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## DOMINANT SOIL CHARACTERISTICS INFLUENCING AVAILABLE POTASSIUM ON SMECTITIC SOILS<sup>1)</sup>

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### ABSTRACT

Research was conducted in laboratory of Indonesian Soil Research Institute to study dominant soil characteristics influencing available K on smectitic soils. The soil characteristics analyzed were three fraction soil textures (pipette), organic-C (Kjeldahl), CEC ( $\text{NH}_4\text{OAc}$ ), clay fraction (X-Ray Diffraction), soluble-K ( $0.0002 \text{ M CaCl}_2$ ), exchangeable-K ( $\text{NH}_4\text{OAc}$ ), total-K ( $\text{HNO}_3 + \text{HClO}_4$ ) and K sorption. The results showed that the content of soil soluble, exchangeable, nonexchangeable, and total K was in order of Vertisols > Alfisols > Inceptisols. The percentage of soil K fraction, however, was in order of soluble-K < exchangeable-K < nonexchangeable-K. Although the soils had high content in total K, most of them were in nonexchangeable form thus they were not available for plant growth. Soil K buffering capacity and maximum K sorption were in order of Vertisols > Alfisols > Inceptisols. The bond energy constant of Vertisols, however, was similar with that of Alfisols, but it was about twice with that of Inceptisols. Soil clay, organic-C, and CEC affected significantly the availability of soil K ( $P > 0.95$ ). Smectite contributed significantly ( $P > 0.95$ ) to soil negative charge so it had an important role in controlling soil K buffering capacity and maximum K sorption. To increase the efficiency of K fertilizer, plant species produced high organic acid exudated from roots can be developed in smectitic soils. The use of Na,  $\text{NH}_4$ , and Fe cations also need to be considered for K management in the soils.

[**Keywords:** Soil chemico-physical properties, potassium, smectite]

### INTRODUCTION

Potassium (K) are absorbed by plant in three forms: soluble K ( $\text{K}_s$ ), exchangeable K, and nonexchangeable K. The first form of K is commonly as fast-available K because it can be absorbed directly by plant root. The second form is slightly slow-available K, while the third form is slow and nonavailable K. The availability of K for plant depends on soil, plant, and climate factors. Soil characteristics influencing soil K availability include amount and type of clay mineral, cation exchange capacity

(CEC), K buffering capacity, humidity, temperature, aeration, and soil pH. Plant species affect K sorption as well, where tolerant plants require K in small amount and the sensitive one need more K. Therefore, K nutrient management for increasing plant production should consider these factors.

The availability of soil K depends on process and dynamic of K in soil especially sorption and desorption processes. If nutrient concentration in soil solution increased because of fertilizer application, the nutrient was immediately absorbed by soil into temporary non-available form; this process was called sorption. If the nutrient concentration in soil solution decreased due to absorption or leaching, the absorbed nutrients were released in solution and absorbed by plant; this process was called desorption (Brady 1984). If the desorption process was slower than sorption process, K availability decreased and it will inhibit plant growth.

Sorption and desorption of K in soil were controlled especially by the type and amount of clay mineral. Clay mineral type 2:1 adsorbed K and released K higher than other clay mineral, such as type 2:1:1, 1:1, oxyde, and alophane. Of clay mineral type 2:1, beidelite or smectite has the highest fixation capacity. Bajwa (1987) who studied K sorption on rice soil in Pakistan which had different mineral compositions reported that K fixation from high to low was in order of smectite > vermiculite > hydrous mica = chlorite = halosite. Other research conducted on Vertisols in India which were dominated by clay mineral of smectite showed that beidelite had the highest K fixation than montmorillonite, mica, illite, dan vermiculite (Murthy *et al.* 1987). K desorption from mica from high to low was in order of phlogopite > biotite > muscovite (Singh and Pasricha 1987).

Soils with clay smectite mineral have good prospect for food crops farmland followed by proper plant and soil management. The soils generally include Alluvial (Inceptisols), Mediteranean (Alfisols), and Grumusols (Vertisols). Those soils have wide distribution in Indonesia, that are Vertisols 2.12 million ha, Inceptisols 70.52 million ha, and Alfisols 5.5 million ha scattered in

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Java (West Java, Central Java, and East Java), Sulawesi (South Sulawesi, Central Sulawesi, and Gorontalo), and Nusa Tenggara (Lombok) (Pusat Penelitian Tanah dan Agroklimat 2000). These soils are the main agricultural soils in Indonesia and commonly used for irrigated and rainfed rice, secondary crops, mixed plantation, sugarcane, tobacco, cotton, coconut, and horticultural crops such as mango (Subagyo *et al.* 2000).

Soils containing smectite clay mineral have high clay fraction (33-92%) and neutral to alkaline soil reaction with soil pH of 6.5-8.0. The availability of micronutrients (Fe, Cu, Zn, dan Mn) was commonly low due to low soil acidity. Organic matter content was low to moderate, while potential K content, bases (Ca dan Mg), and CEC were generally high (Subagyo *et al.* 2000). Even though total K content in soil was high, the availability of K for plant would be a problem because K was fixed by clay mineral type 2:1, such as smectite (Borchardt 1989) which was dominant in that soil. However, the soils had high K-fixing capacity and K-buffering capacity (Ghousikar and Kendre 1987). Therefore, efforts should be done to overcome soil K fixation to increase K availability for plant. Research was conducted to study soil characteristics that influence K availability on smectite clay mineral soils.

## MATERIALS AND METHODS

Top composite soil samples (0-20 cm) were taken from West Java (32 samples), Central Java (32 samples), and East Java (27 samples). Composite soil sampling followed soil distribution described at Reconnaissance Soil Map of West Java, Central Java, and East Java Provinces at a scale of 1:250,000 (Lembaga Penelitian Tanah 1966). These soil samples were top soils from Alluvial, Grumusol, and Mediteranean soils or equal with Inceptisols, Vertisols, and Alfisols (Soil Survey Staff 1998). Soil sample distribution, physiography, and parent materials of each soil types were described in Table 1.

Soil analysis was conducted on soil characteristics that highly correlated with K dynamic in soil. The soil properties were pH-H<sub>2</sub>O, three fraction textures (pipette), organic-C

(Kjeldahl), P-Olsen, K-HCl 25%, exch-Ca, exch-Mg, exch-K, CEC (NH<sub>4</sub>OAc pH 7.0), and exch-Al (KCl 1 N).

Semiquantitative analysis on clay mineral soil was done on 20 soil samples, that are Alfisols 8 samples, Vertisols 8 samples, and Inceptisols 4 samples. Separation of soil primary granules (sand, ash, and clay) was conducted with eliminating soil fixing materials. Elimination of carbonate matters was done by adding HCl pH 5, whereas organic matter was with peroxyde (H<sub>2</sub>O<sub>2</sub>). Fixation matter-free soil sample was dispersed, then coarse sand granules were screened using 50 µm filter. Separation of clay mineral from ash was conducted by falling granule velocity difference principle based on Stokes law. Preparates of each clay suspension sample were treated with saturation of Mg, Mg + glycerol, saturation with K, K + 350°C, and K + 500°C. Clay types on those preparates were then measured by using X-Ray Diffraction (XRD) kit at 4-30° rotating angle and Cu catode lamp.

Soil K fractionations determined were K<sub>i</sub> with CaCl<sub>2</sub> 0.0002 M, exch-K with NH<sub>4</sub>OAc 1 N pH 7.0, and exch-K<sub>i</sub> with HNO<sub>3</sub> + HClO<sub>4</sub>. Determination of K<sub>i</sub> did not use water extract because its extractant was turbid, so determination using atomic absorption spectrophotometry (AAS) method was not accurate. CaCl<sub>2</sub> solution (0.0002 M) was used as water extract substitutes. Nonexch-K was defined as K<sub>t</sub> minus by K<sub>i</sub> and exch-K.

Determination of K sorption was carried out by using Fox and Kamprath (1970) procedure. Each soil sample was weighed 2 g absolute dry weight and put in shaking bottle, added with 20 ml CaCl<sub>2</sub> solution 0.0002 M containing 10 concentration levels of K, i. e. 0, 2.5, 5, 7.5, 10, 15, 20, 30, 40, and 60 ppm K from KCl. Extracted soils were incubated for 6 days and shaken twice a day each for 30 minutes in the morning and afternoon. After incubation, the solution was filtered and purified extract was used for K determination. K concentration in extractant was then measured by using AAS method.

K sorption was calculated by Langmuir model based on Fox and Kamprath (1970) using equation as follows:  $x m^{-1} = kbC (1 + kC)^{-1}$ , where  $x m^{-1}$  = amount of absorbed K per soil weight unit; k = constant relating with fixation energy; b = maximum K sorption capacity; and C = K

Table 1. Distribution of soil samples taken from Java.

Soil type		Physiography	Parent material	Total sample
Lembaga Penelitian Tanah (1966)	Soil Survey Staff (1998)			
Aluvial	Inceptisols	Plateau	Clay sediment	13
Grumusol	Vertisols	Plateau	Calcareous clay sediment	47
Mediteranean	Alfisols	Folding hill	Limestone	31

concentration in balance. The equation was changed into:  $C x^{-1} m^{-1} = 1 kb^{-1} + 1 b^{-1} C$ . Plotting between  $C x^{-1} m^{-1}$  and  $C$  resulted in straight line with regression equation of  $Y = m + nX$ . The  $n$  value of that regression equation =  $1 b^{-1}$  of the above equation, so  $b$  value can be measured. After  $b$  value determined,  $k$  value can be measured.  $b$  value is the maximum sorption and  $k$  is constant of soil fixation energy.

## RESULTS AND DISCUSSION

### Soil Chemical Characteristics

Topsoil characteristics (0-20 cm) of soils from Java were described in Table 2. Based on the criteria of Pusat Penelitian Tanah (1983), all soils tested had clay texture, neutral soil reaction (Inceptisols and Vertisols) until alkaline (Alfisols), low soil acidity, and high base saturation. Organic-C and organic-N contents were low, soil potential K contents were moderate (Inceptisols and Alfisols) to high (Vertisols), and soil potential P content was high. Exch-Ca and exch-Mg contents were moderate (Inceptisols) to high (Vertisols and Alfisols), while exch-Al was low (Inceptisols), moderate (Alfisols), and high (Vertisols). CEC was moderate (Inceptisols) to high (Alfisols and Vertisols).

Based on Reconnaissance Soil Map of 1:250,000 scale for West Java, Central Java, and East Java (Lembaga Penelitian Tanah 1966), the soils tested originated from clay sediment parent material (Inceptisols), calcareous clay sediment (Vertisols), and limestone (Alfisols), so its weathering process resulted in clay-textured soil material. Limestone contained high Ca,  $Mg(CO_3)_2$  and its weathering

process resulted  $Ca^{2+}$ ,  $Mg^{2+}$ , dan  $CO_3^{2-}$ . This caused high soil Ca dan exch-Mg, especially for Alfisols, so base saturation was high. The hydrolysis of  $CO_3^{2-}$  occurred and resulted  $OH^-$  that increased soil pH, while Al cation would precipitate so exch-Al or soil acidity decreased.

The soil tested lies in wet tropic areas (West Java and western Central Java) having average rainfall > 2000 mm/year, to dry (eastern Central Java and East Java) with rainfall < 2000 mm/year (Balai Penelitian Agroklimat dan Hidrologi 2003). High average annual temperature at tropics caused high organic matter decomposition so organic matter turn over in soil was relatively short resulting in low soil organic C and N. Besides, high rainfall also caused high leaching level of organic matter and soil N.

P and soil potential-K were not only affected by soil parent material, but also closely related with soil management. Soils in Java either lowland or dryland were generally used more intensively than that of out Java. This caused P and K residues in soils from fertilizers or K from irrigation water still remained in soils. Soil P and K sources also came from mineral containing P such as apatite and mineral containing K such as mica. Vertisols contained highest potential K than Inceptisols and Alfisols because Vertisols generally contained smectite clay mineral as result of weathering process of mica or plagioclase that contained high K.

### Soil Clay Mineral Characteristics

Qualitative analysis of clay fraction mineral showed that Inceptisols contained less to moderate smectite and

Table 2. Topsoil characteristics of Inceptisols, Vertisols, and Alfisols from Java.

Soil characteristic	Method/extract	Inceptisols	Vertisols	Alfisols
Clay content (%)	Pipette	37 ± 17	63 ± 12	53 ± 18
pH-H <sub>2</sub> O	water (1:2.5)	6.0 ± 0.8	6.5 ± 0.9	7.0 ± 0.9
Organic C (%)	Kjeldahl	1.10 ± 0.11	1.40 ± 0.15	2.04 ± 0.44
Organic N (%)	Kjeldahl	0.09 ± 0.05	0.20 ± 0.10	0.19 ± 0.10
Potential K (ppm K <sub>2</sub> O)	HCl 25%	148 ± 102	239 ± 140	198 ± 96
Potential P (ppm P <sub>2</sub> O <sub>5</sub> )	HCl 25%	516 ± 203	548 ± 274	583 ± 295
Cation exchange value				
Exch-Ca (cmol <sub>c</sub> /kg)	NH <sub>4</sub> OAc pH 7.0	10.06 ± 2.09	36.40 ± 14.26	30.88 ± 11.02
Exch-Mg (mol <sub>c</sub> /kg)	NH <sub>4</sub> OAc pH 7.0	2.99 ± 1.14	6.98 ± 2.34	3.57 ± 1.17
Exch-K (cmol <sub>c</sub> /kg)	NH <sub>4</sub> OAc pH 7.0	0.13 ± 0.11	0.33 ± 0.27	0.25 ± 0.18
CEC (cmol <sub>c</sub> /kg)	NH <sub>4</sub> OAc pH 7.0	16.92 ± 6.92	56.38 ± 22.17	30.83 ± 13.20
Base saturation (%)	NaCl	85 ± 20	84 ± 29	>100 ± 79
Acidity				
Exch-Al (cmol <sub>c</sub> /kg)	KCl 1N	0.28 ± 0.29	0.25 ± 0.30	0.10 ± 0.19
Exch-H <sub>a</sub> (cmol <sub>c</sub> /kg)	KCl 1 N	0.28 ± 0.07	0.29 ± 0.12	0.26 ± 0.08
Total sample		13	47	31

kaolinite and least to less quartz. Vertisols contained most smectite, less kaolinite, and least quartz, while Alfisols had moderate to high smectite and kaolinite and least quartz (Table 3). Vertisols were dominated by smectite, while Alfisols and Inceptisols were by smectite and kaolinite. The results were similar with those of Subagyo (1983) who reported that clay fraction of Vertisols Ngawi were dominated by smectite and less kaolinite (disordered kaolinite).

Smectite was shown by diffraction peak of 14.91 Å, kaolinite 7.22 and 3.58 Å, and quartz 4.26 dan 3.34 Å at saturation treatment with Mg<sup>2+</sup>. Diffraction peak of smectite increased up to 18.57 Å at Mg<sup>2+</sup> + glycerol treatment, decreased to 12.32 Å at saturation with K<sup>+</sup>, and decreased again to 9.85 Å at saturation with K<sup>+</sup> and heating up to 550°C. Kaolinite and quartz diffraction did not change due to saturation with Mg<sup>2+</sup> + glycerol and K<sup>+</sup>, but its diffraction peak was disappear at heating treatment up to 550°C (Figure 1). If trapezoid area under smectite diffractogram having peak of 14.91 Å was used to estimate smectite quantity, so smectite contents in soil from high to low were Vertisols > Alfisols > Inceptisols. Quartz mineral in clay fraction was as primary mineral because quartz mineral is classified as deteriorate resistant mineral. Quartz in clay fraction was estimated come from soft-sized primary mineral such as clay fraction (Prasetyo *et al.* 2005).

Smectite content in soil clay fraction closely related with soil CEC, where the higher the smectite content the higher the soil CEC value. Table 2 showed that Vertisols containing higher smectite had higher CEC than Alfisols and Inceptisols that contained less smectite. These phenomena showed that negative charge originating from permanent charge at smectite gave significant contribution to soil CEC. This charge came from isomorphous substitution resulting in more negative charge either at tetrahedral-S or octahedral-Al.

### Soil K Fractionation

Total soil K content from high to low was in order of Vertisols > Alfisols > Inceptisols. Soil K<sub>f</sub>, exch-K, and nonexch-K from high to low was equal with soil K<sub>t</sub>. K<sub>f</sub> content was 11, 14, dan 13 mg/kg; exch-K 50, 98, and 99 mg/kg, and nonexch-K 171, 347, and 303 mg/kg for Inceptisols, Vertisols, and Alfisols, respectively (Figure 2). K content in soil was affected by soil parent materials, where Inceptisols originated from clay sediment, Vertisols from calcareous clay sediment, and Alfisols from limestone (Lembaga Penelitian Tanah 1966). This was shown by result of sand and ash fraction analyses of topsoils taken from Pati (Inceptisols), Cilacap and Ngawi (Vertisols), Bogor and Blora (Alfisols). Soil mineral composition of

Table 3. Clay mineral composition of topsoils taken from Java.

Sample code	Soil	Smectite	Kaolinite	Quartz
NA-39	Inceptisols	++	++	+
NA-10	Inceptisols	+	+	(+)
NA-1	Inceptisols	+	+	+
DE-28	Inceptisols	++	++	+
B2-1	Vertisols	++++	+	(+)
B3-1	Vertisols	++++	-	-
B2-2	Vertisols	++++	+	(+)
B3-2	Vertisols	++++	-	-
DE-34	Vertisols	++++	-	-
DE-36	Vertisols	++++	+	(+)
NA-5	Vertisols	++++	-	-
NA-6	Vertisols	++++	+	(+)
B1-1	Alfisols	+++	++	(+)
B4-1	Alfisols	++	++++	(+)
B1-2	Alfisols	+++	++	(+)
B4-2	Alfisols	++	++++	(+)
NA-3	Alfisols	+++	+++	(+)
NA-4	Alfisols	+++	+++	(+)
NA-2	Alfisols	++	++	(+)
NA-37	Alfisols	++	+++	(+)

++++ = most, +++ = much, ++ = moderate, + = less, (+) least, - = none.

Inceptisols was dominated by quartz, Vertisols by labradorite association, mineral deteriorant, green hornblende, hiperstine, and quartz, whereas Alfisols by quartz, rock fragment, and sanidine (Nursyamsi 2007). Vertisols, however, although originated from sediment, its topsoil was enriched by intermediary volcanic materials. The volcanic materials enrichment of Vertisols Ngawi was presumed come form Mount Lawu (Prasetyo *et al.* 2007). Among the minerals, the main sources of soil K were labradorite (Vertisols) and sanidine (Alfisols).

Soil K content was also similar to clay fraction mineral analysis result with XRD. Based on the analysis, smectite content in soil clay fraction from high to low was in order of Vertisols > Alfisols > Inceptisols, respectively (Table 3). On the other words, soil K content depends on amount of smectite clay mineral in soil. Smectite can fixate K at that mineral layer interspace where the fixated K was reserved exch-K for plants through release and desorption processes.

The proportion of K forms from low to high at the three soils tested had the same sequence, that were K<sub>f</sub> < exch-K < nonexch-K. K<sub>f</sub> form was 5-7%, exch-K 24-31%, and nonexch-K 63-68% (Figure 3). If K<sub>f</sub> and exch-K were assumed as available K, and nonexch-K as nonavailable K, so most of K in the three soils tested were not available for plants. The similar result was reported by Setyorini *et al.* (2005) that maize plants gave positive response to K fertilizer on Alfisols and Vertisols even though total K contents in both soils were high.

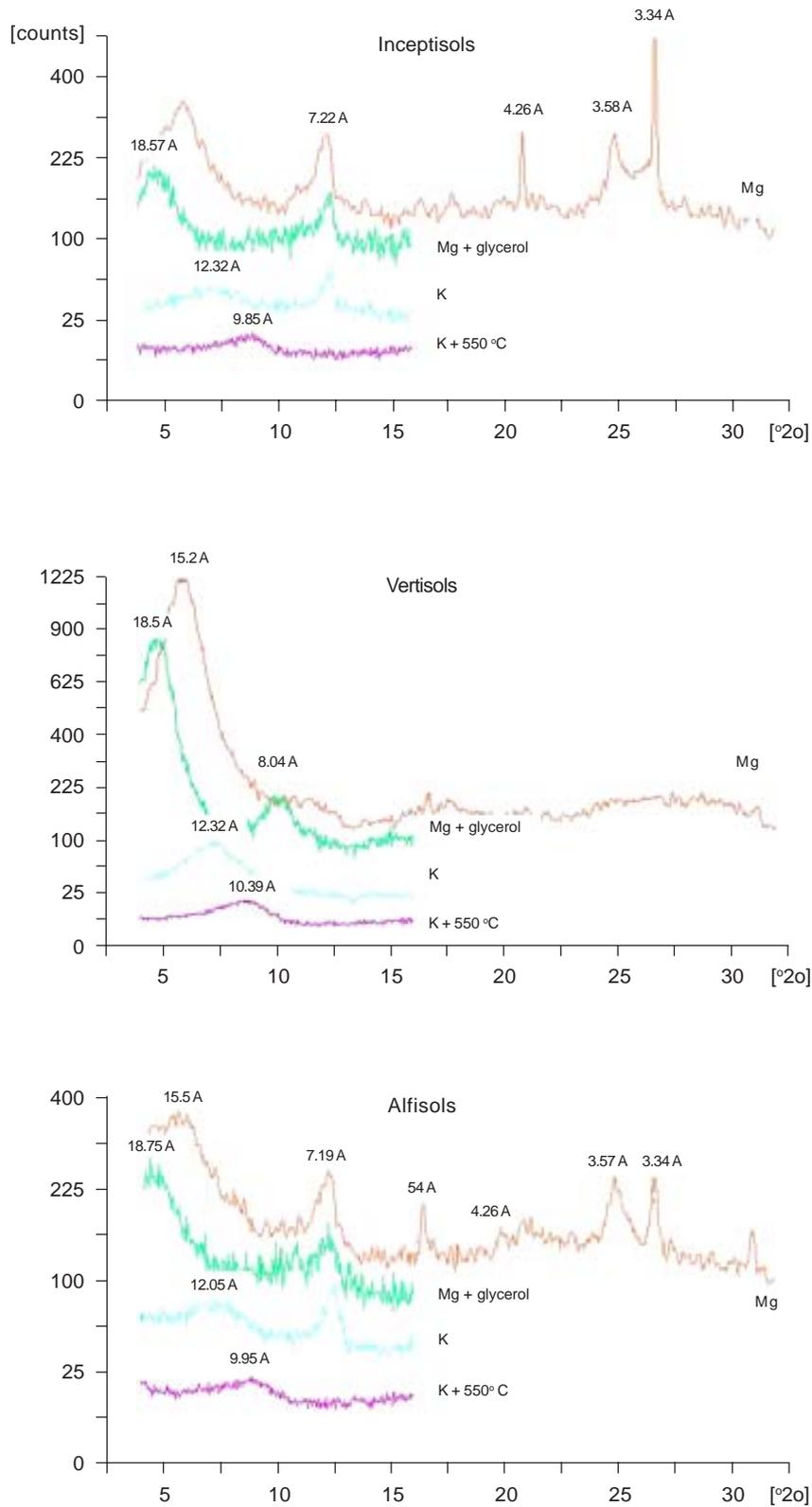


Figure 1. X-ray diffractogram of topsoils of Inceptisols, Vertisols, and Alfisols from Java.

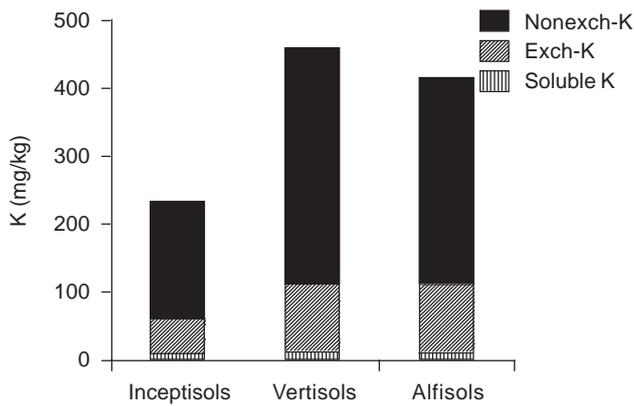


Figure 2. Potassium fraction composition of topsoils of Inceptisols, Vertisols, and Alfisols from Java.

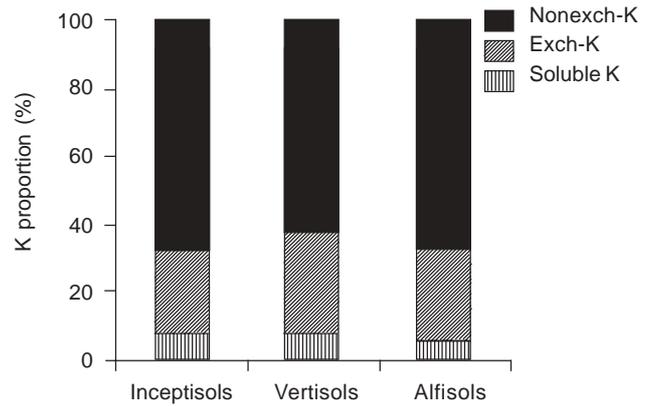


Figure 3. Potassium fraction proportion of topsoils of Inceptisols, Vertisols, and Alfisols from Java.

### Soil K Sorption

K sorption of the three soils tested varied (Figure 4). Soil K sorption from high to low was in order of Vertisols > Alfisols > Inceptisols. This phenomenon closely related to different inherent characteristics of those soils. Soil characteristics influencing K sorption were texture, CEC, and smectite content. The soils tested had different characteristics so the K sorption was varied.

Soil K sorption can be used as indicator of soil capacity in making the nutrients available for plants. Beside intensity (I) and quantity (Q) factors, buffering capacity can also influence soil K availability. Buffering capacity was quantity factor change (absorbed K) per change unit in intensity (soluble K) which showed by equation:  $DS = \frac{\partial Q}{\partial I}$  (Widjaja-Adhi and Sudjadi 1987). Since all the K sorption curve were in quadratic form, the buffering capacity of K was changed in line with K intensity change in soil solution. The buffering capacity could be estimated from curve slope, where the buffering capacity of slope slightly curve was low, while steep curve had high buffering capacity. Furthermore, buffering capacity of those three soils from high to low were in order of Vertisols > Alfisols > Inceptisols. This buffering capacity showed soil capacity level to supply K into soil solution if K concentration in soil solution decreased due to K absorption by plants or leaching.

Critical limit of soil K nutrient in Indonesia empirically was 0.20 me/100 g (Pusat Penelitian Tanah 1983), whereas at Ultisols Lampung and Oxisols Sitiung for maize were 0.41 and 0.72 me/100 g, respectively with extract of  $NH_4OAc$  pH 7.0 (Sulaeman *et al.* 2000). If value of 0.20 me/100 g soil (equal to 6 mg/l solution) was assumed as plant external K requirement, so buffering capacity values of those three soils could be measured and the results were described in

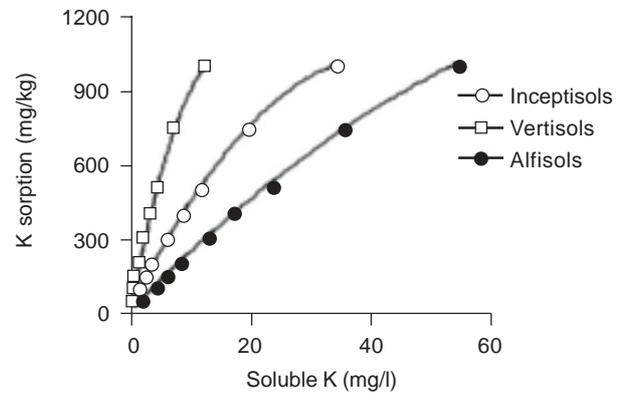


Figure 4. Potassium sorption of topsoils of Inceptisols, Vertisols, and Alfisols from Java.

Table 4. Soil buffering capacity of Vertisols was 103 mg/l, twice more than that of Alfisols of 44 mg/l and four times more than Inceptisols of 24 mg/l. Therefore, Vertisols had the best capacity in supplying K into soil solution than Alfisols dan Inceptisols.

Maximum sorption and bond-energy constanta of the three soils tested counted by using Langmuir model based on Fox and Kamprath (1970) were presented in Table 5. The average maximum sorption of Vertisols (1947 mg/kg) was twice of Alfisols (979 mg/kg), and about three times of Inceptisols (651 mg/kg). Whereas soil bond-energy constanta of Vertisols (0.0652) was slightly equal with Alfisols (0.0701) and about twice of Inceptisols (0.0381). Maximum sorption variable showed soil capacity level in keeping nutrient in soil colloid, while bond-energy constanta showed intensity level of soil colloid in absorbing nutrient which opposite with nutrient ease level to release into soil solution.

Table 4. Equation model of sorption curve ( $Y = aX^2 + bX + c$ ) and soil K buffering capacity at  $I = 6$  mg/l.

Soil	a	b	c	R <sup>2</sup>	Buffering capacity (mg/l)
Inceptisols	-0.119	24.892	0.056	0.999	24.176
Vertisols	-3.961	127.020	34.758	0.996	103.252
Alfisols	-0.565	47.796	24.974	0.998	44.409

$Y = K$  absorbed (quantity factor =  $Q$ ),  $X =$  soluble K (intensity factor =  $I$ ),  $a$ ,  $b$ , and  $c =$  constant,  $R^2 =$  determinant coefficient.

Table 5. Potassium sorption variables of topsoils of Inceptisols, Vertisols, and Alfisols from Java.

Soil K sorption variable	Inceptisols	Vertisols	Alfisols
Constanta ( $m$ )	$0.0680 \pm 0.0076$	$0.0379 \pm 0.0042$	$0.0379 \pm 0.0046$
Direction coefficient ( $n$ )	$0.0018 \pm 0.0002$	$0.0007 \pm 0.0002$	$0.0012 \pm 0.0003$
Determinant coefficient ( $R^2$ )	$0.60 \pm 0.11$	$0.50 \pm 0.16$	$0.63 \pm 0.13$
Maximum sorption ( $b$ )	$651 \pm 128$	$1947 \pm 1111$	$979 \pm 133$
Bond-energy constant ( $k$ )	$0.0381 \pm 0.0016$	$0.0652 \pm 0.0103$	$0.0701 \pm 0.0072$
Total sample	13	47	31

$Y = m + nX$  equal to  $C(x m)^{-1} = 1 kb^{-1} + C b^{-1}$ ; where  $m =$  constant,  $n =$  direction coefficient,  $C =$  dissolved K (ppm K),  $x m^{-1} =$  absorbed K (ppm K),  $b =$  maximum K sorption (ppm K), and  $k =$  K bond energy constant.

### Soil Characteristics Influencing Soil K Availability

Estimation of soil K availability by maximum sorption variable ( $b$ ), bond-energy constant ( $k$ ), buffering capacity at  $I = 6$  mg/l (DS), and soil K content ( $K_e$ ,  $K_{exch}$ ,  $K_{nonexch}$ , and  $K_t$ ) showed that clay content, organic-C, and soil CEC generally significantly positive correlated with one of the variables. Both clay content and soil organic-C contributed to soil as shown by significant correlation between both variables with soil CEC. Furthermore, the three variables significantly positive correlated with maximum sorption, buffering capacity and  $K_{exch}$  and soil CEC significantly positive correlated with  $K_{nonexch}$  and  $K_t$  at Inceptisols. Amongst soil K fraction,  $K_{exch}$  and  $K_{nonexch}$  played an important role in controlling maximum sorption and buffering capacity of soil K at Inceptisols. This was shown by both soil K fraction with both soil K availability variables (Table 6).

Differ from Inceptisols, on Vertisols only clay content that contributed to soil CEC shown by significantly positive correlation between clay content and soil CEC. Furthermore, both clay content and soil CEC highly significantly positive correlated with soil buffering capacity, while soil organic-C content significantly negative correlated with CEC and soil buffering capacity (Table 7). These phenomena showed that soil organic matter reduced

soil buffering capacity as well. There is possibility that soil organic matter covered soil colloid sorption complex surface, so amount of soil negative charge decreased.

As Inceptisols, clay content and organic-C contributed to soil CEC. Furthermore organic-C content and CEC had role in controlling soil buffering capacity as shown by highly significant correlation between both variables and soil buffering capacity.

Bond-energy constant also significantly positive correlated with soil buffering capacity (Table 8). If all samples of the three soils were combined, only clay content that contributed to soil CEC, while soil organic-C did not. Clay content, organic-C, and soil CEC significantly controlled soil K availability as shown by significantly positive correlation among three soil characteristics with soil buffering capacity (Table 9).

Negative charge of soil colloid had role in controlling K availability in the three soils tested (Table 6-9). Soil colloid charge source consisted of permanent charge and pH dependent charge or variable charge. Permanent charge came from isomorphic substitution at siloxane colloid surface (Si-O-Si) at smectite clay mineral (2:1). pH dependent charge was occurred at colloid surface of oxyhydroxy (O-Al-OH), silanol (-Si-OH), aluminol (-Al-OH), ferrol (-Fe-OH) existed at clay mineral of kaolinite (1:1), hydroxide, and amorph. Besides, pH dependent charge can

Table 6. Correlation matrix between soil characteristics and variables of soil K availability of Inceptisols.

Variable	Clay	Org-C	CEC	b	k	DS	K <sub>1</sub>	K <sub>dd</sub>	K <sub>tdd</sub>	Kt
Clay	1.000	0.900**	0.662*	0.706**	0.269	0.772**	-0.073	0.703**	0.391	0.551
Org-C		1.000	0.703**	0.732**	0.327	0.770**	0.109	0.661*	0.431	0.546
CEC			1.000	0.907**	0.231	0.806**	-0.009	0.949**	0.810**	0.903**
b				1.000	0.356	0.888**	-0.092	0.838**	0.776**	0.833**
k					1.000	0.552*	-0.526	0.182	0.031	0.068
DS						1.000	-0.341	0.781**	0.667**	0.729**
K <sub>1</sub>							1.000	-0.079	0.040	0.039
k <sub>dd</sub>								1.000	0.802**	0.914**
K <sub>tdd</sub>									1.000	0.974**
Kt										1.000

N = 13,  $t_{0.05} = 0.553$ ,  $t_{0.01} = 0.684$ , \* = significant at 5% test, and \*\* = significant at 1% test.

Table 7. Correlation matrix between soil characteristics and variables of soil K availability of Vertisols.

Variable	Clay	Org-C	CEC	b	k	DS	K <sub>1</sub>	K <sub>dd</sub>	K <sub>tdd</sub>	Kt
Clay	1.000	-0.123	0.517**	-0.156	0.300	0.496**	-0.153	-0.028	0.102	0.089
Org-C		1.000	-0.343*	-0.189	-0.092	-0.475**	0.200	-0.003	0.181	0.178
CEC			1.000	0.055	-0.016	0.477**	-0.036	0.238	-0.056	-0.024
b				1.000	-0.289*	0.206	0.590**	0.161	-0.064	-0.044
k					1.000	0.334**	-0.272	-0.220	-0.010	-0.031
DS						1.000	-0.164	-0.056	-0.076	-0.084
K <sub>1</sub>							1.000	0.684**	0.121	0.223
k <sub>dd</sub>								1.000	0.135	0.273
K <sub>tdd</sub>									1.000	0.990**
Kt										1.000

N = 47,  $t_{0.05} = 0.288$ ,  $t_{0.01} = 0.372$ , \* = significant at 5% test, and \*\* = significant at 1% test.

originate from organic colloid in form of carboxylate functional group (-COOH), phenol hydroxide, or amine (-H<sub>2</sub>) (Tan 1998).

Organic-C contents of three soils tested were generally low, that were only 1.10% on Inceptisols, 1.40% on Vertisols, and 2.04% on Alfisols (Table 2). Charge source of other variables, that were kaolinite in clay fraction was less to moderate on Inceptisols, least on Vertisols, and moderate to very high on Alfisols. Whereas permanent charge source, namely smectite in clay fraction was less to moderate on Inceptisols, very high on Vertisols, and moderate to high on Alfisols (Table 3). Therefore, variables and permanent charge sources on Inceptisols and Alfisols contributed to soil CEC, while on Vertisols only permanent charge source contributed to soil CEC. The contribution of permanent charge on soil negative charge was more than variable charge. This was shown by higher soil CEC value of Vertisols than Alfisols and Inceptisols, that were 56.38, 30.83, and 16.92 cmol<sub>c</sub>/kg, respectively (Table 2).

### Relationship Between Smectite Content and Soil Characteristics

Smectite as a source of permanent charge had an important role in controlling soil K availability. The positive relationship between smectite content and CEC ( $R^2 = 0.5091$ ) showed that smectite significantly contributed to soil negative charge. On the other hand, the relationship of organic-C content with soil CEC was not significant ( $R^2 = 0.0002$ ) (Figure 5). This showed that organic matter did not give significant contribution to soil negative charge. These phenomena showed that on soils dominated by smectite clay mineral (Vertisols), permanent charge source was more important than variable charge source in controlling soil CEC. On soils dominated by variable charge source, such as Ultisols of Sasamba, East Kalimantan (Prasetyo *et al.* 2001) and Ultisols from andesitic volcanic material of Ungaran, Central Java (Prasetyo *et al.* 2005), organic matter gave significant contribution to soil negative charge.

Table 8. Correlation matrix between soil characteristics and variables of soil K availability of Alfisols.

Variable	Clay	Org-C	CEC	b	k	DS	K <sub>1</sub>	K <sub>dd</sub>	K <sub>tdd</sub>	K <sub>t</sub>
Clay	1.000	-0.046	0.425 *	0.328	0.017	0.082	-0.212	0.139	0.153	0.171
Org-C		1.000	0.377 *	-0.020	0.484 *	0.532 **	-0.228	-0.099	-0.065	-0.089
CEC			1.000	0.207	0.272	0.572 **	-0.233	0.042	0.111	0.110
b				1.000	-0.180	0.051	0.122	0.098	0.354 **	0.362 **
k					1.000	0.790 **	-0.228	-0.215	-0.110	-0.156
DS						1.000	-0.304	-0.059	-0.051	-0.069
K <sub>1</sub>							1.000	0.053	0.105	0.134
k <sub>dd</sub>								1.000	0.107	0.324
K <sub>tdd</sub>									1.000	0.975 **
K <sub>t</sub>										1.000

N = 31,  $t_{0.05} = 0.349$ ,  $t_{0.01} = 0.449$ , \* = significant at 5% test, and \*\* = significant at 1% test.

Table 9. Correlation matrix between soil characteristics and variables of soil K availability of Inceptisols, Vertisols, and Alfisols.

Variable	Clay	Org-C	CEC	b	k	DS	K <sub>1</sub>	K <sub>dd</sub>	K <sub>tdd</sub>	K <sub>t</sub>
Clay	1.000	-0.130	0.668 **	0.296 **	0.052	0.306 *	-0.234 *	0.320 *	0.146	0.165
Org-C		1.000	-0.007	-0.049	0.422 **	0.412 **	-0.103	0.119	0.040	0.051
CEC			1.000	0.147	0.184	0.586 **	-0.081	0.280 *	-0.047	-0.009
b				1.000	-0.273	0.138	0.303 **	0.417 **	0.150	0.183
k					1.000	0.572 **	-0.234 *	-0.077	-0.056	-0.064
DS						1.000	-0.217 *	0.097	0.074	0.077
K <sub>1</sub>							1.000	0.623 **	0.061	0.167
k <sub>dd</sub>								1.000	0.308 **	0.441 **
K <sub>tdd</sub>									1.000	0.989 **
K <sub>t</sub>										1.000

N = 91,  $t_{0.05} = 0.205$  and  $t_{0.01} = 0.207$ , \* = significant at 5% test, and \*\* = significant at 1% test.

The relationship between smectite content with buffering capacity and maximum sorption of soil K was significantly positive with determinant coefficient value of 0.4000 and 0.5320, respectively (Figure 6). This showed that smectite not only played role on soil negative charge but also can control buffering capacity and maximum soil K sorption. Therefore, smectite had important role in supplying K for plants on three soils tested.

### Potassium Management on Soils Dominated by Smectite

Result of soil K fractionation analysis showed that most of K in three soils tested were in nonexchangeable fraction so it was not available for plants (Figure 2 and 3). Besides, soils dominated by smectite had characteristics of clay soil texture, neutral-alkalin soil reaction, low C, organic-N, and CEC, low-high base saturation (Table 2), and high soil sorption and buffering capacity on K (Table 4). To increase

efficiency of K fertilizer, efforts should be carried out to increase K availability for plants.

Even though only K<sub>1</sub> and exch-K which quickly available for plants, nonexch-K including fixed-K and structured-K could be made available for plants. As previously stated that available K was only 29-38% of total K in soils (Figure 2 and 3). Therefore, there was a high possibility to harvest soil K, about 62-71% of total soil K. If the possibility can be used, a half or whole plant K requirements can be fulfilled from soil, so fertilizer application will be efficient.

Research results showed that organic acid from root exudates or microbe activities at rhizosphere had an important role in increasing soil K availability (Kim *et al.* 2004). Zhu and Luo (1993) reported that oxalic acid and citric acid can release nonexch-K into exch-K and K<sub>1</sub> at limestone parental soils. The same result was reported by Song and Huang (1988), where nonexch-K from mineral inner position containing K (biotite, muskovite, microcline, and orthoclas) can be released by oxalic acid and citric acid. Research done by Sparks and Leibhardt (1981) by

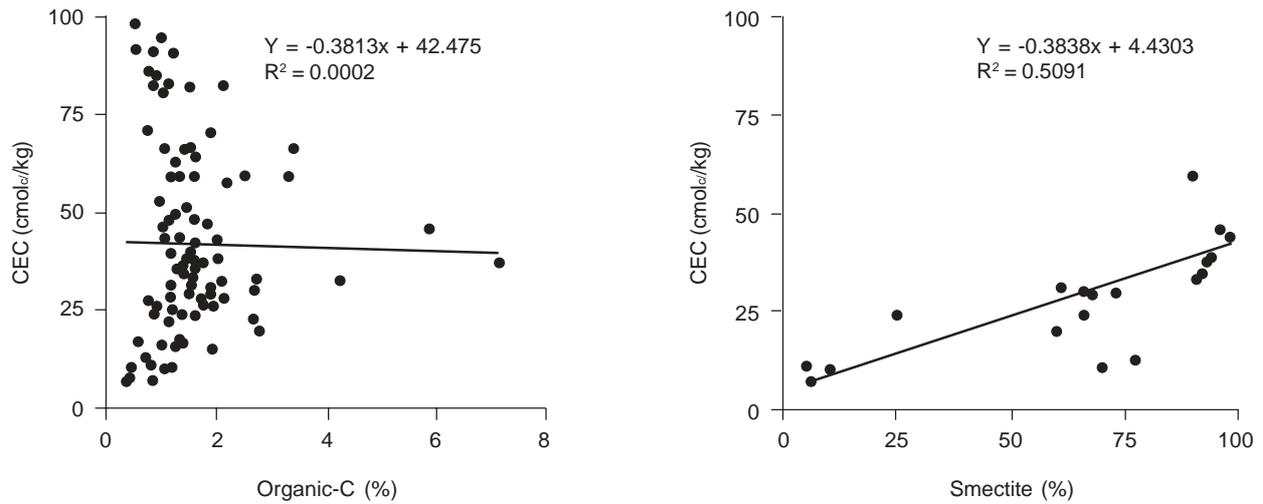


Figure 5. Relationship between soil organic-C and smectite with soil CEC.

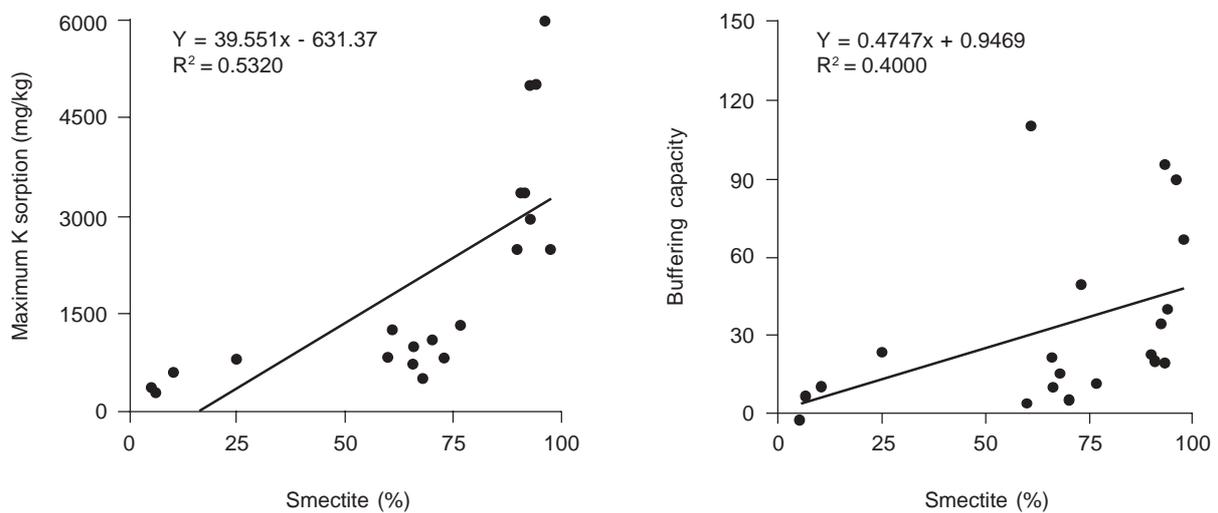


Figure 6. Relationship between soil smectite with maximum K sorption and buffering capacity.

using soils of Middle Atlantic Coastal Region, USA with coarse-texture and having high total K showed that application of oxalic acid 0.01 M could release K from mineral structure of feldspar during 30-day incubation. Therefore, plants that released high organic acid could be developed at soils dominated by smectite. The plants were rice and corn (Nursyamsi *et al.* 2002; Syarif 2005).

Besides organic acid, cations also played role in increasing K availability at soils dominated by clay mineral type 2:1 or mineral having high K. Ca and Na cations can substitute K position at interlayer muskovite mineral due to weathering process. Thus ammonium cation can release fixed-K become available K (Evangelou and Lumbanraja

2002). Research on Vertisols at sugarcane plantation soil showed that Na application from NaCl reduced K fertilizer requirement of sugarcane plant (Ismail 1997). Other research showed that Na application from sodium tetraphenyl boron could release fixed-K become available K at red soil (Alfisols), black soil (Vertisols), and aluvial (Inceptisols) (Dhillon and Dhillon 1992). Besides those cations, Fe also had potential in releasing fixed-K become available K because Fe had higher sorption than K. Fe was a micronutrient required by plants that often became constraint in plant growth at alkaline soil, such as soils dominated by smectite.

## CONCLUSION

Soil  $K_f$ ,  $\text{exch-K}$ ,  $\text{nonexch-K}$ , and  $K_t$  contents from high to low were in order of Vertisols > Alfisols > Inceptisols. Proportion of K fractions from low to high at three soils tested had the same order, that were  $K_f < \text{exch-K} < \text{nonexch-K}$ . Even though soil  $K_t$  was high, more K in the three soils tested was in nonexchangeable form, so K was not available for plants.

Buffering capacity and maximum K sorption of the three soils tested from high to low were in order of Vertisols > Alfisols > Inceptisols. While soil bond energy constant of Vertisols was slightly same with that of Alfisols and about twice of Inceptisols.

Clay, organic-C, and soil CEC significantly affected soil K availability. Smectite significantly contributed to soil negative charge, so it had an important role in controlling buffering capacity and maximum soil K sorption.

To increase K fertilizer efficiency, plants that able to produce high organic acid exudate can be developed at soils dominated by smectite. Addition of Na,  $\text{NH}_4$ , and Fe cations should also be considered in soil K management.

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