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PRINCIPAL COMPONENT ANALYSIS OF FACTORS DETERMINING PHOSPHATE ROCK DISSOLUTION ON ACID SOILS

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ABSTRACT

Many of the agricultural soils in Indonesia are acidic and low in both total and available phosphorus which severely limits their potential for crops production. These problems can be corrected by application of chemical fertilizers. However, these fertilizers are expensive, and cheaper alternatives such as phosphate rock (PR) have been considered. Several soil factors may influence the dissolution of PR in soils, including both chemical and physical properties. The study aimed to identify PR dissolution factors and evaluate their relative magnitude. The experiment was conducted in Soil Chemical Laboratory, Universiti Putra Malaysia and Indonesian Center for Agricultural Land Resources Research and Development from January to April 2002. The principal component analysis (PCA) was used to characterize acid soils in an incubation system into a number of factors that may affect PR dissolution. Three major factors selected were soil texture, soil acidity, and fertilization. Using the scores of individual factors as independent variables, stepwise regression analysis was performed to derive a PR dissolution function. The factors influencing PR dissolution in order of importance were soil texture, soil acidity, then fertilization. Soil texture factors including clay content and organic C, and soil acidity factor such as P retention capacity interacted positively with P dissolution and promoted PR dissolution effectively. Soil texture factors, such as sand and silt content, soil acidity factors such as pH, and exchangeable Ca decreased PR dissolution.

[***Keywords***: Rock phosphate, dissolving, acid soils, principal component analysis]

INTRODUCTION

Phosphate rocks (PR) have been studied in Indonesia as an alternative to superphosphate (Pamin *et al*. 1997; Adiningsih and Fairhurst 1998). The effectiveness of PR is largely determined by the extent of PR dissolution in moist soil. The dissolution is influenced by many factors, including soil pH and pH buffering capacity, soil texture, humic acid, P status such as available P and P retention capacity, Ca status such as Ca exchange capacity and exchangeable Ca, root systems, and the presence of arbuscular mycorrhizal fungi (Bangar *et al*. 1985; Kanabo and Gilkes 1988; Acea and Carballas 1990; Robinson and Syers 1990; Bolland *et al*. 2001; Barea *et al*. 2002; Sikora 2002). Simple and multiple regression of the experimental data indicated that no single soil property adequately predicted PR dissolution in the soil, supporting the conclusions of Wright *et al*. (1992), Hughes and Gilkes (1986; 1994), and Bolland *et al*. (2001) from studies on a range of soils from several countries. Although some of these variables often correlate, they act as if independent and capable of predicting PR dissolution (Kyuma 1973; Kosaki *et al*. 1989; Yanai *et al*. 2001).

The ability to easily assess the extent of PR dissolution in soil would greatly simplify experiments designed to determine the most important soil properties governing the dissolution. To derive a prediction function for PR dissolution, it is important to quantify a number of soil characteristics, and then, carry out a multiple regression analysis using principal component analysis (PCA). PCA can be used to summarize the environmental data to evaluate the relationship between the variables and to extract the factors that may cause variation in dependent variable (Kosaki *et al*. 1989). In this context, environmental factor is soil chemical and physical characteristics and dependent factor is PR dissolution. To interpret each component, the term of factor pattern was introduced which is the product of eigenvector and the square root of the eigenvalue. In other words, eigenvalue (λ) is used to reduce variables which indicate high PC variance ($\lambda > 1$). The study aimed to identify factors determining PR dissolution and evaluate the magnitude of importance of these factors using PCA and multiple regression analysis.

MATERIALS AND METHODS

The experiment was conducted in Soil Chemical Laboratory, Universiti Putra Malaysia and Indonesian Center for Agricultural Land Resources Research and Development from January to April 2002. Indonesian phosphate rocks (IPR) from Ciamis Indonesia were ground to pass a 149-μm sieve. Results for total P and Ca determined by a tri-acid digestion method (O'Connor and Syers 1975), and for solubility in water (AOAC 1980) and 2% (w/w) citric and formic acids (European Economic Community 1977) are given in Table 1.

Soils and Incubation System

The locations of the study were identified using information from a geological map at a scale of 1:500,000 (Geological Survey of Indonesia 1963). Eight soils (Lampung Ultisols, Bogor Ultisols, Bogor Oxisols, Bogor Inceptisols, Sukabumi Inceptisols, Sukabumi Oxisols, Lebak Ultisols, and Subang Inceptisols) taken from surface soil samples (0-20 cm depth) were collected for soil analysis. Description and classification of these soils are presented in Appendix 1. It is expected that these selected soils may cause variation in P retention capacities of the soils (Appendix 2).

The soils were air dried and sieved (< 2 mm) before use. The following physical and chemical properties of soils (Appendix 2) were determined at Soil Chemical Laboratory, Indonesian Center for Agricultural Land Resources Research and Development: organic carbon content using the method of Walkey and Black (1934), pH in a 1 : 5 soil : water solution, P retention capacity using the method of Saunders (1965), Ca exchange capacity by extraction with 0.10 M KNO_3 of the Ca sorbed from 0.025 M $CaCl_2$ (Mackay *et al*. 1986), and estimation of plant available P by extraction with 0.50 M $NaHCO_3$ (Olsen *et al*. 1954). pH buffering capacity was determined at Soil Chemical Laboratory, Universiti Putra Malaysia by pH titration method (Kanabo and Gilkes 1988).

The IPR at a rate of 500 mg P kg^{-1} soil were placed in separate plastic containers containing 200 g of air dried soil, thoroughly mixed, and incubated at 25^{o}C. Duplicate samples of each P fertilizer soil combination were removed for analysis after 90 days. Analysis of the chemical properties was done on moist soil at 90% of field capacity. The extent of PR dissolution was measured from the change in P (ΔP) (Mackay *et al*. 1986) in soil amended with PR compared with a control (without PR) (Hanafi *et al*. 1992). Inorganic P in NaOH extracts was determined using the procedure of Murphy and Relay (1962).

Table 1. Selected characteristics of the phosphate rock materials from Indonesia (IPR).

Characteristics of IPR	Value
Total (g kg^{-1})	
P	153
Ca	356
P extracted (mg kg^{-1}) by	
2% citric acid	119
2% formic acid	123
Water	0.09

Statistical Analysis

Multivariate analysis was performed on factors determining PR dissolution, i.e. PCA of the soil chemical properties. First, PCA was carried out to summarize the data and investigate the relationship between soil properties (Kosaki *et al*. 1989). Second, stepwise multiple regression analysis was carried out using the scores of the extracted PCA and those of the positional data as independent variables and P dissolution as a dependent variable (Kosaki *et al*. 1989; Yanai *et al*. 2001). The Statistical Analysis System (SAS) version 6.12 was used (SAS Institute 1985).

RESULTS AND DISCUSSION

The original data in terms of range, mean, and standard deviation of selected soil characteristics are presented in Table 2. The PCA was first applied using a correlation matrix (Table 3). Numerous significant

Table 2. Range, mean, and standard deviation of Indonesian acid soil characteristics.

Soil characteristics	Range	Mean	Standard deviation
Sand (%)	2-32	8.13	6
Silt (%)	5-31	20.38	11
Clay (%)	43-93	71.50	17
pH H_2O	4-6	4.88	0.83
pH buffering capacity (mmole$_c$ OH kg^{-1} pH)	17-138	43.00	41
Organic C (g kg^{-1})	3-26.10	11.50	7
Calcium exchange capacity (mmole$_c$ kg^{-1})	61-157	92.30	31
Exchangeable Ca (mmole$_c$ kg^{-1})	7-81	41.50	31
P retention capacity (%)	24-82	56.88	16
Olsen P (mg kg^{-1})	3.50-19	10.13	5
P dissolution (mg kg^{-1} soil)	151-549	177.58	132

Table 3. Matrix correlation among soil properties of Indonesian acid soil characteristics.

	Clay	Sand	Silt	pH_{water}	pH buf	Organic C	Ca EC	Exch. Ca	P retention
Sand	-0.923***								
	0.001								
Silt	-0.979***	0.824**							
	0.000	0.012							
pH_{water}	0.045	0.258	-0.204						
	0.915	0.537	0.629						
pH buf	-0.292	-0.036	0.448	-0.490					
	0.483	0.932	0.265	0.217					
Organic C	0.659*	0.425	-0.742*	0.562	-0.591				
	0.076	0.294	0.035	0.147	0.123				
Ca EC	0.071	-0.064	-0.070	0.051	-0.424	-0.020			
	0.868	0.880	0.869	0.905	0.295	0.963			
Exch. Ca	-0.067	0.317	-0.070	0.893**	-0.527	0.601	0.204		
	0.875	0.444	0.869	0.003	0.180	0.115	0.628		
P retention	0.676	-0.787*	-0.575	-0.522	-0.057	0.125	0.363	-0.528	
	0.066	0.021	0.136	0.185	0.893	0.768	0.377	0.179	
Olsen P	0.342	-0.342	-0.321	0.103	-0.027	0.517	-0.279	0.271	-0.173
	0.407	0.406	0.439	0.808	0.949	0.189	0.504	0.517	0.681

linear correlations were existed among soil properties. Some variable relationship between clay and sand, clay and silt content resulted in a relatively very strong negative correlation with r = -0.92*** and r = -0.98*** respectively ($P < 0.001$). All other significant relationship between sand and silk content and between pH water and exchangeable Ca with r = 0.82** and r = 0.89**, respectively, had strong correlation. In addition, clay and organic C content (r = 0.67*), clay content and P retention (r = 0.79*), and silt content and organic C (r = -0.74*) had a relatively moderate correlation ($P < 0.05$).

Since very strong and strong correlations were found in a matrix correlation, it is needed to identify factors determining PR dissolution using PCA. From PCA, the first three principal components (PC_1 to PC_3) with eigenvalue (λ) >1 were selected (Table 4), and accounted for more than 70% of the total variance (Table 5). The remaining components were considered less significant and errors being included as random components of soil variation and various errors in soil sampling and analysis.

Based on the component loading after the varimax rotation (Fig. 1), the first component showed high to moderate loading with sand, silt, clay, and organic C loading. These properties were related to the soil texture status, therefore the first component (PC_1) was referred to as soil texture factor (STF). The second component (PC_2) showed high to moderate loadings with pH, exchangeable Ca, and P retention capacity that corresponded to soil acidity, being component was referred to as soil acidity factor (SAF). The third component (PC_3) showed high loads

Table 4. Eigenvalues and proportions of variance to the total variance for derived principal component (PC).

Principal component	Eigenvalue	Proportion	Cumulative percentage
PC_1	4.06	0.410	41
PC_2	3.10	0.310	72
PC_3	1.62	0.161	88
PC_4	0.62	0.062	94
PC_5	0.42	0.042	98
PC_6	0.17	0.017	100

Table 5. Factor pattern for the first three principal component (PC).

Variable	PC_1	PC_2	PC_3
Sand	-0.826	0.508	0.137
Silt	-0.973	0.052	-0.021
Clay	0.961	-0.220	-0.064
pH H_2O	0.201	0.900	0.035
pHbufferingcapacity	-0.481	-0.545	-0.486
Organic C	0.813	0.487	-0.155
Ca exchange capacity	0.169	-0.044	0.857
Exchangeable Ca	0.164	0.950	0.064
P retention capacity	0.584	-0.704	0.360
Olsen P	0.417	0.219	-0.700

of Ca exchange capacity and Olsen P, hence this component was reffered to fertilization factor (FF). The positive or negative symbol indicates the value of eigenvector that loads on variable observed. Stepwise multiple regression analysis was subsequently performed to obtain the optimum model for predicting P dissolution. In the analysis, P dissolution was used as a dependent variable, and standardized scores of the three PC as independent variables (Table 6).

Characterization of factors was scored for each soil characteristic (Table 4). Since information on the regression model was not available, the linear combination of the first and second degree terms of variables was assumed.

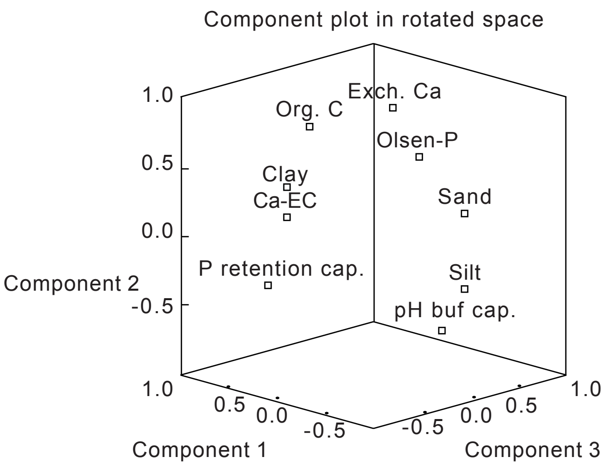

Fig. 1. Loads of variables on three principal component after varimax rotation.

Table 6. Factor scores computed for P dissolution on eight Indonesian acid soils.

Soil types	Maximum P dissolution (ΔP) (mg kg^{-1} soil)	STF	SAF	FF_{ns}
Bogor Ultisols	549	0.47	-0.69	-2.17
Sukabumi Oxisols	456	0.57	0.19	-0.35
Bogor Oxisols	540	1.12	-0.04	-0.85
Bogor Inceptisols	489	-0.62	-1.02	0.26
Lebak Ultisols	443	-0.35	-1.41	0.97
Sukabumi Inceptisols	383	0.90	1.45	0.24
Subang Inceptisols	540	-0.11	0.43	0.51
Lampung Ultisols	151	-1.97	1.08	-0.31

STF = soil texture factor, SAF = soil acidity factor, FF = fertilization factor, ns = not significant.

The proposed model is given as follows (Kosaki *et al*. 1989):

$$\text{P dissolution} = C_0 + C_1(\text{STF})^2 + C_2(\text{STF}) + C_3(\text{SAF})^2 + C_4(\text{SAF}) + C_5(\text{FF})^2 + C_6(\text{FF}) + e \quad [1]$$

where C_0, C_1, C_2, C_3, C_4, C_5, and C_6 are constants and e is random error.

The reason for the inclusion of the second degree terms is that the optimum value to produce the highest P dissolution may lie within the range of the data used. The significance level for introducing and deleting variables was set at $\alpha = 0.05$.

Although this model can explain the relationship between P dissolution (Y) and soil texture (STF), soil acidity (SAF) and fertilization (FF) factors, this model still has a weakness since interaction effect between variables or the terms for the crossing effect is excluded or neglected (Kosaki *et al*. 1989). The most appropriate model obtained from this study was:

$$Y = 433.69 + 83.05\text{STF} - 57.03\text{SAF} - 12.92\text{FF} \quad (R^2 = 0.70^{**}) \quad [2]$$

Since no significant relationship between P dissolution and FF was found, the selected model became:

$$\text{P dissolution} = 436.25 + 85.07\text{STF} - 56.86\text{SAF} \quad (R^2 = 0.68^{**}) \quad [3]$$

The R^2 value of 0.68 for this model indicates that the model explains 68% of the total variance of the dissolved P. The regression coefficients in the equation 3 indicate the magnitude of the contribution of each factor to PR dissolution. STF contributed to P dissolution ($P < 0.01$) with the largest magnitude. Contribution of SAF, the second largest was significantly negative ($P < 0.05$), suggesting that soil acidity status is important as the second degree term for P dissolution. The SAF was slightly less important than STF while FF correlation (r) was not significant, and eliminated from the P dissolution function (Appendix 3).

Clay soil texture plays a significant role in the transformation rate of P nutrient (Kanabo and Gilkes 1988), while P retention capacity provides a sink for $H_2PO_4^-$ released from PR (Hughes and Gilkes 1986; Hanafi and Syers 1994). The previous research has shown that clay content correlates well with P retention capacity (Olsen and Watanabe 1963). However, increase in silt, sand, soil pH, and exchangeable Ca decreased P dissolution in soil in relation to the solubility product principle. The PR dissolution results obtained from this study are similar to those obtained from Bolland *et al.* (2001) where PR dissolution decreased in soil of high pH or with low amount of hydrogen ion (proton) and high Ca.

CONCLUSION

Factors of importance influencing P dissolution were soil texture, soil acidity, then fertilization. Soil texture factors including clay content and organic-C and soil acidity factor, such as P retention capacity interacted positively with P dissolution and promoted PR dissolution effectively. Other soil texture factors, such as sand and silt content, soil acidity factors such as pH, and exchangeable Ca decreased PR dissolution.

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Appendix 1. Location, description, and classification of acid soils in West Java, Banten, and Lampung, Indonesia.

Code	Location		Soil classification (USDA)				Altitude (m asl)	Slope (%)	Parent materials	Landform	Dominant vegetation
	Village/district	County/province	Order	Suborder	Group	Subgroup					
01	Subang/ Merbau Mataram	South Lampung/ Lampung	Ultisols	Udults	Hapludults	Typic Hapludults	100	8-25	Acid, tuff and coarse felsic sedimentary rocks	Strongly dissected rolling plain with hillocks acid plain	*Euphorbia hirta* *Bchiwa walichi*
02	Malangsari/ Cipanas	Lebak/ Banten	Ultisols	Udults	Hapludults	Typic Hapludults	60	3-15	Coarse felsic sedimentary acid rocks	Moderately dissected, undulating to rolling acid tuff plain	*Imperata cylindrica* *Brachiaria holotrica*
03	Sukarasa/ Cigudeg	Bogor/ West Java	Ultisols	Udults	Hapludults	Typic Hapludults	250	8-25	Intermediate, maffic and coarse acid rocks	Strongly dissected rolling plain of acid rocks	*I. cylindrica* *B. holotrica*
04	Cigudeg/ Cigudeg	Bogor/ West Java	Oxisols	Udox	Hapludox	Typic Hapludox	200	3-15	Intermediate, maffic, tuff and coarse acid rocks	Moderately dissected, undulating plain of volcanic rocks	*I. cylindrica* *Spiritex lithorens*
05	Lengkong/ Lengkong	Sukabumi/ West Java	Inceptisols	Tropepts	Dystropepts	Typic Dystropepts	210	3-15	Acid, tuff and coarse felsic sedimentary rocks	Moderately dissected, undulating to rolling acid tuff plains	*I. cylindrica* *S. lithorens*
06	Cikembar/ Cikembar	Sukabumi/ West Java	Oxisols	Udox	Hapludox	Typic Hapludox	140	3-8	Intermediate, maffic and coarse acid rocks	Slightly dissected, flat to undulating acid tuff plains	*I. cylindrica* *Manihot utilissima*
07	Sindangsari/ Cikaum	Subang/ West Java	Inceptisols	Tropepts	Dystropepts	Typic Dystropepts	240	0-8	Fine felsic sedimentary acid rcoks	Slightly dissected, flat to undulating acid tuff plains	*B. holotrica* *S. littorens* *Swietenia mahagoni* *Ageratum conyzoides*
08	Leuwiliang/ Leuwiliang	Bogor/ West Java	Inceptisols	Tropepts	Dystropepts	Typic Dystropepts	200	0-3	Fine felsic sedimentary acid rcoks	Slightly dissected, flat to undulating acid tuff plains	*I. cylindrica* *Manihot esculenta*

Appendix 2. Selected physical and chemical properties of Indonesian acid soil.

Soils	Sand	Silt (%)	Clay	Texture	pH in H_2O	pH-buffering capacity (mmol OH kg^{-1} pH)	Org. C (g kg^{-1})	Ca EC	Exch. Ca[1] .....(mmol$_c$ kg^{-1}).....	P retention capacity (%)	Olsen P (mg kg^{-1})
Bogor Ultisols	5	18	77	Clay	4.40	20.50	6.90	156.60	21.60	82	3.50
Sukabumi Oxisols	6	11	83	Clay	5.00	19.30	14.70	88.00	44.50	65	6.60
Bogor Oxisols	2	5	93	Clay	4.90	30.90	15.00	65.20	21.00	61	13.60
Bogor Inceptisols	12	31	57	Clay	4.10	64.20	7.00	61.30	6.70	60	6.10
Lebak Ultisols	6	29	65	Clay	4.40	137.60	2.70	75.00	15.00	55	10.30
Sukabumi Inceptisols	4	9	87	Clay	5.60	17.20	26.10	98.90	91.10	59	14.90
Subang Inceptisols	9	24	67	Clay	4.50	29.20	12.10	98.50	50.00	49	18.90
Lampung Ultisols	21	36	43	Loamy clay	5.70	24.90	6.90	96.20	81.40	24	5.70

[1]Calcium in 1M NH_4OAc pH 7 percolates (Piper 1947).

Appendix 3. Correlation (r) between P dissolution and soil texture factor (STF), soil acidity factor (SAF) and fertilization factor (FF).

	P-dissolution	STF	SAF	FF
P-dissolution	1	0.703	-0.536	-0.017^{ns}

ns = not significant.