 1-100.
- Bartolome, V. I., M. C. C. Carrasco, L. C. Quintana, M. I. B. Ferino, J. Z. Mojica, A. B. Olea, L. C. Paunlagui, C. G. Ramos, M. A. Ynalvez and C. G. McLaren. 1998. *Experimental design and data analysis for agricultural research*. Vol. 1. IRRI, Manila, Philippines.
- Beauchemin, S. and R. R. Simard. 1999. Soil phosphorus saturation degree: Review of some indices and their suitability for P management in Quebec, Canada. *Can. J. Soil Sci.* **79**: 615-625.
- Black, C. A., D. D. Evans, J. L. White, L. E. Ensminger and F. E. Clark. 1965. *Methods of soil analysis*. Part 2. Am. Soc. Agron. Ins. Publisher Madison, Wisconsin, USA.
- Chand, M., N. S. Randhawa and A. C. Vig. 1995. Phosphate adsorption characteristics of some benchmark soils of N-W India and their relationships with soil properties. *J. Indian Soc. Soil Sci.* **43**: 582-586.
- Donor, D.E. and K. Oya. 2000. Phosphate sorption characteristics of major soils in Okinawa, Japan. *Commun. Soil Sci. Plant Anal.* **31**: 277-288.
- Fontes, P. C. R. and G. E. Wilcox. 1983. Establishing sorption isotherm to meet phosphorous requirement of soils. *Soil Sci. Soc. Amer. Proc.* **34**: 902-907.
- Fox, R. L. and E. J. Kamphath. 1970. Phosphate sorption isotherms for evaluating the phosphorous requirement for soils. *Soil Sci. Soc. Amer. Proc.* **34**: 902-907.
- Friesen, D. K., A. S. R. Juo and M. H. Miller. 1980. Liming and lime-phosphate-zinc interactions in two Nigerian Ultisols: I. Interactions in the soil. *Soil Sci.* **27**: 307-314.
- Harter, R. D. 1984. Curve-fit errors in Langmuir adsorption Maxima. *Soil Sci. Soc. Am. J.* **48**: 749-752.
- Holford, I. C. R., R. W. M. Wedderburn and G. E. G. Mattingly. 1974. A Langmuir tow-Surface equation as a model for phosphate adsorption by soils. *J. Soil. Sci.* **25**: 242-255.
- Holford, I. C. R., C. Hird and R. Lawrie. 1997. Effects of animal effluents on the phosphorus sorption characteristics of soils. *Aust. J. Soil Res.* **35**: 365-373.
- Islam, R. M. 2003. Phosphorus chemistry in wetland rice soil profile of a Vertic Haplustept. M.S. thesis. Department of Soil Science, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Salna, Gazipur.
- Jackson, M. L. 1958. *Soil chemical analysis*. Constable and Co. Ltd. London.
- Kleinman, P. J. A. and A. N. Sharpley. 2002. Estimating phosphorus sorption saturation from Mehlich-3 data. *Commun. Soil Sci. Plant Anal.* **33**: 1825-1839.
- Lindsay, W. L. 1979. *Chemical equilibria in soils*. John Wiley & Sons, New York.

- Loeppert, R. L. and W. P. Inskeep. 1996. Iron. p. 639-664 *In* D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. ASA and SSSA, Madison, WI.
- Lopez-Hernandez, D. and C. P. Burnham. 1974. The effect of pH on phosphate adsorption in soils. *J. Soil Sci.* **25**: 207-216.
- Masud, M. M. 2003. Phosphorus sorption parameter of some rice soils of Bangladesh. M.S. thesis. Soil Science department. Bangladesh Agricultural University, Mymensingh.
- Mead, J. A. 1981. A comparison of the Langmuir, Freundlich and Temkin equations to describe phosphate adsorption properties of soils. *Australian J. Soil Res.* **19**: 333-342.
- Mehadi, A. A. and R. W. Taylor. 1988. Phosphate adsorption by two highly weathered soils. *Soil Sci. Soc. Am. J.* **52**: 627-632.
- Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of the Mehlich 2 extractant. *Commun. Soil Sci. Plant Anal.* **15**: 1409-1416.
- Mehra, O. P. and M. L. Jackson. 1960. Iron oxide removal from soils and clays by dithionite citrate system buffered with sodium bicarbonate. *Proc. 7th Nat. Conf. Clays and Clay Min.* Pergamon Press, New York. 317-327.
- Mokwunye, A. U. and S. H. Chien 1980. Myths and science of fertilizer use in the tropics. p. 121-134. *In* R. Lal and P.A. Sanchez (ed). *Myths and Science of Soils of the Tropics.* SSSA Spec. Pub. 29. SSSA, Madison, WI.
- Mokwunye, U. 1975. The influence of pH on the adsorption of phosphate by soils from Guinea and Sudan Savannah Zones of Nigeria. *Soil Sci. Soc. Am. Proc.* **39**: 1100-1102.
- Muljadi, D., A. M. Posner and J. P. Quirk. 1966. The mechanism of phosphate adsorption by kaolinite, gibbsite, and pseudoboehmite. *J. Soil Sci.* **17**: 212-228.
- Murphy, J. and J.P. Riley. 1962. A modified single solution method for determination of phosphate in natural waters. *Analytica chimica Acta.* **27**: 31-36.
- Nair, P. S., T. J. Logan, A. N. Sharpley, L. E. Sommers, M. A. Tabatabai and T. L. Yaun. 1984. Interlaboratory comparison of a standardized phosphorus adsorption isotherm procedure. *J. Environ. Qual.* **13**: 591-595.
- Nelson, D. W. and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. P.539-77. *In*:Page, A.L., Miller, R.H.,and D.R. Keeney (ed.). *Methods of soil analysis, Part 2. Chemical and Microbiological Properties* Second Edition. Madison, Wisconsin USA. nutrient distribution on vertisols. *J. Prod. Agric.* **7**: 364-373. nutrients in soil profiles. *J. Fert.. Issues* **2**: 86-90.
- Olsen, S.R., and F.S. Watanabe. 1957. A method to determine a phosphorus adsorption maximum of soil as measured by Langmuir isotherm. *Soil Sci. Soc. Am. Proc.* **21**: 144-149.
- Parfitt, R. L. 1977. Phosphate adsorption on an Oxisol. *Soil Sci. Soc. Am. J.* **41**: 1064-1067.
- Rao, A. S., Hasan, R. and A. B. Ghosh. 1983. Phosphate adsorption behaviour under continuous cropping and fertilizer use in an alluvial soil. *J. Indian Soc. Soil Sci.* **31**: 606-607.
- Saleque, M. A. and G. J. D. Kirk. 1995. Root-induced solubilization of phosphate in the rhizosphere of lowland rice. *New Phytol.* **129**: 325-336.
- Sharpley, A. N. 1996. Availability of residual phosphorus in manured soils. *Soil Sci. Soc. Am. J.* **60**: 1459-1466.
- Sharpley, A. N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. *J. Environ. Qual.* **24**: 920-926.
- Shil, N. C. 2002. Effect of organic manure on phosphorus availability in some soils of Bangladesh. M. S. Thesis. Bangabandhu Sheikh Mujibur Rahman Agricultural University, Salna, Gazipur. Department of Soil Science.
- Sibbesen, E., and A.N. Sharpley. 1997. Setting and justifying upper critical limits for phosphorus in soils. p. 151-176. *In* H. Tunney *et al.* (ed.) *Phosphorus loss from soil to water.* CAB International Press, Cambridge, UK.
- Sims, J. T. and Ellis. 1983. Adsorption and availability of phosphorus following the application by soils. *J. Sci. Soc.* **26**: 395-406.
- Sui, Y. and M. L. Thompson 2000. Phosphorus sorption, desorption and buffering capacity in a biosolids Amended Mollisol. *Soil Sci. Soc. Am. J.* **64**: 164-169.
- Syers, J.K., M.G. Brownman, G.W. Smillie, and R.B. Corey. 1973. Phosphate sorption by soils evaluated by the Langmuir adsorption equation. *Commun. Soil Sci. Plant Anal.* **33**: 117-141.
- Tran, T.S., M. Giroux, J. Guilbeault, and P. Audesse. 1990. Evaluation of Mehlich-III extractant to estimate the available P in Quebec soils. *Commun. Soil Sci. Plant Anal.* **21**: 1-28.
- White, R. E. and A. W. Taylor. 1977. Effect of pH on phosphate adsorption and isotopic exchange in acid soils at low and high additions of soluble phosphate. *J. Soil Sci.* **28**: 48-61.
- Zhang, H., J.L. Schroder, J.K. Fuhrman, N.T. Basta, D.E. Storm, and M.E. Payton. Path and Multiple Regression Analysis of Phosphorus Sorption Capacity. *Soil Sci. Soc. Am. J.* **69**: 96-106.