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Determining Phosphorus Adsorption Isotherm in Soil and its Relation to Soil Characteristics

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Abstract: Phosphorus (p) adsorption characteristics of 5 soil samples were studied in soils of Omidie, Southeastern Iran during 2009/2010 cropping season. The concentrations of the solutions were 4, 12, 25, 50, 70 mg P L⁻¹. Some soil properties as well as selected P-adsorption characteristics were studied in these soils. Results show for this study Langmuir adsorption isotherm has better match with phosphorus adsorbed data and has maximum R-square. Differences in P-adsorption was greatly influenced by Soil Organic Carbon (SOC), soil pH, exchangeable calcium, exchangeable aluminium. Regression analysis shows that SOC and Alsat were the highest predictors of P-adsorption in soils of the study site. There is need for inclusion of more soil chemical, physical and mineralogical properties in predicting soil P-adsorption to enhance reliability of information.

Key words: Adsorption isotherm, Langmuir, land use, phosphorus, soil

INTRODUCTION

The release of Phosphorus (P) through natural processes is very scanty, whereas the sinks for P, especially at the floor of oceans are huge. In most agro ecosystem, P-losses outweigh gains and unless augmented by man, P-cycles lose momentum. This is particularly true for tropical upland soils where deficiency of P is the most prevalent initial constraint to plant growth (Von Uexkull, 1989). The uncertainties about P-chemistry in soils are due to its strong interaction with many organic and inorganic solid phases, continual uptake by plants and micro-organisms, continual return from organic decay and slow reaction rates (Isirimah *et al.*, 2003). Although P-adsorption capacities of soil are influenced by Fe and Al oxides (Hakim, 2002), exchangeable calcium and magnesium, soil texture, porosity, pH, ionic strength and hydraulic conductivity (Bubba *et al.*, 2003), it has been reported that land utilization type influences P-adsorption capacity (Amapu *et al.*, 2000).

Man's land use activities affect global P-cycle. If p is applied to soil in excess of crop requirement, P will generally build up in the soil (Zhang *et al.*, 2005) and this increases the chances of P loss in the soil system (Sharpley *et al.*, 1999). Often, farmers practice land application of animal manure in order to meet crop Nitrogen (N) needs and this results in over application of P as N/P ratio of most crops and pastures is 8:1 (USDA, 2001) while that of animal manures is 4:1 (Zhang *et al.*, 2004). In paddy soils, Isirimah *et al.* (2003) attributed high and continued phosphate availability to cycling of P between iron and aluminium forms.

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Nnaji *et al.* (2002) observed variation in available phosphorus when soils of five land utilization types were evaluated. They reported that soils under maize-pepper intercrop, cassava-maize-pepper intercrop, sole cassava and cassava-maize intercrop were 68, 27, 14 and 11%, respectively higher than forest soil in available P. On highly weathered soils of Kenya, maize (*Zea mays* L.) yield doubled by applications of 50 kg P/ha/year as triple super phosphate (Bunemann *et al.*, 2004b) while crops had significant yield when it followed one season *Crotalaria grahamiana* planted fallow (Niang *et al.*, 2002; Smestad *et al.*, 2002). Application of 2 t ha⁻¹ ash was optimum for soil pepper production and resulted to relatively high soil P after the treatment (Odedina *et al.*, 2003). Intensive donkey drawn tillage on a steep slope led to a decline of available P within the tilled layer of 0-15 cm in upper and middle portions of the slope (Li *et al.*, 2004).

Phosphorus is a critical element in natural and agricultural ecosystems throughout the world (Onweremadu, 2007) as its limited availability is often the main constraint for plant growth in highly weathered soils of the tropics (Bunemann *et al.*, 2004a). Phosphorus deficiency problems are common in well-weathered oxisols and ultisols because of strong acidic reactions and abundance of Al and Fe ions (Saleque *et al.*, 2004) and the situation can be worsened with inappropriate P management (Saleque *et al.*, 1998) Rice removed about 2 to 3 kg P for 1 mg of grain produced (Timsina and Connor, 2001). All these show that P-availability and use by plants vary among plants. We hypothesize that P-availability and uptake relate to sorption characteristics of soil. Pased on the above, the major objective of this study was to investigate P-sorption characteristics as influenced by Land Utilization Type (LUT).

MATERIALS AND METHODS

Study Area

This study was carried out during the 2009/2010 cropping season atomidie, Southeastern Iran. The study site is located on latitude 31-53-14 N and 48-40-34 E and with an elevation of 55 m (handheld Global Positioning System-GPS) receiver (Garmin Ltd., Kansas, USA). The predominant parent material for underlying the area from which most soil formed is the Coastal Plain Sands (Benin formation) of the Miocene-Oligocene geological era. Soil are referred to as: silty, clay, loam and are characteristically acidic, of low cation exchange capacity, low base saturation, low fertility status and suffer from multiple nutrient deficiencies (Oti, 2002). The area has a semiarid tropical climate (Igwe and Stahr, 2004) with two distinct seasons, namely wet and dry seasons. Rainfall distribution is bimodal with peaks during the months of July and September. Temperatures are high and change only slightly during the year.

Experimental Design

The study identified 5 points of farmland located within the same area and at close proximity. These points have been consistently under cultivation for 15 years.

These soil samples were air-dried and sieved using 2 mm sieve in readiness for laboratory analysis. Laboratory analysis: Particle size distribution was determined by hydrometer method (Gee and Or, 2002). Soil pH was measured in 1:2.5 soil/liquid ratio in 0.1 N KCl (Herdershot *et al.*, 1993). Soil Organic Carbon (SOC) was estimated by combustion at 8400°C (Wang and Anderson, 1998). Cation Exchange Capacity (CEC) was determined by percolating 2.5 g soil with 100 mL of 1 M ammonium chloride for about 4 h. Before percolating soil samples, samples were soaked with extraction solution overnight.

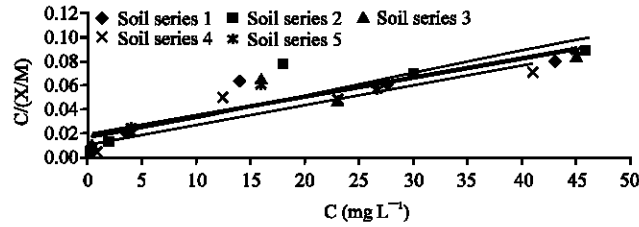


Fig. 1: Linear Langmuir adsorption isotherm

Adsorption Isotherms

A gram of soil sample was equilibrated with 25 mL of varying concentrations of P in 0.01 M CaCl₂ solution in 50 mL centrifuge tubes. The concentrations of the solutions were 4, 12, 25, 50, 70 mg P L⁻¹. The tubes were shaken for 24 h on an end-to-end shaker at 150 oscillations per 60 sec. The samples were then centrifuged for 10 min at 5211 ×g and the supernatant decanted. The P in solution was then quantified calorimetrically using the ascorbic acid method. The amount of P adsorbed was determined by the difference between initial and final amounts of P in solution. Duplicate analyses were conducted on all soil samples. Phosphorus adsorption isotherms were estimated with the linearized form of the Langmuir: van haui, freundlich, linear, equation and when specify the best adsorption equation in this research (Langmuir), then relationship soil properties with p sorption was determined Langmuir equation parameter is shown below with fitting the data is determined that adsorbtion isotherm with Langmuir adsorption constants isotherm this model is suitable for predicting the amount of p adsorbption fitting the data with this isotherm are shown in Fig. 1.

$$\frac{C}{S} = \frac{1}{kS_{max}} + \frac{C}{S_{max}} \tag{1}$$

Where:

- S = Total of amount of P retained
- C = Concentration of P after 24 h equilibrium
- S_{max} = P-sorption maximum

The S_{max} was calculated by regressing C/S versus C, where, C is the equilibrium solution P concentration and S is adsorbed P. The reciprocal of the slope of mean regression is S_{max} (Zhang *et al.*, 2005).

Computations

The following calculations were made:

- The amount of P remaining in solution was taken as equilibrium concentration and the difference between the initial concentration and equilibrium concentration was taken as adsorbed P
- The adsorption isotherm versus equilibrium concentration was plotted for each soil being investigated to obtain a straight line with slope of 1/b and intercept of 1/kb
- The following form of Langmuir equation:

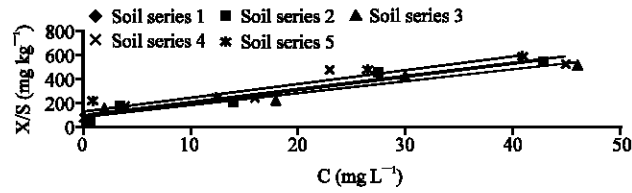


Fig. 2: Linear adsorption isotherm

$$C/C \times 1 m = 1/kb + c/b$$

was used to obtain adsorption capacities and constants related to bonding energy.

Where:

- C = P concentration in equilibrium solution
- x/m = P adsorbed by soil
- b = Adsorption maximum
- k = Constant related to bonding energy of soil for P (affinity constant)

The linear isotherm is defined by:

$$C_s = K \times C_m \quad (2)$$

Where:

- C_s = The concentration of the solute on the surface
- C_m = The concentration of the solute in the mobile phase
- K = Adsorption constant of the solute to the stationary phase surface

The Freundlich isotherm is defined by fitting the data. With this model determined that mean square error for this method is 92.4, this indicates that this model is suitable for predicting the amount of p adsorption. Adsorption isotherm with linear parameters are shown in Fig. 2.

$$C_s = K_f \times C_m^n \quad (3)$$

Where:

- C_s = Concentration in solid phase
- c = Concentration in fluid phase
- K_f = Freundlich adsorption constant
- n = Freundlich exponent

Fitting the data. With this model determined that mean square error for this method is 86.4, this indicates that this model is suitable for predicting the amount of p adsorption. Adsorption isotherm with Freundlich, parameters are shown in Fig. 3.

The Van huay isotherm is defined by:

$$X/m = m + n\sqrt{c} \quad (4)$$

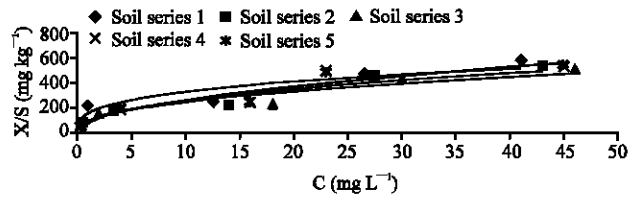


Fig. 3: Freundlich adsorption isotherm

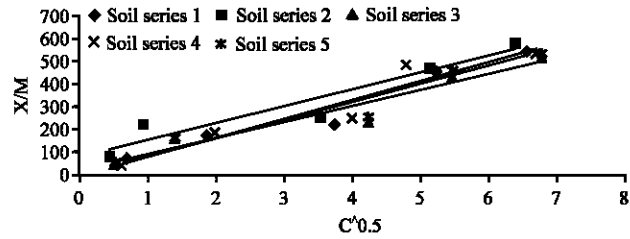


Fig. 4: Van huay adsorption isotherm

Where:

- c = Concentration in fluid phase
- n = Van huay adsorption coefficient
- m = Van huay constant parameter

Fitting the data With this model determined that mean square error for this method is 84.2, this indicates that this model is suitable for predicting the amount of p adsorbption adsorbtion isotherm with Van huay parameters are shown in Fig. 4.

Statistical Analysis

Correlation and regression analyse were performed to relate some soil properties and P-adsorption characteristics using CHB sorption spreadsheets ver 1.4

RESULTS

Soil properties are shown in Table 1. Soil were generally clay in all the field, indicating similarity in parent material source. Slight variations in soil texture and other properties could be attributed to land use history and differential impact of climatic factors on soilsand. Phosphorus adsorption characteristics are shown in Table 2 and 3. Table 2 and 3 indicate that all adsorption equations have good ability to predicting the amount of phosphorus adsorption indicating variabilities in the P-adsorption characteristics of studied soil. Values of Langmuir adsorption constants, equilibrium P and buffering capacity for soils are shown in Table 4. The MBC index of ID = 2 series is more than other soils, wich can be due to the high value of ALSat and SOC in this sample. Also the amounts of SPR and PSI index is higher than other soils the number 4 soil series with more DPS than other soils has more leaching capability than other soils.

Simple correlation result between P-adsorption characteristics and some soil properties are shown in Table 5. The pH and ALSat are goodly indicate amount of adsorption phosphorus in soil samples. Soil clay and ALSat influenced adsorption maxima of P in soils.

Table 1: Selected properties of the studies soil

RAW	Clay	Silt	Sand	SOC	Ca	Al	CEC	Alsat	pH (KCl)
	-(g kg ⁻¹)				-(cmol kg ⁻¹)			(g kg ⁻¹)	
1	530	60	610	14.0	6.6	4.0	19.0	42	6.1
2	300	90	350	25.0	6.8	3.5	14.0	45	6.0
3	350	420	230	30.0	7.5	4.4	18.0	56	6.8
4	640	200	160	12.0	4.3	5.3	20.5	32	6.5
5	300	160	560	23.0	8.2	3.6	15.5	43	6.0

SOC: Soil organic carbon, Alsat: Aluminium saturation, Ca: Calcium, Al: Aluminium, CEC: Cation exchange capacity

Table 2: Values of Langmuir adsorption constants (adsorption maximum affinity constant)

Soil ID	b (mg P kg ⁻¹)	k	r-s	b1 (mg P kg ⁻¹)	k1	b2 (mg P kg ⁻¹)	k2	r-s
1	666	0.08	91**	105	17.0	987	0.02	83**
2	598	0.17	95**	90	16.2	1292	0.01	87**
3	650	0.12	92**	76	14.0	1002	0.03	83**
4	860	0.10	93**	54	16.0	999	0.04	82**
5	554	0.08	91**	97	18.0	1346	0.01	78**

**Significant at p = 0.01, *Significant at p = 0.05, NS: Not significant

Table 3: Values of linear, Van huay, Freundlich, adsorption parameters

Soil ID	Equation						
	Freundlich			Van huay		Linear	
	1/n	k	r-s	n	r-s	k	r-s
1	0.44	92.1	83**	80.45	91**	10.9	86**
2	0.32	156.0	87**	74.49	90**	11.1	79**
3	0.43	90.0	90**	83.00	76**	12.2	84**
4	0.62	111.0	87**	73.00	78**	14.1	81**
5	0.30	82.0	85**	56.00	86**	15.8	82**

**Significant at p = 0.01, *Significant at p = 0.05, NS: Not significant

Table 4: Values of phosphorus characteristics adsorption parameters in samples

Soil ID	MBC	PBC	BI	SBC	SPR	PSI	DPS (%)
1	53.28	10.90	40.5	50.8	42.4	193	8.5
2	101.60	11.14	49.9	92.0	114.7	218	9.2
3	78.00	13.00	38.7	57.0	47.0	135	10.5
4	86.00	12.40	68.8	91.0	113.2	157	15.0
5	44.32	15.00	24.6	50.0	45.0	172	9.5

PSI: Phosphorus sorption index, BI: Buffering index, DPS: Degree of phosphorus saturation, PBC: Phosphorus buffering capacity, SBC: Standard buffering capacity, MBC: Maximum buffering capacity, SPR: Standard phosphorus requirement

Table 5: Simple correlation (r) between Langmuir adsorption constants, selected soil characteristics (n = 5)

Soil properties	b	k
pH (KCl)	0.25**	0.68*
SOC (g kg ⁻¹)	2.1NS	3.3NS
Ca (cmol kg ⁻¹)	- 0.60 *	0.53 NS
Alsat (g kg ⁻¹)	0.56**	0.78**
Clay (g kg ⁻¹)	0.53**	0.35*

SOC: Soil organic carbon, Ca: Calcium, Alsat: Aluminium saturation, b: Adsorption maxima, k: Affinity constant, **Significant at p = 0.01, *Significant at p = 0.05, NS: Not significant

Similar findings were made by Zhang *et al.* (2005) when Soc was correlated with S_{max} ($r = 0.74$) while Borling *et al.* (2001) found significant relationships between oxides of aluminium and S_{max} . Under, there were negative relationship between P adsorption capacity and SOC. Unlike results of other researchers (Dodor and Oya, 2000; Zhang *et al.*, 2005) soil pH had significant ($p < 0.01$) relationship with P-adsorption. Exchangeable Ca was significantly and negatively correlated ($p < 0.05$) with P-adsorption and this contrasts the results of other researchers (Sims *et al.*, 2002). Phosphorus predictive capacities of individual soil properties

Table 6: Pedotransfer functions relating adsorption of P (Y) to some soil properties (n = 5)

Independent variable	Regression equation	R ² -value
pH (KCl)	Y = 166 pH-382	0.25
SOC (g kg ⁻¹)	Y = -10.3 OC+880	0.44
Ca (cmol kg ⁻¹)	Y = -75.6 Ca+1169	0.59
Alsat (g kg ⁻¹)	Y = -8.4 Alsat+1033	0.38
Clay (g kg ⁻¹)	Y = 6.9 Clay+370	0.82

are shown in Table 6. Table 6 show that clay in the soil can be a good feature to predict phosphorus absorption in soil and its ability is more than other indices of soil. The amount of calcium in the soil with regression coefficient equal to 59% can use to predict Amount of phosphorus absorbed in the soil.

DISCUSSION

Soil were generally clay in all the field, indicating similarity in parent material source. Slight variations in soil texture and other properties could be attributed to land use history and differential impact of climatic factors on soils. Onweremadu *et al.* (2007) noted slight temporal textural differences in arable soils resulting from continuous cultivation. Soils with largest cation exchange capacities offer greatest resistance to change in pH and are most strongly buffered (Foth, 1984).

The standard P requirement values, that is, P adsorbed at a standard concentration. There exists two distinct linear portions as calculated from the regression equations implying that these soil had two adsorption maxima (b) and affinity constants (k). It is argued that P-adsorption capacity as suggested by the population of sites in the low equilibrium P (first linear portion) is more important than that of the second linear portion as they represent P-levels for crop production when fertilized (Udo, 1981). High values of k (affinity constants), implying greater bonding energy in the first linear portions show that the tenacity of P-adsorption is higher at low P equilibrium concentration.

In all soils, P-adsorption characteristics were influenced by some soil properties, although at varying levels. Soil properties that correlated with P-adsorption were pH, SOC Alsat, exchangeable Ca and clay. Similar relationships were recorded by Burt *et al.* (2002). Studied soils are highly weathered and the presence of organic matter reduce P-sorption capacity (Gillman *et al.*, 1989) due to direct result of competition for sorption sites between phosphate and organic ligands (Hakim, 2002). He also reported that the same competition exists between Al and Ca. It is also possible that organic matter reduces positive charge on variable charge surfaces by lowering pH and this decreases the attraction of P to the soil surface, indicating that anthropogenic activities do alter soil properties.

CONCLUSION

Sound knowledge about P-sorption properties in soils under different soils is necessary in sustained use of soil for crop production. Results of this study revealed differences in P- adsorption and identified soil pH and SOC as main predictors of P activity in the study areas. There is need for more intensive sampling and multiple regression of physical, chemical and mineralogical properties of soils for more reliable information on soil properties on prediction of P.

REFERENCES

- Amapu, I.Y., V.O. Chude, U. Singl, J.M. Jubrin and S. Adam, 2000. Testing a dynamic phosphorus model in the sub-humid Nigeria savannah agro-ecology. Proceedings of the 26th Annual Conference of Soil Science Society of Nigeria, Oct. 30-Nov. 3, Ibadan, Oyo State Nigeria, pp: 270-278.
- Borling, K.E., E. Oxtabong and E. Barberies, 2001. Phosphorus sorption in relation to soil properties in some cultivated Swedish soils. *Nutr. Cycling Agroecos.*, 59: 39-46.
- Bubba, M.O., C.A. Arias and H. Porix, 2003. Phosphorus adsorption maximum of sands for use as media in subsurface flow cultivated reed beds as measured by the *Langmuir adsorption* isotherms. *Water Res.*, 37: 3390-3400.
- Bunemann, E.K., D.A. Boss, P.C. Smithson and E. Frossard, 2004a. Microbial community composition and substrate use in a highly weathered soil as affected by crop rotation and P-fertilization. *Soil Biol. Biochem.*, 36: 889-901.
- Bunemann, E.K., F. Steinebruner, P.C. Smithson, E. Frossard and A. Oberson, 2004b. Phosphorus dynamics in a highly weathered soil as revealed by isotopic labelling techniques. *Soil Sci. Soc. Am. J.*, 68: 1645-1655.
- Burt, R., M.D. Mays, E.C. Benham and J.F. Ma, 2002. Phosphorus characterization and correlation with properties of selected benchmark soils of the United States. *Commun. Soil Sci. Plant Anal.*, 33: 117-141.
- Dodor, D.E. and K. Oya, 2000. Phosphorus sorption characteristics of major soils in Okinawa, Japan. *Commun. Soil Sci Plant Anal.*, 31: 277-288.
- Foth, H.D., 1984. *Fundamentals of Soil Science*. 7th Edn., John Wiley and Son, New York.
- Gee, G.W. and D. Or, 2002. Particle Size Analysis. In: *Methods of Soil Analysis. Part 4 Physical Methods*, Dane, J.H. and G.C. Topp (Eds.). ASA and SSSA, Madison, WI, pp: 255-293.
- Gillman, G.P., J. Shamsuddin and L.C. Bell, 1989. Soil chemical parameters and organic matter in soil management: Soil management and smallholder development in the pacific islands. Proceedings of a Workshop Organized by the International Board for Soil Research and Management, (IBSRM'89), Bangkok, Thailand, pp: 141-153.
- Hakim, N., 2002. Organic matter for increasing P fertilizer use efficiency of maize ultisol by using ³²P technique. Proceedings of Symposium World Congress on Soil Science, Aug. 14-21, Bangkok, Thailand, pp: 229-229.
- Herdershot, W.H., H. Lalande and M. Duquette, 1993. Soil Reaction and Exchangeable Acidity. In: *Soil Sampling and Methods of Analysis*, Carter, M.R. (Ed.). Lewis Publishers, Boca Raton, FL., pp: 141-145.
- Igwe, C.A. and K. Stahr, 2004. Waterstable aggregates of flooded chemical properties. *Aust. J. Soil Res.*, 42: 171-179.
- Isirimah, N.O., A.A. Dickson and C. Igwe, 2003. *Introductory Soil Chemistry and Biology for Agriculture and Biotechnology*. Osia Publishers Ltd., Diobu, Port Harcourt, Nigeria.
- Li, Y., G. Tian, M.J. Lindstrom and H.R. Bork, 2004. Variation of surface soil quality parameters by intensive donkey-drawn tillage on seep slope. *Soil Sci. Soc. Am. J.*, 68: 907-913.
- Niang, A.I., B.A. Amadalo, J. de Wolf and D.M. Gathumbi, 2002. Specials screening for short-term planted fallows in the highlands of Western Kenya. *Agrofor. Syst.*, 56: 145-154.
- Nnaji, G.U., C.L.A. Asadu and J.S.C. Mbagwu, 2002. Evaluation of physico-chemical properties of soils under selected agricultural land utilization types. *Agro-Science*, 3: 27-33.

- Odedina, S.A., J.N. Odedina, S.O. Ayeni, S.A. Arowojolu, S.D. Adeyeye and S.O. Ojениyi, 2003. Effect of types of ash on soil fertility nutrient availability and yield of tomato and pepper. *Nig. J. Soil Sci.*, 13: 61-67.
- Onweremadu, E.U., 2007. Predicting phosphorus sorption characteristics in highly weathered soils of South-Eastern Nigeria. *Res. J. Environ. Sci.*, 1: 47-55.
- Onweremadu, E.U., E.T. Eshett and G.E. Osuji, 2007. Temporal variability of selected heavy metals in automobile soil. *Int. J. Environ. Sci. Fed.*, 4: 35-41.
- Oti, N.N., 2002. Discriminate functions for classifying erosion degraded lands at Otamiri, Southeastern Nigeria. *Agro-Sci.*, 3: 34-40.
- Saleque, M.A., M.J. Abedin, G.M. Panaullah and N.I. Bhuiyan, 1998. Yield and phosphorus efficiency of some lowland rice varieties at different levels of soil-available phosphorus. *Commun. Soil Sci. Plant Anal.*, 29: 2905-2916.
- Saleque, M.A., U.A. Naher, A. Islan, A.B.M.B.U. Pathan, A.T.M.S. Hossain and C.A. Meisner, 2004. Inorganic and organic phosphorus fertilizer effects on the phosphorus fractionation in wetland rice soils. *Soil Sci. Soc. Am. J.*, 68: 1635-1644.
- Sharpley, A.N., T.C. Daniel, J.T. Sims, J. Lemunyon, R. Stevens and R. Parry, 1999. *Agricultural Phosphorus and Eutrophication*. USDA Mission Publ. ARS-149. US-Gov. Prints Office, Washington, DC. USA.
- Sims, J.T., R.O. Maguire, A.B. Leytem, K.L. Gartely and M.C. Pautler, 2002. Evaluation of Mehlich-3 as an agri-environmental soil phosphorus test for the Mid-Atlantic united states of America. *Soil Sci. Soc. Am. J.*, 66: 2016-2032.
- Smestad, B.T., H. Tiessen and R.J. Buresh, 2002. Short fallows of *Tithonia diversifolia* and *crotalaria grahamiana* for soil fertility improvement in Western Kenya. *Agrofor. Syst.*, 55: 181-194.
- Timsina, J. and D.J. Connor, 2001. The productivity and management of rice-wheat systems: Issues and challenges. *Field Crops Res.*, 69: 93-132.
- Udo, E.J., 1981. Phosphorus forms, adsorption and desorption in selected Nigeria soils. *Nig. J. Soil Sci.*, 2: 51-66.
- USDA, 2001. *Comprehensive Nutrient Management Planning Technical Guidance*. USDA-NRCS, Washington DC.
- Von Uexkull, H.R., 1989. Nutrient Cycling. In: *Soil Management and Smallholder Development in the Pacific Islands*, Pushparajah, E. (Ed.). IBSRM, Bangkok, Thailand, pp: 121-132.
- Wang, D. and D.W. Anderson, 1998. Direct measurement of organic carbon content in soils by the Leco CR-12 carbon analyzer. *Commun. Soil Sci. Plant Anal.*, 29: 15-21.
- Zhang, H., G. Jorgenson and M. Fram, 2004. *Managing Phosphorus from Animal Manure*. Oklahoma State University, Stillwater, UK.
- Zhang, H., J.L. Schroder, J.K. Fuhrman, N.T. Basta, D.E. Storm and M.E. Payton, 2005. Path and multiple regression analyses of phosphorus sorption capacity. *Soil Sci. Soc. Am. J.*, 69: 96-106.