Oxalate and EDTA extractable soil phosphorus and iron in relation to P availability in lowland rice soils of West Africa

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SUMMARY

There is a complex relationship between iron (Fe) and phosphorus (P) in lowland soils grown to rice. There is, therefore, the need for quick and reliable extraction methods to assess their availability. The ability of ethylene diamine tetra acetic acid (EDTA) and ammonium oxalate $(NH_4)_2C_2O_4 \cdot H_2O$ to simultaneously extract Fe and P in soils was assessed with 15 soils from five important rice-growing countries in West Africa. The relationships between Olsen and Bray II P, inorganic P fractions and rice dry matter production and P uptake were also evaluated. The results showed that inorganic P fractions were in the order: Fe-P>Ca-P>Al-P for 12 of the test soils, whereas Al-P>Fe-P>Ca-P was the order followed for two soils, and Ca-P>Fe-P>Al-P for one soil. The mean Fe-P recorded was 77 mg P kg^{-1}, although residual P recorded a higher mean of 153 mg P kg^{-1}. Results of correlation analysis showed that correlation between EDTA-Fe and Oxalate-P was positive and highly significant (r= 0.92; P<0.001). Similarly, highly significant relationship was established between EDTA-Fe and Fe-P, indicating that the two extractants were similar in selectivity of dissolution of inorganic phosphates and extractable Fe. Results from greenhouse pot experiments showed that there was higher and significant relationship (r = 0.75; P = 0.001) between Oxalate-P and P uptake by the rice cultivar Bouake 189 than with EDTA-P (r = 0.70; P = 0.004). The plant P uptake data also showed the superiority of Olsen's method over that of Bray II in predicting P nutrition of rice. The results underscored the usefulness of EDTA and ammonium oxalate to simultaneously extract both Fe and P in West African rice soils.

RÉSUMÉ

NARTEH, L. T. & SAHRAWAT, K. L.: *Oxalate et EDAT, le phosphore terreux et le fer terreux extractibles par rapport à la disponibilité de P dans les sols de la plaine du riz de l'Afrique de l'Ouest.* Il y a un rapport compliqué entre le fer (Fe) et le phosphore (P) dans les sols de la plaine où le riz est cultivé. Il y a donc la nécessité de trouver des méthodes d'extraction rapides et fiables pour évaluer leur disponibilité. La capacité d'éthylène diamine d'acide tétra-acétique (EDAT) et d'oxalate d'ammonium $\{(NH_4)_2 C_2 O_4.H_2O\}$ d'extraire simultanément Fe et P dans les sols étaient évaluées utilisant 15 sols de cinq pays principaux de la cultivation du riz en Afrique de l'Ouest. Les rapports entre le P d'Olsen et Bray II, les fractions de P inorganique et la production de la matière sèche de riz et la consommation de P étaient également évalués. Les résultats montraient que les fractions P inorganique étaient dans l'ordre: Fe-P>Ca-P>Al-P pour 12 des sols de l'essai, tandis qu' Al-P>Fe-P>Ca-P était l'ordre suivi pour deux sols et Ca-P>Fe-P>Al-P pour un sol. La moyenne de Fe-P enregistrée était 77 mg P kg^{-1}, malgré le fait que P résiduaire enregistrait une moyenne plus élevée de 153 mg P kg^{-1}. Les résultats de l'analyse de corrélation montraient que la corrélation entre EDAT-Fe et Oxalate-P était positive et fortement considérable (r = 0.92; P< 0.001). De la même façon un rapport fortement considérable était établi entre EDAT-Fe et Fe-P indiquant que les deux solvants étaient semblables en sélectivité de la dissolution des phosphates inorganiques et Fe extractible. Les résultats d'expériences potagères de serre montraient qu'il y avait un rapport plus élevé et considérable (r = 0.75; P = 0.001) entre Oxalate-P et la consommation de P par la variété du riz Bouaké 189 qu'avec EDAT-P (r = 0.70; P = 0.004). Les données de la consommation de P par plante montraient la supériorité de la méthode d'Olsen au-dessus de Bray II en ce qui

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concerne la prédiction de la nutrition de P de riz. Les résultats soulignaient l'utilité d'EDAT et d'Oxalate d'ammonium à simultanément extraire non seulement Fe mais aussi P de sols du riz de l'Afrique de l'Ouest.

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Introduction

Rice grown on wetland soils often develops symptoms of P deficiency due to transformation processes caused by the wetting and drying which the soils undergo (Sah & Mikkelsen, 1986). The physico-chemical changes which occur in anoxic-flooded soils affect the Fe fractions when drained and the conditions become aerobic (Willet & Higgins, 1980). The nature and magnitude of changes in forms of Fe and their impact on P availability are not well understood (Sah & Mikkelsen, 1989). It is suggested that the main factor which increases P availability in rice soils is the reductive dissolution of Fe^{3+} to Fe^{2+} which increases the solubility of Fe-P (Willet & Higgins, 1978). Studies have shown that greater availability of soil P under flooded conditions is related to increased ammonium oxalate extractable Fe (Khalid, Patrick Jr & Delaune, 1977; Willet, 1986). Oxalate extractable Fe and P have also been shown to correlate positively with Fe and P availability in soils of southern USA (Shahandeh, Hossner & Turner, 1994a).

Chemical extractants have been used to characterize soil P and its availability, including dilute acids (Troug, 1930; Morgan, 1937), dilute alkali and their salts (Williams, 1950; Oslen *et al.*, 1954). Some of these methods have proved useful in evaluating response to soil fertilizer phosphates in some soils from Sierra Leone (Haque & Lahai, 1977), Nigeria (Enwezor, 1977), and from Ethiopia (Mamo & Haque, 1991).

The relationship of organic P and certain inorganic P fractions and P availability in some Nigerian soils have also been studied (Enwezor & Moore, 1966). The influence of soil properties including organic C, clay content, *p*H and extractable Fe and A1 on P retention has been studied on some cacao soils (Ahenkorah, 1968). The relative importance of these factors on P sorption characteristics and availability of some upland soils in Ghana has been studied (Owusu-Bennoah & Acquaye, 1989). Sahrawat (1977) showed that EDTA extractable P was related to available P and inorganic P fractions, especially Fe-P and Ca-P in semi-arid, tropical soils from India. Selective extraction by EDTA of amorphous iron oxides, which are known to absorb P from soil solution, has been reported (Borggaard, 1981), and work by Shahandeh *et al.* (1994 b) on soils from Texas, USA, has confirmed the relationship between extractable Fe and P.

Although information on extraction and availability of P in upland soils is available, they do not apply to lowland rice soils in which P availability is controlled by reduction and oxidation.

This study, therefore, aimed at examining the usefulness of selected chemical extractants for the inorganic P fractions, and at assessing their relationship with uptake and dry matter yield of rice grown under flooded conditions in West Africa.

Materials and methods

Soils

The soils used in the study were collected from the surface (0-15 cm) of 15 different rice-growing locations in five West African countries. The locations were the benchmark areas for the Problem Soils Task Force of the West Africa Rice Development Association (WARDA), where studies on Fe toxicity to rice were conducted.

Table 1 summarizes background information on the location, and some important physical and chemical characteristics of the soils. Classification of the soils (FAO, 1988) has previously been reported (Narteh & Sahrawat, 1997). Soils 14 and 15 (from Côte d'Ivoire) which were upland soils, were added to increase the diversity of the soils. The soils cover a wide range of *p*H(4.3-7.7), organic C (7.4 -46.0 g kg^{-1}), total N (0.5 - 3.3 g kg^{-1}),

TABLE 1

Some Important Physical and Chemical Properties of the Soils Studied

Soil no. and location	*Ecology*	*Classification (FAO, 1988)*	*Texture*	p*H* (H_2O)	*Clay*	*Org. C* (g kg^{-1})	*CEC* (cmol kg^{-1})
1. Edozhighi, Nigeria 9°06'N 5°59'E	Savanna	Dystric Gleysol	Silt loam	4.3	163	7.8	5.6
2. Ikot-Obong, Nigeria 5°01'N 7°56'E	Forest	Dystric Gleysol	Loamy sand	5.2	53	11.4	1.4
3. Ifaki-Ekiti, Nigeria 7°14'N 5°8'E	Forest	Eutric Gleysol	Clay	7.7	510	46.0	30.0
4. Itoikin, Nigeria 6°36'N 3°32'E	Forest	Dystric Gleysol	Silt loam	4.9	215	9.8	6.5
5. Fumesua, Ghana 6°54'N 1°35'W	Forest	Gleyic Arenosol	Loamy sand	5.4	45	8.8	0.8
6. Kikam, Ghana 4°53'N 2°14'W	Forest	Dystric Gleysol	Clay loam	5.1	350	35.2	17.0
7. Kou valley, Burkina Faso 11°11'N 4°18W	Transition	Dystric Gleysol	Silt loam	6.1	262	13.4	11.1
8. Karfiguela, Burkina Faso 10°36'N 4°45'W	Savanna	Dystric Gleysol	Silt loam	5.6	308	9.2	14.5
9. Korhogo, Côte d'Ivoire 9°22'N 5°31'W	Savanna	Dystric Gleysol	Silt loam	5.4	275	20.0	12.5
10. Kilissi, Rep. of Guinea 10°3'N 12°49'W	Forest	Dystric Gleysol	Sandy clay loam	5.6	220	25.2	12.7
11. Farannah, Rep. of Guinea 10°01'N 10°47'W	Savanna	Dystric Gleysol	Silt clay loam	5.5	300	23.2	16.8
12. Kissidougou, Rep. of Guinea 9°48'N 10°8'W	Forest	Dystric Gleysol	Silt	5.3	60	19.6	8.8
13. Bouake, Côte d'Ivoire 7°42'N 5°00'W	Transition	Dystric Gleysol	Clay loam	6.1	318	23.0	8.7
14. Bouake, Côte d'Ivoire 7°42'N 5°00'W	Transition	Eutric Leptosol	Sandy loam	6.3	88	7.4	2.0
15. Man, Côte d'Ivoire 7°31'N 7°37'W	Forest	Ferric Acrisol	Loam	5.0	298	15.6	8.6

cation exchange capacity (CEC) (0.8 -30 cmol kg^{-1}), and clay (45.510 g kg^{-1}). The soil samples were air-dried and ground to pass through a 2-mm sieve. The *p*H was measured by glass electrode at a soil: water ratio of 1:2.5. Particle size was analyzed by the pipette method (Gee & Bauder, 1986). Organic C was determined by the Walkley and Black method (Nelson & Sommers, 1982). CEC of the samples was determined as described by Chapman (1965).

Analyses

Triplicate air-dried soil samples were extracted for P by the Bray II (Bray & Kurtz, 1945) and Olsen methods. Bray II P was extracted by shaking 1g soil with 7ml of extractant containing 0.03 *M* NH_4F and 0.025 *M* HCl for 1 min (Olsen & Sommers, 1982). Olsen P was extracted by shaking 5g soil with 20 ml 0.5 *M* $NaHCO_3$ (*p*H 8.5) for 30 min (Olsen & Sommers, 1982). The extracts were centrifuged and filtered and P in the solution was determined by the method of Murphy & Riley (1962). For the EDTA extraction, 2g of soil was shaken with 20 ml 0.025 *M* EDTA for 30 min. Iron in the extract was measured by atomic absorption spectrophotometry and P by the method described (Murphy & Riley, 1962). The oxalate Fe and P were extracted by shaking incubated soil suspension with 0.2 *M* acidic ammonium oxalate $\{(NH_4)_2C_2O_4.H_2O)\}$ at a soil: solution ratio of 1:40 for 4 h in the dark (Sheldrick, 1984). The extracted Fe was measured by atomic absorption spectrophotometry after filtering and P was determined by phosphomolybdate blue method (John, 1970) after drying and ashing an aliquot at 500 °C for 1 h and dissolved in 1 *M* HCl. The fractionation of soil P was carried out according to the scheme suggested by Peterson & Corey (1966).

Greenhouse pot studies

Seven kilogrammes soil (<2 mm) was placed in glazed pots, saturated with distilled water and puddled. Six to eight seeds of three lowland rice cultivars were planted per pot and thinned to two seedlings per pot 2 weeks after emergence (WAE). The rice cultivars were Bouake 189 (a popular cultivar, widely grown in Côte d' Ivoire), Suakoko 8 and CK 4. Whereas Bouake 189 is susceptible to iron toxicity, Suakoko 8 and CK 4 are iron-tolerant. The level of submergence of soil under water was increased as seedlings grew and subsequently was maintained at about 5 cm throughout the growing period. The pots were arranged in a randomized complete block design with three replications of the three cultivars and 15 soils, giving a total of 135 pots. The plants were harvested at the maximum tillering (9 WAE), washed and separated into roots and shoots, and oven-dried at 50 °C for 1 week for dry matter determination. The plant tops were ground and digested with a 2:1 mixture of nitric and perchloric acids. Phosphorus in the digest was measured colorimetrically by the vanadomolybdate yellow method (IITA, 1984). The data on plant dry matter and P content were statistically analyzed according to the SAS statistical package (SAS, 1987). Correlation studies were made between Fe and P extracted by the two extractants and also with the inorganic P fractions.

Results and discussion

Generally, extracted Fe-P was the highest, with a mean value of 77 mg kg^{-1}, and the mean residual P was 153 mg kg^{-1} (Table 2). The order of magnitude was Fe-P>Ca-P>Al-P except in Soils 2, 3 and 6 where the order was Al-P>Fe-P>Ca-P for Soils 2 and 6, and Ca-P>Fe-P>Al-P for Soil 3. Table 3 shows the means and standard errors of Fe and P extracted by NH_4-oxalate and EDTA for the 15 test soils. Also included are data on P extracted by the Bray II and Oslen methods. The oxalate solution extracted more Fe and P than EDTA. The amount of P extracted by oxalate was between 11 and 245 mg kg^{-1}, while amount extracted by EDTA was between 3 and 214 mg kg^{-1}.

The highest concentration of both extractable Fe and P was from Soil 3 but the lowest P was from Soil 2 and Fe from Soil 14 (Table 3). This was expected because oxalate extracts poorly crystalline Fe (Campbell & Schwertmann, 1984) which is the most reactive fraction of soil iron

TABLE 2

Inorganic Soil P Fractions in 15 West African Rice Soils

Soil no.	*Fe-P*	*Al-P*	*Ca-P*	*Red.-P*	*Res.-P*	*Tot-P*
	(mg kg^{-1})					
1	55	33	8	35	31	162
2	23	26	5	19	7	80
3	320	161	333	80	231	1125
4	39	13	12	25	74	163
5	23	13	9	18	26	89
6	13	22	3	62	348	448
7	36	13	23	17	87	176
8	63	15	19	27	124	248
9	130	23	23	15	272	463
10	230	64	42	25	184	545
11	83	14	22	27	154	300
12	49	38	12	35	366	500
13	30	20	8	17	105	180
14	35	15	12	27	122	211
15	33	13	8	10	170	234
Mean	77	32	36	30	153	328
SE	22	10	21	4	29	68

TABLE 3

Bray II and Olsen Available P and Fe and P Simultaneously Extracted by EDTA and NH_4-oxalate in 15 West African Rice Soils

Soil no.	*P*				*Fe*	
	EDTA	*NH_4-oxalate*	*Bray II*	*Olsen*	*EDTA*	*NH_4-oxalate*
	(mg kg soil^{-1})					
1	8	40	8	17	600	3175
2	3	13	8	5	150	1187
3	214	245	2	104	2200	11412
4	4	20	5	7	550	3400
5	3	19	8	6	350	3562
6	3	19	8	8	325	1100
7	3	11	6	9	575	3052
8	3	33	2	6	800	6750
9	7	106	2	16	1275	10737
10	14	89	2	21	1375	9812
11	3	30	2	5	800	5837
12	7	26	5	2	450	1562
13	7	23	4	9	150	1875
14	8	28	11	7	125	925
15	3	18	6	4	125	1525
Mean	19	48	5	15	656	4394
SE	14	16	0.75	6.5	149	944

oxides (Hartwig & Leopert, 1993). The soils are mostly Fe rich and, therefore, mostly rich in Fe-P. It seems therefore, that oxalate, a more efficient extractant, dissolves the poorly crystalline Fe than EDTA (Campbell & Schwertmann, 1984).

The wide differences between the Bray II and Olsen methods were also understandable (Table 3). The difference between the Bray II and Olsen methods in Soil 3 was exceptionally large, but several repetitions of the analysis yielded the same results. The differences in the mechanism of selectively extracting P were considered to be the factor. Nelson & Sommers (1982) noted that low estimates of available P in calcareous soils (such as Soil 3) which were determined with the Bray II test have been attributed to the rapid neutralization of the acid by CaCO$_3$ (Blanchair & Caldwell, 1964; Randall & Grava, 1971). Similar results have been reported by Syers, Smillie & Williams (1972) and Smillie & Syers (1972) who suggested an additional mechanism involving the formation of CaF$_2$ from calcite which subsequently immobilized some solution P. The very high available P determined for Soil 3 with the Olsen method may be explained by the postulation that in calcareous alkaline or neutral soils containing Ca phosphates, Olsen extractant decreased the concentration of Ca in solution by precipitating Ca as CaCO$_3$, and thus resulting in the increase in the concentration of solution P (Olsen *et al.*, 1954).

The findings of this study are generally in accord with the earlier studies which have shown that Olsen's method was superior to Bray's. Cholitkul & Tyner (1971) compared several P extractants on 64 lowland rice soils of Thailand and agreed with Mahapatra & Patrick (1971) that what was basically needed for air-dried samples of lowland soils was an extractant that specifically extracts Fe-P. Similarly, Ekpete (1976) evaluated several chemical methods for extracting available P in 13 waterlogged soils (*p*H 4.2-6.1) and concluded that Olsen's method was better than all the other methods used, and that it could be used on air-dried soils to predict P availability and rice response to P fertilization in lowland soils.

High correlation (r) was found between EDTA-Fe and Oxalate-Fe ($r = 0.94$; $P<0.001$) (Table 4). The results show that both EDTA and oxalate are

TABLE 4

The Matrix of Correlation Coefficients (r) among Fe and P Extracted by EDTA and NH$_4^+$-oxalate and Soil P Fractions

	EDTA-Fe	*Oxalate-Fe*	*EDTA-P*	*Oxalate-P*	*Fe-P*	*Al-P*	*Ca-P*	*Red.-P*	*Res.-P*
Oxalate-Fe	0.94 (<0.001)	-	-	-	-	-	-	-	-
EDTA-P	0.76 (0.001)	0.55 (0.03)	-	-	-	-	-	-	-
Oxalate-P	0.92 (<0.001)	0.81 (<0.001)	0.91 (<0.001)	-	-	-	-	-	-
Fe-P	0.95 (<0.001)	0.86 (<0.01)	0.81 (<0.001)	0.89 (<0.001)	-	-	-	-	-
Al-P	0.81 (<0.001)	0.61 (0.02)	0.95 (<0.001)	0.93 (<0.001)	0.89 (0.001)	-	-	-	-
Ca-P	0.81 (<0.001)	0.61 (0.02)	0.91 (<0.001)	0.93 (<0.001)	0.85 (<0.001)	0.95 (<0.001)	-	-	-
Red.-P	0.54 (0.04)	0.27 (0.32)	0.75 (0.001)	0.63 (0.01)	0.53 (0.04)	0.75 (0.001)	0.73 (0.002)	-	-
Res.-P	0.19 (1.0)	0.14 (1.0)	0.06 (1.0)	0.19 (1.0)	0.13 (1.0)	0.15 (1.0)	0.006 (1.0)	0.035 (1.0)	-
Total-P	0.83 (<0.001)	0.66 (0.01)	0.85 (<0.001)	0.90 (<0.001)	0.85 (<0.001)	0.90 (<0.001)	0.86 (<0.001)	0.77 (<0.001)	0.53 (0.04)

efficient extractants for poorly crystalline iron oxides and the P associated with them (Alexander & Robertson, 1972; Campbell & Schwertmann, 1984; Borggaard, 1988). It is not surprising, therefore, that the positive and highly significant correlations were as follows: EDTA-Fe and Oxalate-P (r=0.92; P<0.001); Oxalate-P and EDTA-P (r=0.91; P<0.001); Fe-P and EDTA-Fe (r=0.95; P<0.001). In this study, oxalate and EDTA were used to simultaneously extract Fe. It seems logical, therefore, that high correlation coefficients be expected between the performance of these extractants. Chang & Juo (1963) have observed that when two extractants similar in selectivity of dissolution are applied to a group of soils with a similar phosphate distribution pattern, it is most likely that the values of available P determined by these two methods will be highly correlated.

Among the cultivars, Suakoko 8 recorded the highest mean P uptake of 1522 mg plant^{-1} while the susceptible variety, Bouake 189, recorded the lowest, 1336 mg plant^{-1} (Table 5). Generally, rice plants grown on the sandy soils (Soils 2, 5, 14 and 15) recorded low dry matter (ranging between 1

TABLE 5

Shoot Dry Weight and P Uptake at Maximum Tillering Stage of Three Lowland Rice Cultivars Grown in the Greenhouse under Submerged Conditions Without Application of Plant Nutrients on 15 West African Rice Soils

	Shoot dry weight (g plant^{-1})				*P uptake (mg plant^{-1})*			
Soil no.	*Bouake 189*	*CK 4*	*Suakoko 8*	*Mean*	*Bouake189*	*CK 4*	*Suakoko 8*	*Mean*
1	7	7	7	7	1885	1591	1858	1778
2	4	3	5	2	928	724	1423	1025
3	11	12	11	11	2947	2594	2641	2727
4	5	7	7	6	1271	1345	1925	1515
5	2	3	2	2	716	811	421	649
6	6	6	8	7	1220	1095	1795	1370
7	7	6	8	7	1469	1104	1852	1475
8	5	7	7	6	1236	1507	1817	1520
9	8	9	7	8	1787	2432	2075	2098
10	5	7	7	7	1490	2198	1290	1659
11	4	5	5	5	836	1092	982	970
12	10	12	11	11	2055	2359	2138	2184
13	5	6	7	6	1251	1343	1343	1407
14	1	1	3	2	394	325	590	436
15	3	3	2	3	560	522	388	490
Mean	6	6	6	6	1336	1403	1522	1420
SE	——	0.65	——	0.38	——	182	——	105
CV (%)	17				22			

and 5 g plant^{-1}). Plants on Soils 3 and 12 (clay and silt types) produced high mean dry weight values of 1 1g plant^{-1}.

There was a higher and significant relationship between Oxalate-P and plant P uptake than with Bray II Olsen-available P. The correlation coefficients (r) between Oxalate-P and P uptake of Bouake 189, CK 4 and Suakoko 8 were 0.75 ($P<0.001$), 0.69 ($P=0.004$), and 0.55($P=0.05$), respectively. Olsen-P, however, recorded slightly lower correlation coefficients with P uptake (i.e., $r=0.73$, $P<0.002$; $r = 0.62$, $P = 0.04$; and $r=0.51$, $P<0.002$; respectively). Bray II-P, on the other hand, recorded negative correlation coefficients (Table 6). Similarly, lower correlation coefficients were recorded by EDTA-P with plant P uptake as compared with Olsen-P. For the three varieties, high and significant correlation between extractable P and dry matter (DM) production was in the order: Oxalate-P>Olsen-P>EDTA-P. Although Olsen and Bray available P have been accepted as good indices for P availability, for simultaneous extraction of Fe and P from iron-rich, lowland rice soils, EDTA-P or Oxalate-P seem more useful.

TABLE 6

Correlation Between Bray and Oslen Available P and Dry Matter and P Uptake of Three Rice Cultivars Grown on 15 West African Rice Soils Under Submerged Conditions in the Greenhouse

	Dry matter				*P uptake*			
Analytical method	*Bouaké 189*	*CK 4*	*Suakoko 8*	*All cultivars*	*Bouake 189*	*CK 4*	*Suakoko 8*	*All cultivars*
Bray II-P	-0.47 (0.07)	-0.62 (0.01)	-0.44 (0.09)	-0.55 (0.03)	-0.48 (0.07)	-0.69 (0.004)	-0.42 (0.12)	-0.57 (0.03)
Olsen-P	0.57 (0.03)	0.54 (0.04)	0.48 (0.07)	0.52 (0.05)	0.73 (0.002)	0.62 (0.04)	0.51 (0.05)	0.62 (0.01)

Probability levels of significance, *P*, in parenthesis

Conclusion

EDTA and oxalate can be used to simultaneously extract Fe and P in rice soils, but EDTA is more reliable than oxalate to predict P availability to lowland rice. The usefulness of an extractant is based on the selectivity in dissolution of inorganic phosphates. For lowland rice soils, Fe-P, and to a large extent Al-P, are the major contributors to P nutrition in rice.

REFERENCES

Ahenkorah, Y. (1968) Phosphorus-retention capacities of some cocoa-growing soils of Ghana and their relationship with soil properties. *Soil Sci.* **105**, 24-30.

Alexander, T. G. & Robertson, J. A. (1972) EDTA extractable phosphorus in relation to available and inorganic forms in soils. *Soil Sci.* **114**, 69-72.

Blanchair, R. W. & Caldwell, A. C. (1964) Phosphorus uptake by plants and readily extractable phosphorus in soils. *Agron. J.* **56**, 218-221.

Borggaard, O. K. (1981) Selective extraction of amorphous iron oxides by EDTA from soils of Denmark and Tanzania. *J. Soil Sci.* **32**, 427-432.

Borggaard, O. K. (1988) Phase identification by selective dissolution techniques. In *Iron in soils and clay minerals* (ed. J. W. Stucki, B. A. Goodman and U. Schwertmann), pp. 83-98. Dordrecht. The Netherlands, Ridel Publishing Co.

Bray, R. H. & Kurtz, L. T. (1945) Determination of total, organic, and available forms of phosphorus in soils. *Soil Sci.* **59**, 39-45.

Campbell, J. M. & Schwertmann, U. (1984) Iron oxide mineralogy of placic horizons. *J. Soil Sci.* **35**, 569-582.

Chang, S. C. & Juo, S. R. (1963) Available P in relation to forms of phosphates in soils. *Soils Sci.* **95**, 91-96.

Chapman, H. D. (1965) Cation exchange capacity. In *Methods of soil analysis* (ed. C. A. Black *et al.*), pp. 891-990. *Agronomy* **9**. Madison, W. I., American Society of Agronomists.

Cholitkul, W. & Tyner, E. H. (1971) Inorganic phosphate fractions and their relation to some chemical indices of phosphate availability for some lowland rice soils of Thailand. In *Proceedings of the International Symposium on Fertility Evaluation*, pp. 7-20. Indian Society of Soil Science.

Ekpete, D. M. (1976) Evaluation of chemical methods for the determination of available phosphorus in waterlogged soils. *Soil Sci.* **121**, 217-221.

Enwezor, W. O. (1977) Soil testing for phosphorus in some Nigerian soils: 1. Comparison of methods of determining available phosphorus in some soils of southeastern Nigeria. *Soil Sci.* **123**, 48-53.

Enwezor, W. O. & Moore,.A. W. (1966) Phosphorus status of some Nigerian soils. *Soil Sci.* **100**, 322-328.

FAO (1988) *Soil map of the world.* Revised Legend. *World Resources Report* **60**. Rome, Food and Agriculture Organisation.

Gee, G. W. & Bauder, J. W. (1986) Particle size analysis. *In Methods of soils analysis.* Part 1-*Physical and mineralogical methods* (ed. A. Klute), pp. 383-411). *Agronomy* **9**. Madison, WI, American Society of Agronomists.

Haque, I. & Lahai, A. C. (1977) Assessment of soil analytical methods for available phosphorus in some Sierra Leone soils. *Ghana Jnl agric. Sci.* **10**, 199-204.

Hartwig, R. C. & Loepert, R. H. (1993) Evaluation of soil iron. In *Characteristics of iron stress response* (ed. L.C. Barton and B. C. Hemming). New York, USA. Academic Press.

IITA (1984) *Soil and plant analysis study guide for agricultural laboratory directors and technologists working in tropical research.* Ibadan, Nigeria: IITA.

John, M. K. (1970) Colorimetric determination of phosphorus in soil and plant materials with ascorbic acid. *Soil Sci.* **109**, 214-220.

Khalid, R. A., Patrick Jr., W. H., & Delaune, R. D. (1977) Phosphorus sorption characteristics of flooded soils. *Soil Sci. Soc. Am. Proc.* **41**, 303-310.

Mahapatra, I. C. & Patrick Jr., W. H. (1971) Evaluation of phosphate fertility in waterlogged soils. *Sym. Soil Fert. Eva.* **1**, 53-61.

Mamo, T. & Haque, I. (1991) Phosphorus status of some Ethiopian soils. II. Forms and distribution of inorganic phosphates and their relation to available phosphorus. *Trop. Agric.* (Trin.). **68**.(1), 2-8.

Morgan, M. F. (1937) The universal soil testing system. *Conn. agric. Exp. Stn Bull.* **392**.

Murphy, J. & Riley, J. P. (1962) A modified single solution method for the determination of phosphate in natural waters. *Anal. Chem. Acta.* **27**, 31-36.

Narteh, L. T. & Sahrawat, K. L. (1997) Potentially mineralizable nitrogen in West African lowland rice soils. *Geoderma* **76**, 145-154.

Nelson, D. W. & Sommers, L. E. (1982) Total carbon, organic carbon and organic matter. In *Methods of soil analysis,* Part 2 (ed. A. L. Page *et al.*), pp. 539-579. *Agronomy* 9 (2nd edn).

Olsen, S. R., Cole, C. V., Watanabe, F. S. & Dean, L. A. (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *US Dept. Agric. Circ.* **939**.

Olsen, S. R. & Sommers, L. E. (1982) Phosphorus. In *Methods of soil analysis*, Part 2 (ed. A. L. Page *et al.*), pp. 403-427. *Agronomy* **9** (2nd edn).

Owusu-Bennoah, E. & Acquaye, D. K. (1989) Phosphate sorption characteristics of selected major Ghanaian soils. *Soil Sci.* **148**, 114-122.

Peterson, G. W. & Corey, R. B. (1966) A modified Chang and Jackson procedure for routine fractionation of inorganic soil phosphate. *Soil Sci. Soc. Am. Proc.* **30**, 563-565.

Randall, G. W. & Grava, J. (1971) Effect of soil: Bray no. I ratios on the amount of phosphorus extracted from calcareous Minnesota soils. *Soil Sci. Am. Proc.* **35**, 112-114.

Sah, R. N. & Mikkelsen, D. S. (1986) Effects of anaerobic decomposition of organic matter on sorption and transformation of phosphate in drained soils: 1. Effects on phosphate sorption. *Soil Sci.* **142**(5), 267-273.

Sah, R. N. & Mikkelsen, D. S. (1989) Phosphorus .behaviour in flooded-drained soils: I- Effects on phosphorus sorption. *Soil Sci. Soc. Am. J.* **53**, 1718-1722.

Sahrawat, K. L. (1977) EDTA extractable phosphorus in soils as related to available and inorganic phosphorus forms. *Commun. Soil Sci. Plant Anual.* **8**, 281-287.

SAS (1987) *SAS user's guide: Statistics*. Cary, N. C., SAS Institute Inc.

Shahandeh, H., Hossner, L. R. & Turner, F. T. (1994a) Phosphorus relationship in flooded soils with low extractable phosphorus. *Soil Sci. Soc. Am. J.* **58**, 1184-1189.

Shahandeh, H., Hossner, L. R. & Turner, F. T. (1994b) A comparison of extraction methods for extracting Fe and P in flooded rice soils. *Plant Soil* **165**, 219-225.

Sheldrick, B. H. (1984) *Analytical methods manual. LRRI No.* **84-30.** Ottawa. Canada, Land Resources Research Institute.

Smillie, G. W. & Syers, J. K. (1972) Calcium flouride formation during extraction of calcareous soils and in soils to which rock phosphate has been added. *Soil Sci. Soc. Am. Proc.* **36**, 25-30.

Syers, J. K., Smillie, G. W. & Williams, J. D. H. (1972) Calcium flouride formation during extraction of calcareous soils with flouride. I. Implications to inorganic P fractionation schemes. *Soil Sci. Soc. Am. Proc.* **31**, 752-756.

Troug, E. (1930) The determination of the readily available phosphorus of soils. *J. Am. Soc. Agron:* **22**, 879.

Willet, I. R. (1986) Phosphorus dynamics in relation to redox processes in flooded soils. *Trans. 13th int. Congr. Soil Sci.* **6**, 748-755.

Willet, I. R. & Higgins, M. L. (1978) Phosphate sorption by reduced and reoxidized rice soils. *Aust. J. Soil Res.* **16**, 319-326.

Willet, I. R. & Higgins, M. L. (1980) Phosphorus sorption and extractable iron in soil during irrigated rice-plant crop rotation. *Aust. J. exp. Agric. Anim. Husb.* **20**, 346-353.

Williams, C. H. (1950) Studies on soil phosphorus. I. A method for partial fractionation of soil phosphorus. *J. agric. Sci.* **40**, 233-242.