Agropedology 2014, 24 (01), 82-94

Soil maturity assessment along a toposequence in Chotanagpur Plateau, West Bengal using inorganic soil phosphorus based weathering index, soil taxonomy and other chemical indices: A comparative study

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Abstract: Different forms of inorganic soil phosphorus were characterized in relation to soil properties in five pedons belonging to Entisols, Inceptisols and Alfisols, occurring along a toposequence in hot dry subhumid agroecological subregion (AESR 12.3) of West Bengal, falling under Chotanagpur plateau region. Based upon overall Profile Weighted Mean (PWM) values maximum amount of phosphorus was found to be in the form of Reductant Soluble Phosphate (RS-P) [95.8 mg kg^{-1}] while minimum amount was in the form of Saloid Phosphate (S-P) [1.7 mg kg^{-1}] contributing 27.6% and 0.5% to total phosphorus content respectively. Sequential extraction of various soil inorganic phosphorus fractions revealed that the mean relative abundance of inorganic phosphorus followed the order as : RS-P > Fe-P> Ca-P>Al-P ˜ occluded P> S-P. The overall relative abundance of the different inorganic phosphorus fractions in terms of their average ratios were found to be S-P(0.1) : Al-P(1.0) : Fe-P(2.4) : Ca-P(1.2) : RS-P(6.9) : Occluded-P (1.0). PWM - total P content revealed that the soils were fairly rich in phosphorus reserve ranging from 421.6 mg kg^{-1} to 287.6 mg kg^{-1} with an overall mean of 347.1 mg kg^{-1}. A close relationship between total P and different forms of soil inorganic phosphorus suggested the existence of an equilibrium between the former and the later. Overall collective contribution of all the inorganic soil phosphorus fractions to total P was found to be in the tune of 50.6%. The study reconfirmed the poor P-fertility status of the study soils.

Additional key words: *Inorganic soil phosphorus, sequential extraction, weathering index (WI), relative abundance, P-fertility, agro-ecological subregion, toposequence*

Introduction

The interpretation of phosphorus transformation with soil development and landscape position is often complicated by intense weathering, variable leaching and colluvial mixing that result from the complex interaction of lithology, weathering and colluvial, action in hot dry subhumid environment of varying slope, annual moisture deficit and intense rainfall (Agbenin and Tiessen 1995). The importance of soil phosphorus as an indicator of soil weathering have been reported by several workers (Smeck 1976; Uriyo and Kessaba 1973; Puranik *et* *al*. 1979; Singh *et al*. 2003) which tend to change inorganic P-forms from a more soluble Ca-P to less soluble Fe-P and Al-P. It has also been reported that variation in phosphorus fraction is a function of pedogenic manifestation (Walkers and Syers, 1976), stage of soil development (Smeck 1976; Chang and Jackson 1958) and age of the soils (Birkland 1984). Transformation of phosphorus from one form to the other occurs as weathering proceed from younger to older stage (Harrison 1994). As soil maturity increases the Ca-P gets transformed into Al-P (Fenton 1983) and sesquoxide bound phosphorus (Ibia and Ido 1983). Puranik *et al*. (1979) proposed a useful index of pedogenetic weathering process based upon inorganic phosphorus fractions which was in good agreement with the study on weathering conducted by Chang and Jackson (1958). Mandal (2007) further re-confirmed the validity of the proposed index in West Bengal Soils.

Tiwari (2002) reported inorganic phosphorus to be the dominant part of total soil phosphorus in rice growing soils of West Bengal. However database on IP fractions pertaining to the part of the state falling under Hot dry subhumid agro-ecological subregion (AESR 12.3) (Velayutham *et al.* 1999) *i.e*. under the Chotanagpur Plateau Region (CNP) is meager, perhaps due to the tedious analytical methodology required for accurate and precise estimation of the same. Moreover the CNP is reported to be generally low to medium in soil fertility status manifested by major soil related constraints *viz*. soil erosion, soil acidity, deficiency of major and micronutrients, richness in hydrated oxide of iron and aluminium leading to P-fixation thereby resulting in nutrient imbalance particularly for the red and lateritic soils (Sarkar 2002).

The distribution of different forms of iron oxides may be used as an indicator of soil development (Arduino *et al*. 1986) and has been used as a criterion in interpreting soil formation processes (McKeague and Day 1966; Blume and Schwertmann 1969). Schwertmann (1985) reported iron oxides to be most abundant oxides in most soils and are sensitive indicators of pedogenic environment. Such oxides exist in the tropical soils mainly in the form of amorphous and crystalline inorganic oxides with a little portion in the form of organic complexes. Nayak *et al*. (2002) reported the crystallization of iron oxides as a major process of soil genesis in tropical and subtropical climate and therefore the ratio Fe_o/Fe_d (active iron ratio) is often used as a relative measure of the degree of ageing. Sharma *et al*. (1996), Shyampura *et al*. (1993), Gawande and Biswas (1967) have also reported the use of molar silica – sesquioxide ratio as an index of soil weathering from pedogenic consideration.

In view of the afore stated fact the objectives of the present investigation are (1) to determine the molar silica-sesquioxide ratio and active iron ratio for evaluating soil maturity along a toposequence in hot, dry subhumid agro-ecological subregion of West Bengal (I1) to determine the trend in distribution pattern of the different inorganic fractions of soil phosphorus and subsequent computation of Weathering Index (WI) based upon the same, (III) to evaluate the soil maturity in accordance with the computed WI and (IV) to compare the different soil maturity indices.

Materials and Methods

Site description

The study area (22°35'36'' to 22°39'51'' N latitude and 86°42'51'' to 86°47'02'' E longitude) is located at Belpahari block of Jhargram subdivision under West Medinipur district of West Bengal, India and falls under Chotanagpur Plateau Region (Hot dry subhumid agro-ecological subregion 12.3) with dominantly granite-gneiss parent material. The landform is undulating plateau with some isolated hillocks. The mean annual temperature ranges between 25°C to 26°C (mean annual summer temperature is 32°C, mean annual winter temperature is 20°C). The area receives mean annual rainfall ranging from 1300-1500 mm covering more than 85 per cent of mean annual Potential Evapotranspiration (PET) ranging between 1400-1600 mm. In general the area qualifies for *ustic* soil moisture and *hyperthermic* soil temperature regime with Length of Growing Period (LGP) varying from 150-180 days (Velayutham *et al.* 1999).

A prominent toposequence with upper, mid and lower slope representing changes in slope gradient and soil characteristics were selected for sampling. The location and site characteristics of the profiles are given in table 1.

Experimental

The morphological properties of the soils were studied in the field as per the procedure of USDA (Soil Survey Staff 1951). The soils were classified at family level of USDA Soil Taxonomy (Soil Survey Staff 1996, 1998) and they belong to Entisols, Inceptisols and Alfisols (Table 1).

Physico-chemical properties were determined by following standard procedures. SiO_2, Fe_2O_3 and Al_2O_3 content of the soils were determined by fusion analysis and total phosphorus was determined by perchloric acid digestion method as described by Jackson (1973). The crystalline form of iron was determined by the Citrate – Bicarbonate – Dithionite (CBD) method outlined by Mehra and Jackson (1960). The amorphous form of iron was determined by acid ammonium oxalate method of McKeague and Day (1966). The inorganic soil phosphorus fractions were estimated following sequential P-fractionation procedure of Chang and Jackson (1958) as modified by Petersen and Corey (1966). Total inorganic phosphorus was estimated following the method of Legg and Black (1955).

Table 1. Site characteristics of the study area and soil classification

Pedon	Location	Landform	Slope (%)	Elevation (m)	Drainage	Erosion	Land use	Soil classification
P1	Garrapahar-I Vill.Belpahari Dist.West Medinipur Lat:22°39′51″ N Long: 86°41′55″ E	Hill side slope	>30	240	Somewhat excessively drained	Very severe	Forest (F1)	Loamy skeletal, Lithic Ustorthents
P2	Garrapahar-II Vill.Belpahari Dist.West Medinipur Lat:22°39′48″ N Long: 86°42′09″ E	Pediment	8-15	155	Well drained	Severe	Cultivated paddy (C1)	Fine, Typic Haplustepts
P3	Goalbera-I Vill.Belpahari Dist.West Medinipur Lat:22°39′25″ N Long: 86°42′38″ E	Moderately sloping upland	3-5	135	Moderately well drained	Moderate	Cultivated paddy (C1)	Fine loamy, Typic Haplustepts
P4	Goalbera-II Vill.Belpahari Dist.West Medinipur Lat:22°39′27″ N Long: 86°43′24″ E	Sloping land	1-5	125	Moderately well drained	Moderate	Cultivated paddy (C2)	Fine, Typic Haplustalfs
P5	Chitadanga Vill.Belpahari Dist.West Medinipur Lat:22°39′27″ N Long: 86°43′51″ E	Valley	0-1	120	Imperfectly drained	Slight	Cultivated paddy (C2)	Fine, Fluventic Haplustepts

F1: Thin forest, sparse vegetation; C1: Cultivated single crop, C2: Cultivated double crop.

Quantification of soil parameters

Profile Weighted Mean (PWM) values

The PWM values were determined as the ratio of summation of depth of an individual horizon (D) multiplied by any parameter of soil (X) and total profile depth (Dp).

$$PWM - X = DX/Dp$$

Weathering Index (WI)

Weathering Index was the determined as the ratio of active P and occluded P as proposed by Puranik *et al*. (1979).

$$\text{Weathering index (WI)} = \frac{(\%S\text{-}P + \%Ca\text{-}P + \%Al\text{-}P + \%Fe\text{-}P)}{(\%R\text{-}SP + \%Occluded\text{-}P)}$$

where; S-P: Saloid Phosphate, Ca-P : Calcium Phosphate, Al-P : Aluminium Phosphate, Fe-P: Iron Phosphate, R-SP: Reductant Soluble Phosphate

Results and Discussion

Soil morphological and physico-chemical characteristics

The morphological and physico-chemical parameters are presented in table 2. The depth of the soils were shallow (<0.5 m) in the hill side slopes and gradually increased from deep to very deep (>1.5 m) probably due to accumulation of eroded materials from across the slope. The soil colour varied from dark reddish brown (5YR 3/3 M) to yellowish brown (10YR 5/6 M). The dark reddish colour might probably be due to the formation of non-hydrated iron oxides (Gerrad 1981). The texture varied from loam to silty clay loam in different horizons (clay content: 31.3%- 44.8% in the surface horizon). Soils mostly had subangular blocky structure differing in size and grade.

Table 2. Important morphological and physico-chemical characteristics of the soils

Pedon	Horizon	Depth (m)	Colour (M)	Structure	Texture	pH (aq)	O.C. gkg^{-1}	Clay (%)	CEC cmol(p+) kg^{-1}	NaHCO$_3$-P (mgkg^{-1})	NH$_4$OAc-K (mgkg^{-1})
P1	A	0.00-0.09	5YR3/4	f1sbk	cl	5.8	26.3	33.9	24.6	2.6	45
	AC	0.09-0.25	5YR3/3	f1sbk	cl	5.6	21.5	30.5	23.1	2.2	39
	C	0.25-0.42	5YR4/6	-	l	5.6	17.9	35.3	21.0	2.0	37
	R	0.42+	Hard pan								
P2	Ap	0.00-0.10	10YR5/6	m1sbk	sic	5.8	14.3	39.1	25.2	3.8	34
	Bw1	0.10-0.25	10YR5/4	m2sbk	cl	6.1	6.4	43.1	23.8	3.8	24
	Bw2	0.25-0.55	10YR4/3	m2sbk	sic	6.2	4.5	43.3	25.0	2.0	29
	Bw3	0.55-0.78	10YR4/3	m3sbk	c	6.3	4.5	52.1	24.3	2.5	27
	Bw4	0.78-1.04	10YR3/3	m2sbk	sic	6.5	4.5	46.1	24.8	2.6	20
	Bw5	1.04-1.35	10YR3/3	-	sic	6.7	4.8	44.3	24.1	2.2	18
P3	Ap	0.00-0.17	7.5YR4/4	m2sbk	sicl	5.8	9.8	31.3	11.1	2.8	23
	Bw1	0.17-0.45	7.5YR4/4	m2sbk	sicl	6.6	7.0	33.4	10.9	2.8	27
	Bw2	0.45-0.71	5YR4/6	m2sbk	sicl	6.5	4.8	33.2	11.0	2.8	32
	Bw3	0.71-0.97	5YR4/6	-	sicl	6.5	5.6	31.8	11.9	2.0	31
	Bw4	0.97-1.50	5YR4/4	-	cl	6.5	4.5	33.4	12.7	2.3	35
P4	Ap	0.00-0.12	10YR5/4	m2sbk	cl	6.0	5.9	37.5	25.1	2.8	23
	Bw	0.12-0.28	10YR5/4	m2sbk	cl	6.4	4.6	38.6	25.5	2.0	32
	Bt1	0.28-0.64	10YR5/6	-	c	6.6	4.6	44.9	22.4	1.7	32
	Bt2	0.64-0.86	10YR5/4	-	c	6.6	4.7	44.9	20.3	2.1	36
	BC	0.86-1.25	10YR3/3	-	cl	6.7	4.3	36.8	19.4	1.6	38
P5	Ap	0.00-0.13	10YR4/3	m2sbk	sic	6.1	4.6	44.8	24.2	3.2	30
	Bw1	0.13-0.38	10YR4/4	m2sbk	sic	6.3	6.0	42.1	24.2	2.0	36
	Bw2	0.38-0.65	10YR4/4	-	sic	6.3	6.7	45.3	23.1	2.0	36
	Bw3	0.65-0.91	10YR4/4	-	cl	6.5	4.3	39.1	19.9	2.6	37
	Bw4	0.91-1.50	10YR5/4	-	cl	6.5	5.0	34.6	18.4	2.2	40

The soils were slightly acidic to neutral in reaction (pH_{aq}. 5.6 – 6.7). The organic carbon content in Pedon 1 exhibited very high value ranging from 17.9 g kg^{-1} to 26.3 g kg^{-1} while in other pedons it varied from 4.3 to 14.3 g kg^{-1}. The high value of organic carbon in the uppermost pedon may be due to forest cover and virgin nature of the soil. In general, the organic carbon decreased gradually along the slope of the toposequence and also with increase in depth of the pedons except in Pedon 5, which might probably be due to the fluvial nature of the soil. The cation exchange capacity varied from 10.9 to 25.5 [cmol (p^+)kg^{-1}]. $NaHCO_3$-P content in the surface layers varied from 2.6 to 3.8 $mgkg^{-1}$ thereby suggesting low available P status perhaps due to high P-fixation by hydrated iron and aluminium oxides and presence of low active clays (Sarkar 2002). NH_4OAc-K in the surface layers varied from 23 to 45 mg kg^{-1} suggesting medium available K-status due to slightly acidic nature of such soils (Muhr *et.al.* 1965).

Silica – sesquioxide molar ratio of the soils and its relation to soil maturity

The SiO_2 content was found to be very high in comparison to Al_2O_3 and Fe_2O_3 and varied from 43.1% to 60.3% (Table 3). In general the silica content was high in the surface horizon and thereafter decreased gradually in lower horizons probably due to illuvial accumulation and more weathering (Mandal 2007). The Fe_2O_3 content varied from 14.9% to 19.2% and the Al_2O_3 content varied from 11.2% to 15.5% in the soils of the toposequence under study. Similar sort of findings were reported by Pal and Roy (1978) in ferruginous granite-gneiss soils of Bankura district, West Bengal and also by Walia and Rao (1996) in some Alfisols and Inceptisols of Uttar Pradesh, India. High silica – sesquioxide molar ratio was also observed in the surface horizon which gradually decreased down the depth of the pedons probably due to loss of silica and subsequent enrichment of sesquioxides in the lower part of the profile. Similar type of observation was also reported by Sharma *et al.* (1996), Shyampura *et al.* (1993) and Gawande and Biswas (1967).The PWM of silica – sesquioxide molar ratio varied from 2.9 to 3.8 (Table 3). Irrespective of topographic position, in general the high silica – sesquioxide molar ratio thus obtained due to high silica and relatively low Al_2O_3 and Fe_2O_3 is indicative of less weathering in such soils. Accordingly considering silica – sesquioxide molar ratio as an indicator of the degree of weathering the sequence with respect to the state of soil development/maturity obtained followed the order: P4>P3>P2>P5>P1.

Active iron (Fe_o/Fe_d) ratio of the soils and its relation to soil maturity

The ratio of Fe_o and Fe_d varied from 0.14 – 0.44 (Table 3) and in general increased with increasing depth. Nayak *et al.* (2002) reported that the active Fe ratio in soils of red and lateritic region is relatively low and decreases with increase in depth which clearly indicates that higher proportion of iron oxides are present in crystallized forms in the lower horizons of the well drained profiles occurring in such regions. Data revealed that Fe_d was more abundant than Fe_o in all the pedons and the difference increased with depth. Similar type of findings were reported by Nayak *et al.* (1999), Nayak *et al.* (2002). In the initial stages of weathering and soil development the release of iron from primary minerals is likely to exceed the rate of crystallization in secondary compounds causing the active iron ratio to increase but thereafter the ratio decreased with increasing soil age as crystallization progressed. Red-ox condition of the soils is perhaps the key factor governing the crystallization of iron oxides together with pH and organic matter which also exert pronounced effect upon the crystallization of iron oxides thereby decreasing the ratio with soil development. Considering PWM of Fe_o/Fe_d ratio of the different pedons (Table 3), the state of soil development was found to be in the order as: P4>P3>P2>P5>P1.

Inorganic P fractions and total P

The inorganic fractions of soil phosphorus viz. S-P, Al-P, Fe-P, Ca-P, RS-P, occluded-P, total IP, as well as total P are presented in table 4. The discussions presented herein are based upon Profile Weighted Mean (PWM) values.

In general, all the pedons exhibited similarity in respect of distribution of active P and RS-P plus occluded P and the little differences observed may be

Table 3. Molar silica- sesquioxide (SiO_2/R_2O_3) ratio and active iron (Fe_o/Fe_d) ratio in the soils

Pedon	Depth (m)	SiO_2 %	Fe_2O_3 %	Al_2O_3 %	SiO_2/R_2O_3	PWM of SiO_2/R_2O_3	Oxalate extractable Iron(Feo)	Dithionite extractable Iron(Fed)	Fe_o/Fe_d	PWM of Fe_o/Fe_d
P1	0.00-0.09	43.3	15.1	14.5	3.1		0.68	1.82	0.37	
	0.09-0.25	46.9	17.7	15.1	3.0	2.9	0.77	1.84	0.42	0.40
	0.25-0.42	43.1	19.2	13.3	2.8		0.73	1.96	0.37	
	0.42+	Hard pan								
P2	0.00-0.10	48.1	15.7	14.8	3.4		0.76	1.70	0.44	
	0.10-0.25	45.7	15.9	12.4	3.6		0.68	1.72	0.39	
	0.25-0.55	45.9	16.3	13.1	3.3		0.36	1.78	0.20	
	0.55-0.78	44.1	15.8	15.4	2.9	3.4	0.56	1.73	0.32	0.24
	0.78-1.04	43.2	15.1	11.8	3.6		0.30	1.75	0.17	
	1.04-1.35	43.5	15.5	11.2	3.6		0.33	1.95	0.17	
P3	0.00-0.17	52.8	15.2	14.4	3.7		0.67	1.52	0.44	
	0.17-0.45	50.5	15.8	15.5	3.3		0.31	1.65	0.19	
	0.45-0.71	50.1	15.1	12.8	3.7	3.5	0.33	1.72	0.19	0.20
	0.71-0.97	50.5	15.6	13.1	3.7		0.37	1.88	0.19	
	0.97-1.50	49.2	15.9	14.8	3.3		0.26	1.87	0.14	
P4	0.00-0.12	60.3	15.5	13.1	4.4		0.57	1.74	0.38	
	0.12-0.28	58.6	15.8	12.3	4.4		0.37	1.80	0.20	
	0.28-0.64	59.8	16.1	14.8	4.0	3.8	0.34	1.92	0.17	0.18
	0.64-0.86	54.1	17.3	14.5	3.6		0.33	1.88	0.17	
	0.86-1.25	53.5	17.2	14.9	3.5		0.30	1.97	0.15	
P5	0.00-0.13	43.8	14.9	13.9	3.2		0.53	1.37	0.33	
	0.13-0.38	44.1	15.2	14.1	3.1		0.69	1.88	0.36	
	0.38-0.65	42.5	16.1	12.8	3.1	3.0	0.63	1.79	0.35	0.34
	0.65-0.91	42.8	15.8	12.2	3.2		0.62	1.84	0.33	
	0.91-1.50	40.3	15.6	13.3	2.9		0.64	1.88	0.34	

attributed to the differences in slope, erosion and soil forming processes under similar parent material and agro-ecological situation (Roberts *et al*. 1985). A scan through the data in the table 3 reveals that minimum amount of phosphorus was in the saloid fraction (S-P) where as maximum amount was in reductant soluble form (RS-P). The RS-P varied from 85.9 mg kg^{-1} – 103 mg kg^{-1} in the soils and such high values may be attributed to the acidic to neutral soil reaction (pH_{aq}. 5.6 – 6.7) and high content of Fe_2O_3 (14.9% - 19.2%) (Mandal 2007; Kothandaraman and Krishnamoorthy 1979). Similar sort of RS-P dominance was reported by Lakshminarayana (2007) in rice soils of Mizoram. The predominance of RS-P in these soils may be responsible for non-responsiveness to P fertilization particularly under low lying condition since RS-P is regarded to be the most difficult inorganic phosphorus fraction to release phosphorus under upland situation, while under low lying and/or flooding condition reduction of hydrated ferric oxides to ferrous hydroxide aids in releasing a part of the RS-P (Patrick and Mikkleson 1971). Based upon overall PWM values the content of RS-P was found to be 95.8 mg kg^{-1} contributing 53.0% and 27.6% to the total IP and total P respectively. Similar sort of findings were reported by Puranik(1979), Kothandaraman and Krishnamoorthy (1979) for red and lateritic soils of Tamil Nadu and also by Sharma and Tripathi (1992) in some acid hill soils of North West India.

Table 4. Inorganic P Fractions and Total P content in soils

Pedon	Depth (m)	S-P	Al-P	Fe-P	Ca-P	RS-P	Occl-P	Total-Inorganic P	Total-P
		(mgkg^{-1})							
P1	0.00-0.09	0.8	18.3	63.1	15.0	115	19.5	240.9	526.3
	0.09-0.25	2.0	13.1	46.5	9.5	108	20.0	207.3	403.1
	0.25-0.42	1.5	27.5	47.9	11.0	92	13.3	195.3	383.3
	PWM-P*	0.6	20.0	50.6	11.3	103	17.2	209.6	421.6
		(0.1)**	(4.7)	(12.0)	(2.7)	(24.4)	(4.1)		
		[0.3]***	[9.5]	[24.1]	[5.4]	[49.1]	[8.2]		
P2	0.00-0.10	1.5	18.6	50.0	12.5	125	24.1	240.5	503.1
	0.10-0.25	2.8	17.5	49.2	19.5	75	25.0	194.0	387.5
	0.25-0.55	2.0	15.0	45.4	18.0	80	18.3	181.6	400.0
	0.55-0.78	2.8	17.3	38.4	21.0	91	17.5	190.2	316.8
	0.78-1.04	1.5	10.9	27.0	19.5	94	13.2	170.1	380.6
	1.04-1.35	0.8	10.6	29.5	19.0	109	7.0	178.5	340.3
	PWM-P	1.8	14.1	37.8	18.8	94.0	15.8	200.2	374.6
		(0.5)	(3.8)	(10.1)	(5.0)	(25.1)	(4.2)		
		[0.9]	7.0]	[18.9]	[9.4]	[47.0]	[7.9]		
P3	0.00-0.17	2.8	12.4	46.3	18.0	103	9.3	200.6	400.0
	0.17-0.45	2.0	10.1	29.2	20.0	82	12.5	160.5	346.8
	0.45-0.71	2.8	10.4	30.0	19.0	91	8.5	165.2	370.6
	0.71-0.97	2.7	9.4	25.0	19.5	98	10.0	166.1	362.5
	0.97-1.50	2.0	10.6	20.0	11.5	108	12.5	167.3	312.5
	PWM-P	2.4	11.4	27.3	16.5	97.9	11.0	169.1	347.5
		(0.7)	(3.3)	(7.9)	(4.8)	(28.2)	(3.2)		
		[1.4]	[6.7]	[16.1]	[9.8]	[57.9]	[6.5]		
P4	0.00-0.12	2.8	11.3	31.7	18.5	112	11.9	196.6	383.1
	0.12-0.28	2.0	10.6	25.0	13.0	80	13.5	150.7	296.9
	0.28-0.64	2.0	12.0	20.8	15.5	86	13.5	153.2	306.9
	0.64-0.86	1.5	9.4	20.7	18.5	104	10.0	165.4	290.6
	0.86-1.25	1.5	10.1	20.8	18.6	110	13.0	175.2	287.5
	PWM-P	1.8	10.7	22.4	17.0	98.4	12.6	166.1	304.0
		(0.6)	(3.5)	(7.4)	(5.6)	(32.4)	(4.1)		
		[1.1]	[6.4]	[13.5]	[10.2]	[59.2]	[7.6]		
P5	0.00-0.13	2.8	20.6	47.3	18.5	80	13.0	193.3	402.1
	0.13-0.38	2.8	18.1	33.4	21.5	78	13.5	169.5	306.5
	0.38-0.65	2.0	16.6	27.9	20.5	81	12.5	162.9	301.8
	0.65-0.91	2.0	11.8	25.0	20.9	90	12.0	165.1	286.2
	0.91-1.50	1.5	10.1	23.3	22.2	91	10.3	160.8	248.6
	PWM-P	2.0	13.8	28.2	21.2	85.9	11.8	166.2	287.6
		(0.7)	(4.8)	(9.8)	(7.4)	(29.9)	(4.1)		
		[1.2]	[8.3]	[17.0]	[12.8]	[51.7]	[7.1]		
		1.7	**14.0**	**33.3**	**17.0**	**95.8**	**13.7**	**182.2**	**347.1**
Grand Mean		**(0.5)**	**(4.0)**	**(9.6)**	**(4.9)**	**(27.6)**	**(3.9)**		
		[1.0]	**[7.6]**	**[17.9]**	**[9.5]**	**[53.0]**	**[7.5]**		

*PWM-P - Profile Weighted Mean phosphorus.
**Figures within ( ) indicates per cent to total P.
***Figures within [ ] indicates per cent to total inorganic P.

Fe-P was found to be the next predominant form after RS-P and varied from 22.4 mg kg^{-1} to 50.6 mg kg^{-1}. No definite trend in distribution pattern was observed within the pedons but a general tendency of decrease in content of Fe-P was observed along the slope of the toposequence from higher to the lower topographic position (Uriyo and Kesseba 1973). The Al-P varied from 10.7 mg kg^{-1} to 20.0 mg kg^{-1} and the proportion was much less in comparison to RS-P and Fe-P and slightly less than Ca-P. No definite trend in distribution pattern of Al-P was observed both within the pedons and also along the toposequence. Based upon overall PWM values the content of Fe-P and Al-P was found to be 33.3 mg kg^{-1} and 14.0 mg kg^{-1} thereby contributing 17.9% and 9.6% and 7.6% and 4.9% to the total IP and total P respectively. The Fe-P and Al-P slowly make up the available pool of soil phosphorus and builds up with application of phosphate fertilizer which in turn help to maintain available pool of P in Soils (Bhattacharyya and Dey 1983). Presence of substantial amounts of Fe-P and Al-P altogether may be ascribed to the presence of sesquioxides which might have transformed a portion of added/native P in these forms (Rokima and Prasad 1991). However, lower content of Al-P in such soil seem to accompany strong weathering in the tropics under well drained condition (Westin and Debrito 1969).

The Ca-P content was found to vary from 11.3 mg kg^{-1} to 21.2 mg kg^{-1} and was present in less proportion in comparison to RS-P and Fe-P. The low amount of Ca-P is suggestive of higher degree of soil maturity (Udo and Ogunwale 1977; Walkers and Syers 1976; Smeck 1985; Sharma and Tripathi 1992; Uriyo and Kesseba 1973). Based upon overall PWM values the content of Ca-P was found to be 17.0 $mgkg^{-1}$ thus contributing 9.5% and 4.9% to the total IP and total P respectively.

The occluded P is the unavailable form which is accumulated in the soil (Bhattacharyya and Singh 1990) and it P varied from 11.0 mg kg^{-1} to 17.2 mg kg^{-1} without any definite trend in vertical distribution pattern both within the pedons and along the toposequence. Based upon overall PWM values the content of occluded P was found to be 13.7 mg kg^{-1} thereby contributing 7.5% and 3.9% to the total IP and total P respectively.

The saloid-P was found to be very low in comparison to all other forms of inorganic soil phosphorus and varied from 0.6 mg kg^{-1} to 2.4 mg kg^{-1} which might probably be due to high P-fixing capacity of these soils (Sarkar 2002; Kothandaraman and Krishnamoorthy 1979). Based upon overall PWM values the S-P was found to be 1.7 mg kg^{-1} contributing only 1.0% and 0.5% to the total IP and total P respectively.

PWM - total P content revealed that the soils were fairly rich in phosphorus reserve ranging from 421.6 mg kg^{-1} to 287.6 mg kg^{-1} with an overall mean of 347.1 mg kg^{-1} (Sharma and Tripathi 1992). A close relationship between total P and different forms of soil inorganic phosphorus suggested the existence of an equilibrium between the former and the later.

The inorganic phosphorus fractions have been found to constitute a relatively large portion of total P in all the pedons. However, the overall collective contribution of all the inorganic soil phosphorus fractions to total soil P was found to be in the tune of 50.6%. Similar trend in results was also observed by Rao and Chakraborty (1994); Mandal (2007) ,Sharma and Tripathi (1992) and Puranik *et al* (1979).

Sequential extraction of various soil inorganic phosphorus fractions revealed that the mean relative abundance of inorganic phosphorus followed the order as: RS-P > Fe-P> Ca-P>Al-P ˜ occluded P> S-P. The overall relative abundance of the different inorganic phosphorus fractions in terms of their average ratios were found to be S-P(0.1) : Al-P(1.0) : Fe-P(2.4) : Ca-P(1.2) : RS-P(6.9) : Occluded-P (1.0).

Correlation statistics

The significant correlation matrix between different fraction of inorganic soil phosphorus and soil parameters is presented in table 4.

The variation in RS-P (the most dominant fraction) amongst the soils may be ascribed to the variation in organic carbon (0.441*) as well as total P (0.410*) as is evident in terms of significant association of the same with these parameters. Both Fe-P and Al-P were positively and significantly correlated with organic carbon (0.724***; 0.484*) and total P (0.842***; 0.442*) while negative correlation was observed with soil pH (-0.844***; -0.677***). Tomar (2000) in his extensive review based article on dynamics of phosphorus in soils also pointed out the existence of such sort of relationship. Moreover there existed a significant positive association between Al-P and Fe-P (0.476*) which is obvious because both these forms of inorganic phosphorus occur simultaneously in soils and under acidic soil environment it is simply the transformation of one form to the another. Wang and Shuman (1994) also observed similar sort of relationship while studying transformation in rice rhizosphere in acidic soils. Ca-P was found to be negatively and significantly correlated with total P (-0.409*) and organic carbon (-0.602**). Saloid-P exhibited significant negative correlation with organic carbon (-0.440*), however, it showed positive correlation with available P, though non-significant (r = 0.31). The significant negative association of saloid-P with organic carbon can be ascribed to the binding of this form with soil organic matter rendering less of P to be extracted as saloid-P while on the other hand positive association of saloid-P with available P ($NaHCO_3$-P) may be due to the more release of P into easily available P form (S-P) from available-P pool of the soils. Similar findings were also reported by Singh and Sharma (2007) and Kothandaraman and Krishnamoorthy (1979).

Soil phosphorus forms in relation to soil maturity

Soil maturity was examined in terms of PWM of total P and computed Weathering Index (WI) based upon the PWM of inorganic phosphorus fractions. Perusal of data in table 3 revealed that PWM – total P was maximum in P1 (421.6 mg kg^{-1}), thereafter decreased gradually down the slope of the toposequence and ultimately attained a minimum of 287.6 mg kg^{-1} in P5. The decrease in PWM – total P down the slope of the toposequence is indicative of increased weathering. Similar type of vertical distribution trend in PWM of total P was observed by Chang and Jackson (1958), Lajtha and Schlesinger (1988), Agbenin and Tiessen (1995). Based upon PWM – total P soil maturity was found to follow the sequence as: P5 (most matured) >P4>P3>P2>P1 (least matured).

Scan through data in table 5 revealed that the WI gradually decreased from P1 to P4, thereafter slightly increased in P5 due to decrease of active P viz. S-P, Ca-P, Al-P and Fe-P with subsequent increase of RS-P and occluded-P. With increase in soil maturity the active P content was found to decrease together with increase in RS-P and occluded P and consequently the WI narrowed down with the soil development thereby suggesting soil maturity to be in the order as: P4 (most matured) > P3>P2 ˜ P5>P1 (least matured).

Table 5. Weathering index of the studied soil pedons based upon IP fractions

Pedon	Sum of relative proportion (%) of active P fractions to total inorganic P	Relative proportion of %RSP + % occluded P to total inorganic P	Weathering index (WI)
1	39.3	57.3	0.69
2	36.2	54.9	0.66
3	33.7	64.4	0.52
4	31.2	66.8	0.47
5	39.3	58.8	0.67

Soil phosphorus forms in relation to soil maturity vis-à-vis other chemical indices and soil taxonomy

The trend in soil maturity sequence as observed from soil taxonomic classification (Soil Survey Staff 1999) (Table 1) dictates the maturity sequence as: P4 (most matured) > P2, P3, P5> P1 (least matured) which is not in agreement with the maturity sequence based upon PWM – total P. Inspite of containing the least amount of PWM – total P, the lowest pedon in the toposequence under study is less matured than soils in pedons P4, P3 and P2 which may be ascribed to fluvial interference in the toe and slope position, excessive crop uptake of P due to intense agricultural activity and the surface run-off of phosphorus (Williams and Walker 1969). Moreover, soil development in P5 may also possibly be hampered due to recurring deposition of alluvium materials, addition of fertilizers and excessive disturbance by agricultural practices (Agbenin and Tiessen 1995). The criterion of PWM – total P, therefore proved to be a poor indicator of relative degree of soil maturity across the toposequence under the existing situation. However, good agreement in maturity sequence was observed between IP based WI, molar silica sesquioxide ratio, active iron ratio and soil taxonomic classification in terms of soil maturity thereby indicating a close relationship between the former and the later. Thus, IP based WI proved to be a very suitable and extremely useful index for adjudging soil maturity in terms of pedogenic development of the soils.

Conclusion

The foregoing results revealed that there existed a marked variation among the various inorganic P-forms in the soils of the toposequence under the hot dry agro-ecological subregion (AESR 12.3) of West Bengal falling under Chotanagpur plateau region. The soils were found to be fairly rich in total P reserve which showed a close relationship with the other forms of soil inorganic phosphorus thereby suggesting the existence of an equilibrium between the former and the later. Sequential extraction of various soil inorganic phosphorus fractions revealed that the mean relative abundance of inorganic phosphorus followed the order as : RS-P > Fe-P> Ca-P>Al-P ˜ occluded P> S-P. The overall relative abundance of the different inorganic phosphorus fractions in terms of their average ratios were found to be S-P(0.1) : Al-P(1.0) : Fe-P(2.4) : Ca-P(1.2) : RS-P(6.9) : Occluded-P (1.0). However, the collective contribution of all the inorganic soil phosphorus fractions to total soil P was found to be in the tune of 50.6% which is certainly less in comparison to the range value of 54% - 65% in rice growing soils of West Bengal as was reported by Tiwari (2002). The saloid-P was also found to be very low in such soils indicating poor available P status which is a matter of serious concern as regards P-fertility in the soils of the study area falling under Chotanagpur plateau region which is already reported to be affected by severe soil erosion, poor soil nutrient status and also vulnerable to high degree of P-fixation leading to extensive land degradation. Soil maturity sequence derived from Weathering Index (WI) based upon soil Inorganic Phosphorus fractions (IP) viz. P4 (most matured)>P3>P2 ˜ P5> P1 (least matured) was found to be in good agreement with the maturity sequence obtained from silica sesquioxide (SiO_2/R_2O_3) molar ratio and active iron (Fe_o/Fe_d) ratio viz. (P4>P3>P2>P5>P1), as well as from Soil Taxonomy (P4> P2, P3, P5 > P1) but did not corroborate with maturity sequence obtained based upon total P (P5>P4>P3>P2>P1). The study emphasized the suitability of soil IP based WI for adjudging soil maturity in terms of pedogenic development of soils.

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Received : November, 2013 Accepted : February, 2014