Phosphorus Sorption and Saturation in the Ganges Tidal Floodplain Soils of Bangladesh

(Serapan Fosforus dan Penepuan dalam Tanah Dataran Banjir Pasang Surut Ganges di Bangladesh)

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ABSTRACT

The soils developed from the Ganges sediments in the coastal area of Bangladesh and India extend several thousand hectares and important from the view point of rice cultivation. Phosphorus, one of the important environmental and agricultural element, retention behavior of the Ganges floodplain soils is poorly reported. The objective of this study was to determine maximum phosphorus adsorption capacity (MPAC) and to develop P_{sat} for 13 Ganges Tidal Floodplain soils of Bangladesh. The MPAC value and P_{sat} based on Mehlich-3 extractions were determined. The conventional adsorption equations, such as the Langmuir, Freudlich and Temkin equations were used to describe the P sorption of the studied soils. The MPAC value varied from 1250 to 2000 mg/kg and correlated with EC ($r = 0.59$, $p<0.05$) and CEC ($r = -0.74$, $P<0.01$). The sorption capacity of the tested soils ranged from 511 to 545 mg/kg and the calculated energy of adsorption of the soils varied from 0.192 to 1.00 µg/mL and it was a positively correlated with clay ($r=0.7$, $p<0.01$) and CEC ($r = 0.63$, $p<0.05$) but negatively with silt ($r= -0.80$, $p<0.01$), $pH_{(H2O)}$ ($r=-0.60$, $p<0.05$) and with MPAC ($r=-0.59$, $p<0.05$) values. Phosphorus saturation indices of the studied sample demonstrated a far below the threshold critical limit of 25%.

Keywords: Adsorption; Bangladesh; buffering capacity; Langmuir equation; phosphorus sorption

ABSTRAK

Tanah yang dibangunkan daripada enapan Ganges di pesisir pantai negara Bangladesh dan India menganjur beberapa ribu hektar dan penting daripada sudut pandangan penanaman padi. Fosforus, salah satu unsur penting dalam alam sekitar dan pertanian, tingkah laku penahanan di tanah dataran banjir Ganges telah dilaporkan secara tidak tepat. Objektif kajian ini adalah untuk menentukan kemampuan maksimum penjerapan fosforus (MPAC) dan untuk membangunkan P_{sat} bagi 13 tanah Dataran banjir air pasang surut Ganges di Bangladesh. Nilai MPAC dan P_{sat} berdasarkan pengekstrakan Mehlich-3 telah ditentukan. Persamaan penjerapan konvensional, seperti persamaan Langmuir, Freudlich dan Temkin telah digunakan untuk menggambarkan serapan P daripada tanah yang dikaji. Nilai MPAC berbeza-beza daripada 1250 kepada 2000 mg/kg dan berkorelasi dengan EC ($r = 0.59$, $p<0.05$) dan CEC ($r =-0.74$, $P<0.01$). Nilai kapasiti serapan tanah yang diuji adalah daripada 511 kepada 545 mg/kg dan tenaga yang dihitung daripada penjerapan tanah berbeza-beza daripada 0.192 kepada 1.00 µg/mL dan ia berkolerasi secara positif dengan tanah liat ($r= 0.7$, $p<0.01$) dan CEC ($r=0.63$, $p<0.05$) tetapi negatif dengan keladak ($r=-0.80$, $p<0.01$), $pH_{(H2O)}$ ($r=-0.60$, $p<0.05$) dan MPAC ($r=-0.59$, $p<0.05$). Indeks tepu fosforus sampel yang dikaji menunjukkan ia lebih rendah daripada had kritikal ambang 25%.

Kata kunci: Bangladesh; keupayaan penampanan; penjerapan; persamaan Langmuir; serapan fosforus

INTRODUCTION

Information on the behavior of phosphorus in soil is fundamental to understand the plant nutrition and soil biogeochemical cycle. Soil represents a temporary reservoir for phosphorus (P) in which its availability effects on plant growth and biological processes, such as litter decomposition and microbial activity (Wardle et al. 2004). In the developed countries, the use of phosphate fertilizers has declined since the last decades of the twentieth century; however, in the developing countries like Bangladesh, their use is continuously increasing, which results in increasing global consumption (Lair et al. 2009). In Bangladesh, the Ganges Tidal Floodplain region occupies 1706573 ha which covers about 11% of the total land of tidal floodplain soils (FRG 2005; Islam et al.

2015a). For plants in floodplain soils, periodical flooding is generally considered an environmental factor of major importance (Huber et al. 2009).

Phosphorus (P) adsorption of soils is important, because adsorbed phosphate equilibrates with P in soil solution and this P is the immediate source for plant. Phosphorus adsorption isotherm integrates P intensity; capacity and quantity parameters of soil and these factors play an important role in controlling the P-flux to roots of growing plants (Hoque et al. 2015). The sorption reactions of phosphorus in soil have been extensively studied for both agronomic and environmental purposes (Zhang et al. 2005). Phosphorus sorption isotherms are widely used to describe P sorption and desorption characteristics in soils and to predict the risk of P loss to fresh water (Zhou

& Li 2001). From the agronomic point of view, P that is strongly retained by soil make less available for plant uptake which is a great concern. On the other hand strong retention of P by soil may prevent losses of soluble P in runoff as well as movement to ground water which is beneficial for the environment. Thus, sorption and desorption reactions of P and the P-buffering capacities of soil may play an important role both in agronomic and environmental aspects of P management (Islam et al. 2010; Sui & Thompson 2000).

Phosphate sorption capacity of soils is a necessary component in the interpretation of soil test values as well as specific fertilizer recommendations (Hoque et al. 2015). The phosphorus sorption capacity of rice-growing soils in the Asian countries has so far received little attention, although the P availability of these soils changes tremendously with seasonal variations in temperature (Saleque et al. 2004). Several approaches have been reported for the estimation of P saturation (Kleinman & Sharpley 2002). Mehlich-3 extraction is widely used to assess the amount of P available to a plant during the growing season which works well in soils with a wide range of pH (Hoque et al. 2015; Mallarino 1997). The study area recently has been raised attention to public concern due to the extensive production of rice. To date, no scientific research regarding P adsorption and saturation issues in the study areas have been conducted so far. Therefore, the objectives of this study were therefore to quantify P adsorption capacity, bonding energy and other adsorption parameters of the Langmuir, Freundlich and Temkin models on the Ganges Tidal Floodplain soils of Bangladesh; to examine the relationship of these adsorption parameters with dominant soil properties.

MATERIALS AND METHODS

SITE DESCRIPTION AND SAMPLING

The sampling sites were located at Dumki and Kalapara area of Patuakhali district, Amtali area of Borguna district, Wuzirpur and Gouranadi area of Barisal district and Borhanuddin and Lalmohan area of Bhola district in Bangladesh (Figure 1). About one hundred thirty samples covering thirteen soil series were collected from cultivated rice fields (0-15 cm) during January and March 2008. The collected soil samples were air-dried and ground to pass a 2-mm sieve and then mixed to form a composite sample.

SOIL ANALYSIS

Soils were analyzed in the laboratory of Patuakhali Science and Technology University and regional laboratory of Soil Resources Development Institute, Dhaka, Bangladesh. The sand, silt and clay content of soils were determined using the hydrometer method (Islam et al. 2015b). Soil pH_{H2O} was measured in a 1:2.5 soil water ratio, using glass electrode pH meter method (Islam et al. 2014) and the pH_{KCl} was
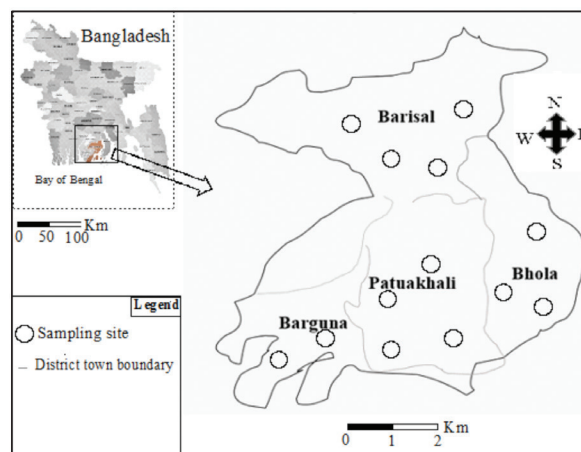

FIGURE 1. Map of the study area in the southern part of Bangladesh

also measured by using a 1.0 M KCl in a similar manner as in pH_{H2O} determination. Organic carbon of soil was determined by Walkley and Black wet digestion method as outlined by Nelson and Sommers (1982). Mehlich-3 (M3) extractable P was determined by using the Mehlich-3 extraction method (Mehlich 1984). Available Fe was determined by Sodium dithionate-citrate system buffered with sodium bicarbonate (Mehra & Jackson 1960).

PHOSPHORUS SORPTION

Phosphorus sorption isotherms were constructed using the standardized phosphorus adsorption isotherm procedure (Manning et al. 2006). Briefly one gram of the soil sample was taken in 25 mL test-tube with various addition of P (0, 1, 3, 6, 12, 18, 24, 30, 37, 43, 55, 68 and 80 ppm) in 20 mL of 0.01M $CaCl_2$ solutions separately. The resultant P content was 0, 20, 60, 120, 240, 360, 480, 600, 740, 860, 1100, 1360 and 1600 mg kg^{-1}. The test tubes were shaken for 24 h on horizontal shaker with low oscillation. The suspensions were centrifuged (2200 g×30 min) and the supernatants decanted and filtered (< 0.45 μm). The pH values of the equilibrium solutions were recorded. Phosphorus in solution was determined spectrophotometrically using the molybdenum blue method (Murphy & Riley 1962). The retained P concentration (P_{sorbed}) was calculated as the difference between the initial amount of P added and the amount in the equilibrium solution (C_e). KCl-extractable P in the original soil ($C_{e\ P0}$) was subtracted from the equilibrium concentrations after P sorption (Lair et al. 2009). The equilibrium P concentration data were interpreted following equations:

The Langmuir adsorption equation is given by:

$$C/(x/m) = 1/kb + C/b \qquad (1)$$

where C is the equilibrium P concentration (mg L^{-1}); x/m is the mg P sorbed per kg soil; b is the adsorption maxima

(the 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.

Freundlich equation is described by,

$$x/m = aC^b \qquad (2)$$

By taking log in both sides, the equation becomes

$$log\ (x/m) = log\ a + blogC$$

where x/m is mg of P adsorbed per kg 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 leads to calculate a and b from the intercept and slope, respectively.

The form of Temkin equation is,

$$x/m = a + blnC \qquad (3)$$

where x/m is the amount of P adsorbed on unit mass of adsorbent (mg/kg); C is the equilibrium P concentration (mg L^{-1}) and a and b are constant. A plot of x/m against lnC gives a straight line. The b of the equation (3) is considered as the P buffering capacity.

STATISTICAL ANALYSIS

All measurements of P were done in duplicate and data were analyzed by ANOVA using the statistical software IRRISTAT 4.1 (Windows version: Bartolome et al. 1998).

RESULTS AND DISCUSSION

PHYSICOCHEMICAL PROPERTIES OF SOIL

The physical and chemical characteristics of the studied soils are presented in Table 1. The particle size distribution showed that the texture of the soils were silty clay loam, silty clay and clay. Silt and clay fractions are dominated over the sand fraction in the studied soils. This is typical for the parent materials of delta tidal floodplain soils because larger particles, including most of the sand fraction are deposited further upstream and many of the remaining fine particles (silt and clay) are deposited in the floodplain area due to the back-and-forth movement of water in the tidal zone (Saleque et al. 2010). The soils were slightly acidic to moderately alkaline. Extreme acidity (pH < 5) was found in some soils, indicating that the soils were probably acid sulfate. Some soils showed an alkaline soil reaction, presumably resulting from repeated equilibration with surface waters and ground waters (Hoque et al. 2011). Organic carbon status of tested 13 coastal soils ranged from 0.71% to 10.86% which is much more than other parts of Bangladesh (Hoque et al. 2011). The water logging of delta soils might reduce organic matter decomposition, causing higher organic matter concentrations than in other soils of Bangladesh (Saleque et al. 2010). Although the organic carbon content of the soil was generally low, Satla soil series had the highest value of 10.86% (Table 1). The pH values for most of the soils were acidic which can be due to the decomposition of organic matter and subsequent formation of carbonic acid (Islam et al. 2014, 2015b). Higher soil acidity (lower pH values) favors the availability of cations in soil (Adeniyi et al. 2008; Islam et al. 2014).

PHOSPHORUS SORPTION

The mean solution concentrations and adsorption of P due to the effects of different soils and P concentrations are presented in Table 2. 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 of P sorption (545 mg/kg) was found in soil no. 1 (Barisal series of PSTU farm) and the lowest (511 mg/kg) in soil 13 (Barisal series of Barisal) (Table 2). The mean solution P concentration (due to the high amount of P application) varied significantly ($P <$

TABLE 1. Initial soil properties of the test soil for the sorption study

Soil No.	Sand (%)	Silt (%)	Clay (%)	Textural class	EC (dS/m)	pH (H_2O)	pH (KCl)	ΔpH	CEC (meq/ 100 g soil)	O.C (%)	Available P (M3) (ppm)	Available Fe (μ g/g soil)
Soil 1	3.30	28.16	68.54	Clay	1.45	6.20	4.58	-1.62	16.5	2.28	4.1	158.95
Soil 2	3.33	38.17	58.50	Clay	2.50	5.90	4.71	-1.19	14.0	2.69	5.2	118.75
Soil 3	4.26	54.27	41.47	Silty clay	6.15	5.80	4.94	-0.86	12.4	2.45	10.7	131.96
Soil 4	4.32	70.95	24.73	Silty clay loam	7.60	7.00	7.75	0.75	9.4	0.71	22.6	16.33
Soil 5	3.70	73.70	22.60	Silty clay loam	3.80	7.50	7.63	0.13	10.5	0.93	13.3	17.17
Soil 6	8.48	54.67	36.85	Silty clay loam	1.16	7.36	6.25	-1.11	12.1	1.40	5.3	98.44
Soil 7	8.00	68.72	23.28	Silt loam	1.23	7.49	5.97	-1.52	10.0	1.43	16.5	79.21
Soil 8	7.13	40.02	52.85	Clay	1.26	5.99	3.76	-2.23	13.4	0.74	4.3	253.10
Soil 9	7.81	37.27	54.92	Clay	1.23	5.70	7.04	1.34	15.5	2.49	6.1	248.43
Soil 10	16.87	55.67	27.46	Silty clay loam	2.11	6.30	5.27	-1.03	15.6	5.14	8.5	157.73
Soil 11	19.50	48.32	32.18	Silty clay	4.18	5.90	4.82	-1.08	15.4	10.86	6.0	494.74
Soil 12	10.81	45.29	43.90	Silty clay	0.98	6.10	4.68	-1.42	14.9	2.07	8.3	258.76
Soil 13	3.02	41.47	55.51	Clay	1.05	6.60	5.38	-1.22	16.3	2.91	19.9	185.42

TABLE 2. Phosphorus adsorption, solution P concentration and pH of the aliquot
in some Ganges Tidal Floodplain soils

Variable	N (Number of observation)	P adsorption (mg kg^{-1})	Solution P (mg L^{-1})
Soil			
Soil 1	26	545	35
Soil 2	26	521	51
Soil 3	26	532	48
Soil 4	26	514	57
Soil 5	26	537	43
Soil 6	26	527	53
Soil 7	26	523	57
Soil 8	26	544	36
Soil 9	26	545	35
Soil 10	26	529	52
Soil 11	26	523	54
Soil 12	26	535	45
Soil 13	26	511	69
LSD$_{0.05}$		5.35	1.23
Phosphorus (ppm)			
0	26	0.00	0.01
1	26	20	0.06
3	26	50	0.45
6	26	118	1.66
12	26	233	7.02
18	26	344	16.24
24	26	455	25.37
30	26	559	40.88
37	26	687	53.44
43	26	787	72.60
55	26	993	107.11
68	26	1227	132.57
80	26	1424	176.05
LSD$_{0.05}$		5.35	1.23
	df		
Replication	1	0.65	0.67
Soil (S)	12	*P<0.001*	*P<0.001*
Phosphorus (P)	12	*P<0.001*	*P<0.001*
S X P	144	*P<0.001*	*P<0.001*
Residual	168		

df = Degree of freedom

0.001) in different soils. The highest P concentration value of 69 mg/kg solution P was found in soil 13, while the lowest concentration of 35 mg/kg, was observed in soil no. 1 and soil 9 (Jhalakhati series). The second highest value (57 mg/kg) of solution P concentration was found in soil 4 (Nilkamal series) and soil 7 (Katra series) followed by 54 mg/kg in soil 11 (Satla series), 53 mg/kg in soil 6 (Ramgati series), 52 mg/kg in soil 10 (Harta series) and 51 mg/kg in soil 2. Phosphorus sorption of soils was greatly influenced by soil pH (Rupa et al. 2001). The sorption of P decreases with the increases in soil pH within the acidic range (Islam et al. 2007). There is also some evidence to show that phosphate sorption decreases with increases in soil pH up to 5.0 - 6.0, beyond which it increases due to

the difference in the exchangeable Al values of the soils (Lair et al. 2009).

The Langmuir, Freundlich and Temkin adsorption isotherm explains the adsorption maxima and energy of adsorption of a soil and values are presented in Table 3. The Langmuir equations were found well to explain the P adsorption in most soils where the R^2 value ranged from 0.6707 to 0.9595. The highest value of R^2 (0.9595) was observed in soil no. 9 and the lowest 0.6707 was in soil 7. The good fit of the Langmuir adsorption isotherm explain that the sorption affinity of soils remaining constant with increasing surface saturation (Wang et al. 2008). Mehadi and Taylor (1988) reported that P adsorbed basically with energy of adsorption and might explain the good

fit to the linear Langmuir equation. The R² value of the Freundlich equation was more than 0.9469 for the studied soils and ranged from 0.9469 to 0.990. The highest R² value (0.990) was observed in soil 1 and the lowest was in the soil 8. The Freundlich model had a good description of the sorption data, given by significantly high coefficient of determination (R² = 0.9469 to 0.990) of different studied soils (Table 3). The higher value of R² in Feundlich equation than in the Langmuir equation in the studied soils explained that the P sorption affinity of these soils decreased logarithmically with increasing of surface saturation (Islam et al. 2007). The slope of the Temkin equation ranged from 111.00 (soil 2) to 243.19 (soil 5). The intercept ranged from 521.05 to 761.75. Soil 4 was found to fit the poorest for the Temkin adsorption isotherm, meaning to say that the adsorption capacity of the soil did not decrease linearly with the increasing surface saturation (Islam et al. 2007). These results are in line with the findings of Babou et al. (2007) and Nizam et al. (2008).

MAXIMUM PHOSPHORUS ADSORPTION CAPACITY (MPAC)

Maximum phosphorus adsorption capacity (MPAC) was calculated from the Langmuir adsorption isotherm, which showed that the MPAC varied with the background of P concentration of soil (Figure 2). The MPAC of different soils varied from 1250 to 2000 mg/kg. The highest value of MPAC (2000 mg/kg) was observed in soil 4 and the lowest 1250 mg/kg was found in soil 13. Islam et al. (2007) observed the maximum P adsorption of 110 to 625 mg/kg for 14 acid piedmont soils of Bangladesh. Adsorption maxima of 233 mg/kg for virgin soil and 250 mg/kg for cultivated soil in the USA were observed by Mehadi and Taylor (1988). Harter (1984) has showed 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 sorption parameters. Correlation studies showed that neither soil reaction, organic carbon nor the clay concentration influence the MPAC of soil significantly.

TABLE 3. Intercept, slope, maximum adsorption capacity, binding energy and R² for Langmuir, Freundlich and Temkin adsorption isotherm in different soils

|	Langmuir adsorption isotherm			Freundlich adsorption isotherm			Temkin adsorption isotherm		
Soil	Intercept	Slope	R²	Intercept	Slope	R²	Intercept	Slope	R²
1	0.0008	0.0007	0.9449	2.788	0.38	0.99	748.82	194.53	0.83
2	0.0012	0.0007	0.8105	2.6555	0.4234	0.9795	662.77	111	0.7
3	0.0017	0.0006	0.7964	2.6176	0.5039	0.9738	600.12	196.82	0.72
4	0.0026	0.0005	0.8368	2.4611	0.7019	0.9812	521.05	213.4	0.75
5	0.0016	0.0006	0.7953	2.6032	0.6007	0.9818	589.55	243.19	0.76
6	0.0017	0.0007	0.7819	2.6319	0.4239	0.9656	609.33	160.71	0.68
7	0.0025	0.0006	0.6707	2.4956	0.6057	0.9816	569.77	149.36	0.68
8	0.0007	0.0007	0.852	2.7384	0.4558	0.9469	738.8	140.44	0.78
9	0.0007	0.0007	0.9595	2.7989	0.3698	0.9819	761.75	190.9	0.84
10	0.0014	0.0007	0.8346	2.6743	0.3757	0.9699	646.2	142.84	0.69
11	0.0012	0.0007	0.8577	2.6412	0.4566	0.9809	645.91	139.81	0.75
12	0.0013	0.0006	0.9068	2.6934	0.4411	0.9815	633.98	222.16	0.82
13	0.0017	0.0008	0.812	2.5578	0.4799	0.964	576.88	145.46	0.75
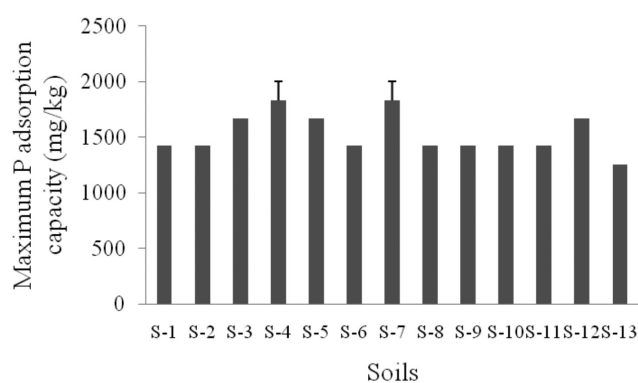
FIGURE 2. Maximum phosphorus adsorption capacity (MPAC) in thirteen Ganges Tidal Floodplain (Bars represent the standard error)

ADSORPTION ENERGY

The energy of adsorption was highest in soil 8 and 9 which was 1.00 µg/g and the lowest was 0.192 µg/mL in soil 4 (Figure 3). In fact, there was apparently a negative correlation (r = -0.59; $p < 0.05$) (Table 4) between the energy of adsorption (k) and the maximum phosphorus adsorption capacity (MPAC, b) values observed in the most of the studied soils. Similar relationship between k and b values was also observed by Abedin and Saleque (1998); Islam (2003); Islam et al. (2007). In their study they revealed that the increase of k values decreases the b value. The energy of adsorption expresses the binding energy required to adsorb phosphorus. Thus, a soil with lower energy of adsorption showed high P adsorption capacity compared to a soil with high energy of adsorption.

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

& Thompson 2000). The range of buffering capacity was from 111.00 to 243.19 (Figure 4). The highest buffering capacity (243.19) was observed in soil 5 and the lowest (111.00) was found in soil 2. In most of the cases, the trend was almost similar which was observed in the maximum phosphorus adsorption capacity (Figure 4). Buffering capacity of three soils was found above 200, which were 213.40 (S4), 222.16 (S12) and 243.19 (S5). In between 150-200, buffering capacity, four soils (S1, S3, S6, S9,) were identified. The buffering capacity of three soils (S7, S10, and S13) ranged from 142.84 to 149.36.

PHOSPHORUS SATURATION

Water extractable P (PH$_2$O) was used as the index of soil P to evaluate runoff losses in many studies (Davis et al. 2005; Ige et al. 2005). Phosphorus saturation (P$_{sat}$) was calculated from Mehlich-3 (M3) extractable P and maximum phosphorus adsorption capacity (MPAC). The P$_{sat}$ of different soils varied from 0.27 to 1.59% (Figure
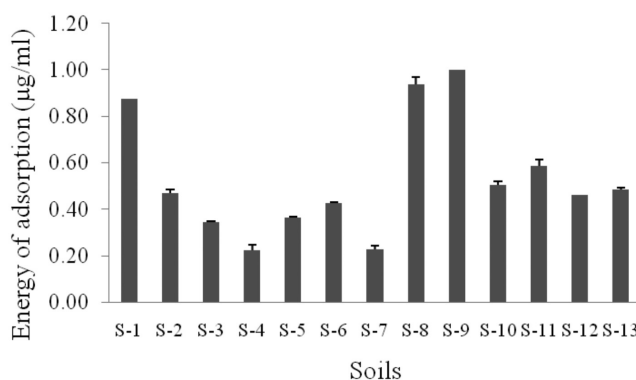

FIGURE 3. Energy of P adsorption in thirteen Ganges Tidal Floodplain soils of Bangladesh (Bars represent the standard error)

TABLE 4. Correlation coefficient (r) of adsorption parameters with soil properties

	MAC[1]	K[2]	BC[3]	A[4]	P$_{sat}$
Sand (%)	-0.39	0.04	-0.28	0.14	-0.30
Silt (%)	0.50	-0.80**	0.35	-0.77**	0.44
Clay (%)	-0.33	0.72**	-0.23	0.66**	-0.30
EC(dS/m)	0.59*	-0.49	0.34	-0.50	0.22
CEC(me/100 g soil)	-0.74**	0.63*	-0.31	0.69**	-0.26
pH (H$_2$O)	0.32	-0.60*	0.27	-0.62*	0.46
pH (KCl)	0.36	-0.19	0.61*	-0.21	0.36
△pH	-0.14	-0.24	-0.42	-0.21	-0.06
O.C (%)	-0.41	0.08	-0.39	0.11	-0.17
Fe (D)	-0.36	0.49	-0.33	0.45	-0.35
Fe (M3)	-0.34	0.32	-0.23	0.26	-0.08
MAC	1.00	-0.59*	0.60*	-0.54*	0.21
K		1.00	-0.21	0.89**	-0.58*
BC			1	-0.85**	0.10
A				1.00	-0.75**
P$_{sat}$					1

[1]Maximum adsorption capacity (MAC), [2]Energy of adsorption, [3]Buffering capacity, [4]Intercept of Freundlich equation
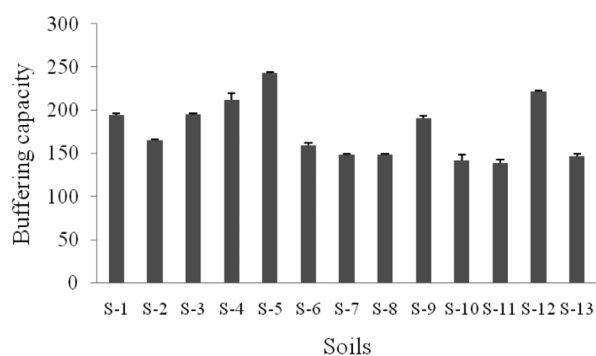*Significant at 5% level, ** Significant at 1% level

FIGURE 4. Buffering capacity of phosphorus in thirteen Ganges Tidal Floodplain soils of Bangladesh (Bars indicate the standard error)

5). The highest value of P_{sat} 1.59% was observed in soil 13 and the lowest 0.27% was observed in soil 1 due to the concentration of Mehlich-3 extractable P. 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 & Simard 1999). A critical DPS (degree of saturation) of 25% has been established for Dutch soils (Sharpley 1996). Above this limit, the risk of P losses to leaching and surface runoff become unacceptable to the Dutch Government and further applications of manure may be prohibited. In our tested samples, none of the soil seems to have P saturation of above the critical level of 25%. All of the tested soils have much low P saturation, where the application of P fertilizer or manure is safe from environmental point of view.
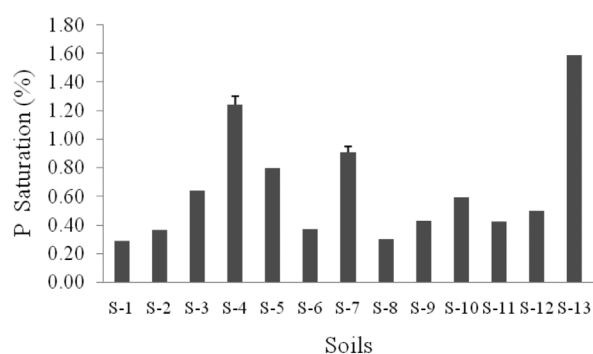

FIGURE 5. Phosphorus saturation (%) in thirteen Ganges Tidal Floodplain soils of Bangladesh (Bars represent the standard error)

PHOSPHORUS ADSORPTION BEHAVIOR

Correlation of adsorption parameters with some soils properties are presented in Table 4. The correlation study showed that silt had good negative correlation with energy of adsorption and intercept of the Freundlich adsorption isotherm. The correlation coefficient (r) between silt and energy of adsorption was -0.80, $P < 0.01$ and -0.77, $P < 0.01$, respectively. A good and positive correlation of

clay was observed with energy of adsorption (r = 0.72, $P < 0.01$) and with intercept of the Freundlich adsorption isotherm. A good positive correlation of cation exchange capacity (CEC) with energy of adsorption (r = 0.63, $P < 0.05$) and intercept of the Freundlich adsorption isotherm (r = 0.66, $P < 0.01$) was observed. CEC was also negatively correlated with maximum adsorption capacity (r = -0.74, $P < 0.01$) (Table 4). A negative correlation was observed with energy of adsorption (r = -0.60, $P < 0.05$) and intercept of the Freundlich adsorption isotherm (r = -0.62, $P < 0.05$). Sand, $pH_{(KCl)}$, ΔpH, and organic carbon did not show any significant correlation with any of the adsorption parameters of P, which reflects its low affinity for anions due to negative surface charges in the pH range of the studied soils. These results are similar to those of other investigators (Islam et al. 2007; Zhang et al. 2005) did not found any significant relations between soil pH and maximum P adsorption capacity. $Fe_{(D)}$ and $Fe_{(M3)}$ also did not show any relationship with any of the adsorption parameters or with P saturation; these results were supported by Zhang et al. (2005) and Islam et al. (2007) where they did not found any significant relationship between $Fe_{(M3)}$ and maximum P adsorption capacity. Litaor et al. (2005) stated that maximum P adsorption capacity obtained from Langmuir equation did not correlate well with most of the soil properties.

The adsorption parameters of the studied soils showed good relationship with each other. There was a negative correlation (r = -0.59, $P < 0.05$) between MAC and k values observed in the studied soils. Similar relationship between maximum adsorption capacity and k value was also observed by Abedin and Saleque (1998) and Islam et al. (2007). In their study, they revealed that the increased of k value decreased the maximum adsorption capacity. The maximum adsorption capacity also showed significant positive relationship with buffering capacity (r = 0.60, $P < 0.05$) and negative relationship with energy of adsorption (r = -0.59, $P < 0.05$) and with intercept of the Freundlich adsorption isotherm (r = -0.54, $P < 0.05$) and these results are in agreement with the results of Islam et al. (2007). The relation between energy of adsorption and intercept of the Freundlich adsorption isotherm was positive (r = 0.89, $P < 0.01$) but it was negatively correlated (r = -0.58, $P < 0.05$) with P saturation. The correlation between soil properties and sorption equation constants indicated that soil texture, crystalline and amorphous forms of Al and Fe forms play a vital role in P sorption characteristics of the soils influencing buffering capacity and maintaining optimum soil solution P concentration for sustainable crop production.

CONCLUSION

For the sustainable management of phosphorus it is important to understand the behavior of P in agroecosystems. Energy of adsorption and intercept of Freundlich equation was correlated with soil properties (silt and clay content,

TABLE S1. Location and description of the studied Ganges Tidal Floodplain soil samples

Designation	Farmer and Village	Upazilla and District	USDA Soil Family	Soil Series
Soil 1	PSTU farm	Dumki, Patuakhali	TypicEdoaquept	Barisal
Soil 2	AbddusSattar Zalisha	Dumki, Patuakhali	TypicHaplaquept	Jhalakhati
Soil 3	Ajit Kumar Kutba	Borhanuddin Bhola	AericHaplaquept	Bhola
Soil 4	Mazibur Rahman Gazipur	Borhanuddin Bhola	TypicHaplaquept	Nilkamal
Soil 5	Amin Ali Badarpur	Lalmohan Bhola	TypicHaplaquept	Nilkamal
Soil 6	ManikHowlader Patabania	Dumki, Patuakhali	TypicEdoaquept	Ramgati
Soil 7	GolamMostafa Moradia	Dumki, Patuakhali	TypicFluvaquept	Katra
Soil 8	Anil Kumar Das Rajnagar	Bhauphal Patuakhali	TypicHaplaquept	Barisal
Soil 9	Kabirul Islam Amragasia	Mirzajang Patuakhali	TypicHaplaquept	Jhalakhati
Soil 10	Musa Mia Borakuta	Wzirpur Barisal	Thapto-Histic Haplaquept	Harta
Soil 11	Mizanur Rahman Uttar shatla	Wzirpur Barisal	Histosols	Satla
Soil 12	MozammelHaq Barthy	Gournandi Barisal	Aquic Eutrochrept	Sara
Soil 13	BRRI, Regional Station, Sagardi	BarisalSadar Barisal	Typic Haplaquept	Barisal

CEC and pH_{H2O}) but not with other soil properties. The maximum P sorption capacity varied from 1250 to 2000 mg/kg and the P adsorption energy of the soils ranged from 0.19 to 1.00 µg/mL. Similarly, the P buffering capacity of the studied soils varied from 111 to 243. The P saturation indices (P_{sat}) of different tested soils ranged from 0.27 to 1.59%. Phosphorus saturation provides useful information about the risk of P run-off and P leaching and it may helpful in identifying soils with increased risk for P loss. Thus, the over application of P fertilizer can be limited. Therefore, we need in-depth future research on P chemistry and P fertility of the soil of this region.

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