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Chemical Characteristics of Representative High Aluminium Saturation Soil as Affected by Addition of Soil Amendments in a Closed Incubation System

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ABSTRACT

Soil acidity is one of the main factors that limits profitable and sustained agricultural production. This study examined the performance of selected amendments in improving soil fertility of acidic tropical soils. The best two acidic tropical soils from Malaysia, Batu Anam and Durian, were selected to represent acid soils from Colombia while the five soil amendments selected were ground magnesium limestone (GML), magnesium carbonate (MgCO3), gafsa phosphate rock (GPR), gypsum, and kieserite. They were incubated in a closed incubation system for two months. The measured parameters were soil pH, exchangeable aluminium (Al), exchangeable cations, and available P. The treatments were organised in a factorial completely randomised design (CRD) with three replications. There was a significant difference in response among soils, amendments, rates and their interaction effects for the different soil parameters evaluated, with GML giving a high soil pH (0.339) effect and amelioration of the exchangeable Al (-0.838 cmolc/kg) per ton applied. MgCO3 and GPR gave similar effects in neutralising exchangeable Al (~ -0.6 $cmol_c$/kg) per ton ha^{-1} with a slight increase in soil pH (0.1 unit). Kieserite and Gypsum had a significant effect on amelioration of aluminum ((~ -0.16 $cmol_c$/kg) in Batu Anam soil. GML was the most cost-effective amendment in increasing soil pH and neutralising Al at USD$ 118.5 per $cmol_c$/kg of Al.

Keywords: Acidic soils, exchangeable aluminium, Gafsa Phosphate Rock, ground magnesium limestone, incubation system, soil amendments

INTRODUCTION

Soil acidity is one of the main factors that limits and prevents profitable and sustained agricultural production in many parts of the world. In most cases, this condition is not treated or corrected suitably. Approximately 50% of the world's arable soils are

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acidic and may be subjected to the effects of aluminium (Al) toxicity; the tropics and subtropics account for 60% of the acid soils in the world (Sumner and Noble 2003). The negative effects of high levels of soluble Al on plant growth have been widely reported (Marschner 1986; Zang and Rengel 1999; Matsumoto 2002; Langer *et al*. 2009). Liming acid soils is generally practised to reduce Al toxicity and is considered by many soil scientists as the first step towards providing a balanced nutrition for cultivated plants (Brown and Stecker 2003; Essington 2004). There are few agricultural practices in the tropics which can add as many valuable advantages to crop development and final yield as liming of acidic soils (Prochnow 2008). There are four major factors that affect the successful neutralisation of soil acidity by agricultural limestone. They are (i) lime rate, (ii) lime purity (compared to pure calcium carbonate and expressed as calcium carbonate equivalent (CCE)), (iii) lime particle size distribution or fineness of grind, and (iv) degree of incorporation or mixing with the soil (Goh *et al*. 1998; Conyers *et al.* 1996; Anon. 2006b). Lime requirements of soil are not only related to soil pH, but also to its buffer capacity or cation exchange capacity (CEC). Addition of lime raises the soil pH and eliminates two major problems of acid soils: excess (toxic) soluble Al and slow microbial activities. Lime also has the following benefits: improves the physical condition of the soil, reduces excess soluble manganese and iron (as possible toxin) by causing them to form insoluble hydroxides, increases the CEC in variable charge soils, increases availability of several nutrients, such as calcium and magnesium, improves symbiotic nitrogen fixation by legumes, increases plant-available molybdenum, and reduces the solubility and plant uptake of potentially toxic heavy metals, such as cadmium, copper, nickel, and zinc (Truog 2004; Prochnow 2008). A variety of techniques have been developed to measure the lime requirement of soils. The procedures that involve longer equilibration times for reacting soil with a liming material (anywhere from days to months) provide a better estimation for the lime requirement. However, the price for improved accuracy is the loss of time (Essington 2004).

Oil palm is mainly cultivated in tropical regions (Corley and Tinker 2003; Anon. 2006a). With the exception of the use of phosphate rock (PR) for direct-application to supply phosphorus (P), adding soil amendments in oil palm plantation is not generally practised. We observed that in acid Colombian soils, there exists a strong relationship between high Al saturation in soils and the occurrence of bud rot disease of mature oil palm. Addition of soil amendments could possibly alleviate Al toxicity, increase soil pH, and improve soil fertility status. Generally, these materials are of interest to oil palm growers because of low cost and ready availability. However, selection of a suitable soil amendment is not based on technical criteria (Munevar *et al.* 2005). There is a lack of information related to performance and comparison of amendments with very high Al saturation on acidic soils. Therefore, the specific objective of this study was to evaluate the effects of selected amendments used in oil palm cultivation to improve soil fertility, representing high Al saturation soil, using two acidic Malaysian soils in a closed-incubation system.

MATERIALS AND METHODS

Soil Sampling and Analysis

Four acid Malaysian soils were selected for the initial characterisation according to USDA soil taxonomy (Paramananthan, 2000). They were Batu Anam (clayey, kaolinitic, isohyperthermic, Aquic Paleudult,), Durian (clayey, mixed, Isohyperthermic, Plinthaquic Paleudult,), Bungor (clayey, kaolinitic, isohyperthermic, Typic Paleudult), and Melaka (clayey-skeletal, kaolinitic isohyperthermic, Xanthic Hapludox,). Thirty-six soil samples were collected from these four soils to give a combination of 3 depths, 3 sampling sites, and 4 soil series. These samples were taken from a five-year-old oil palm estate located in Negeri Sembilan. The soil samples were air-dried and passed through a 2-mm sized sieve. The following soil characteristics were determined: (i) pH_{water} (1:1 soil/water ratio) and pH_{KCl} (1:2.5, soil/1M KCl solution ratio); (ii) CEC and exchangeable cations (Ca, Mg, K, and Na) extracted with 1M NH_4OAc at pH 7 (Jones 2001) and the elements determined using atomic absorption spectrophotometry (AAS); (iii) available phosphorus extracted with Bray II (Jones 2001) solution and P concentration analysed using an auto analyser (AAS); (iv) total soil carbon determined using infrared absorption method (LECO CR – 412); and (v) soil texture determined using the pipette method (Boon Sung and Talib 2006).

The Al forms in soil were sequentially extracted by the following procedures: (i) exchangeable Al was extracted with 1M KCl at 1:10 (soil/solution ratio) by shaking for 24 hours, (ii) weakly organically bound Al forms were extracted with 0.3M $CuCl_2$ at 1:10 (soil/solution ratio) by shaking for 2 hours, and (iii) total organically bound Al forms were extracted with 0.1 M $Na_4P_2O_7$ at 1:10 (soil/solution ratio) by shaking for 24 hours. In all steps, soil solution was separated by centrifugation for 20 minutes at 13500 rpm, and when necessary, further purified by filtration. Content of strongly organically bound Al was calculated as the difference between $Na_4P_2O_7$ extracted- and $CuCl_2$ extracted- Al (Drabek *et al.* 2003). The Al in solution was analysed using inductively couple plasma atomic emission spectroscopy (ICP AES).

Soils Selected and Amendments

Batu Anam and Durian soils were selected for the evaluation of the performance of various amendments. Both soils had high concentrations of exchangeable Al and Al saturation, clayey textural class and low soil pH (Table 1). The following amendments were used: (i) ground magnesium limestone, (ii) magnesium carbonate, (iii) Gafsa phosphate rock, (iii) gypsum, and (iv) kieserite. The Ca and Mg of the materials were extracted by dissolution in 1.0 M HCl and analysed by AAS (Conyers *et al.* 1996). The chemical characteristics of the amendments used are given in (Table 2).

Table 1
Selected physical and chemical properties of four acidic Malaysian soils

Depth	Particle size			Organic	pH		Aluminum				Exchangeable cations				Sum	CEC	ECEC **	Al ***	P	Ca/Mg	(Ca+Mg)/K
	Clay	Silt	Sand	C	H_2O 1 : 1	KCl 1 : 2.5	Exchangeable	Weakly	Total	Strongly	Ca	Mg	K	Na	Cation *	pH 7		saturation	Available		
cm	------------------%------------------						---------- cmolc/kg ----------											%	mg kg^{-1}		
Batu anam series																					
0 - 15	39.9	38.9	21.2	1.1	3.43	3.66	3.05	5.68	14.08	8.40	0.22	0.14	0.27	0.05	0.68	10.29	3.73	81.71	6.16	1.52	1.33
15 - 30	43.5	31.3	25.1	0.9	3.77	3.63	4.05	6.21	14.66	8.46	0.02	0.08	0.19	0.03	0.32	9.75	4.37	92.73	5.74	0.27	0.50
30 - 45	44.0	38.3	17.7	0.5	3.70	3.65	4.95	6.50	14.78	8.28	0.07	0.05	0.23	0.03	0.39	10.50	5.34	92.74	6.81	1.28	0.52
Bungor series																					
0 - 15	25.7	6.7	67.7	1.2	4.10	3.75	1.06	2.80	7.89	5.09	0.36	0.06	0.17	0.03	0.62	8.14	1.68	63.07	18.78	6.32	2.40
15 - 30	36.6	6.0	57.4	0.9	3.75	3.79	2.59	3.43	8.85	5.41	0.40	0.08	0.14	0.03	0.65	6.94	3.23	80.05	11.61	4.95	3.36
30 - 45	45.7	5.3	48.9	0.5	3.76	3.63	3.30	4.47	10.25	5.78	0.12	0.02	0.12	0.02	0.29	8.71	3.59	91.98	5.35	5.54	1.14
Durian series																					
0 - 15	28.7	19.5	51.7	1.8	4.25	3.74	2.19	4.25	14.86	10.61	0.96	0.20	0.53	0.03	1.73	7.21	3.92	55.92	5.10	4.69	2.19
15 - 30	53.5	9.2	37.3	1.1	4.18	3.63	3.46	4.98	15.53	10.55	0.27	0.15	0.45	0.03	0.90	10.50	4.36	79.41	4.60	1.76	0.96
30 - 45	58.3	7.7	34.0	0.9	4.07	3.62	3.86	3.83	12.76	8.93	0.41	0.10	0.42	0.02	0.95	7.71	4.82	80.19	3.76	4.03	1.24
Melaka series																					
0 - 15	31.8	50.2	18.0	1.9	4.90	3.98	0.50	2.36	11.33	8.97	1.25	0.26	0.49	0.03	2.03	5.51	2.53	19.80	4.46	4.81	3.06
15 - 30	27.0	33.0	40.0	1.2	4.40	3.89	0.85	4.29	12.22	7.93	0.62	0.15	0.36	0.02	1.15	7.36	2.00	42.45	5.92	4.01	2.11
30 - 45	10.5	49.6	39.9	1.1	3.95	3.91	1.66	2.62	13.64	11.01	0.39	0.14	0.33	0.05	0.91	9.03	2.57	64.63	5.35	2.87	1.58

*Sum cation = ∑ Ca, Mg, K and Na
** ECEC = ∑ Ca, Mg, K, Na and Al
***Al saturation (%) = [Al / (∑ Ca, Mg, K, Na and Al) x 100]

Physical Composition of Amendments

The commercial soil-amendments with the exception of kieserite were granular. They were dried and sieved for 5 minutes using a mechanical shaker (British standard sieves of 500, 250, and 100 micrometers aperture). Gypsum had the finest particle sizes of < 0.25 mm (96%) and the coarsest was $MgCO_3$ (52%) (Table 2).

Application of the Amendments

About 100g of subsoil samples (5 to 30cm depth) were placed in plastic pots and the appropriate amounts of amendments added. The plastic pots were covered with a cloth material so as to reduce loss of moisture and allow for the exchange of O_2 and CO_2 (Munevar *et al*. 2005; Zapata 2004). Soil moisture was adjusted every third day to 90% field capacity, which was measured before the incubation study; the value for Batu Anam was 22.8% and for Durian, it was 23%.

Experimental Design

The treatments consisted of control (without amendment), five amendments, four rates (2.2, 3.5, 4.8, and 6.1) and two soil series. The treatments were organised in a factorial complete random design (CRD) with three replications. After a 60-day incubation period, the soils were air-dried and ground to pass through a 2-mm sieve size. The following soil properties were determined: soil pH, exchangeable Al, exchangeable cations (Ca, Mg and K), and available P, following the methods mentioned earlier.

The analysis of variance (ANOVA), polynomial contrast and regression analysis were performed with the software Statistix version 8 (USDA and NRCS 2007)

RESULTS AND DISCUSSION

Soil Characterisation

The topsoils (0 – 15cm) were very strongly acidic to strong acidic (Jones 2003) with pHw values ranging between 3.4 (Batu Anam soil) and 4.9 (Melaka soil). The majority of the subsoils (15 - 45 cm) evaluated, were very strongly acidic with pHw values less than 4.4. The pH_{KCl} showed a similar trend as in pH_w, ranging between 3.7 (Batu Anam) to 4.0 (Melaka). A significant negative correlation between pHKCl and exchangeable Al (r = -0.73*) was found indicating that a 4 unit increase in the pH_{KCl} value would allow for the exchangeable Al to be totally neutralised (data not shown). Exchangeable Al and Al saturation in the topsoils ranged from 0.5 (Melaka) to 3.05 (Batu Anam) $cmol_c$/kg, and 19.8% (Melaka) and 81.7% (Batu Anam), respectively. In general, the exchangeable Al and saturation increased with the soil depth for all soil series reaching 92.7% of Al saturation in Batu Anam soil. Malacca soil showed the lowest Al concentration and saturation and the highest pH value, indicating less severe acidity constrains. These results were probably influenced by previous application of oil palm empty fruit bunches (EFB) mulching as reflected by a high soil C (Table 1).

Table 2
Chemical composition and particle size of the amendments

Amendments & abbreviation	Origin	$MgCO_3$	$CaCO_3$	SO_4	P_2O_5	Particle size distribution (%)			
		%				> 0.5 mm	0,25 - 0.5 mm	0.1 - 0.25 mm	< 0.1 mm
Ground magnesium limestone (GML)	Malaysia	32.8 ± 0.12	42.8 ± 0.13			7.00 ± 0.03	4.95 ± 0.04	50.08 ± 0.95	37.98 ± 0.91
Magnesium carbonate ($MgCO_3$)	Antioquia, Colombia	41.8 ± 0.11				30.53 ± 0.05	17.55 0.02	27.00 ± 0.15	24.93 ± 0.17
Gafsa phosphate rock (GPR)	Tunisia		87.5 ± 0.12		25.2 ± 0.10	15.05 ± 0.12	15.20 ± 0.02	64.78 ± 0.12	4.98 ± 0.02
Gypsum	Palmira, Colombia		56.7 ± 0.10	48.8 ± 0.01		1.67 ± 0.05	2.37 ± 0.02	51.13 ± 0.33	44.83 ± 0.35
Kieserite	Germany	52.3 ± 0.05		59.9 ± 0.03					

Each value is the mean of three replicates ± SE.

The soil CEC qualified as very low with organic C being very low to moderate. The calcium and magnesium concentration and saturation (data not shown) and phosphorus concentration were classified as low to moderate category for the majority of soils studied according to the soil nutrient classification tables (Munevar 2001; Fairhurst *et al*. 2005). The Ca/Mg and (Ca + Mg)/K ratio showed high variability indicating imbalance among the exchangeable cations (Table 1).

There was a high variability in particle size among the soil series. The Batu Anam and Durian soils were characterised by high clay fraction, the Bungor soil by sand fraction, and Melaka soil by silt fraction (Table 1).

Aluminium Forms

Batu Anam and Durian soils showed the highest value of the different Al forms; Batu Anam soil had the highest value of exchangeable Al indicating major influence of soil acidity with the potential to release exchangeable Al to the soil solution. Bungor and Melaka soils showed the lowest exchangeable Al (Table 1).

Effect of Amendments on Different Chemical Properties of Soils

Soil pH

There was a significant difference among soils, amendments, and rates and their respective two-way interactions with the exception of the three-way interactions (Table 3). The best responses were obtained for Batu Anam soil. The interaction between amendments x rates for Batu Anam and Durian soils were significant, and the linear and quadratic polynomial contrast for both soils were significant (Table 3). GML raised the soil pH by 0.34 and 0.32 units for Batu Anam and Durian soils, respectively. $MgCO_3$ and GPR showed an increase in pH of 0.10 and 0.11 for Batu Anam and 0.05 and 0.08 unit for Durian. Kieserite and gypsum had a significant negative effect on soil pH (Table 5). This study showed that the performance of GML and gypsum are comparable with the results reported by Shamshuddin *et al* (1991); in which the application of limestone increased the soil pH in the zone of incorporation for maize at harvest but gypsum had no consistent effect. Shamshuddin (1995) found that gypsum application showed a tendency for a decrease in soil pH on the topsoil in an Ultisol. Suswanto *et al*. (2007) reported that an application of 4 t GML/ha ameliorated the aluminum toxicity by increasing soil pH from 4.27 to 4.93. Goh *et al*. (1998) showed that continuous applications of GML increased soil pH quadratically from 4.3 to 4.7. The quadratic response to lime on this soil could be attributed to its buffering capacity, low CEC, and coarser particles of the GML. In addition to the benefit of adding plant available P to the soil, phosphate rock (PR) may also serve as a liming agent. Sinclair *et al*. (1993) observed that a single superphosphate treatment decreased soil pH by 0.16 units over a 6-year period, while PR treatment kept soil pH level ranging from 5.5 to 6.0 in a variety of soils. Liming material had a much greater influence on increasing soil pH compared to the PRs (Sikora, 2002).

Exchangeable Aluminium and Aluminium Saturation

There was a significant difference in exchangeable Al among soils, amendments, and rates, and their respective interactions (Table 3). The best response in amelioration of Al was obtained for Batu Anam soil. GML for both soils gave a high response in neutralising Al exchangeable 0.84 and 0.56 $cmol_c$/kg, and 0.66 and 0.34 $cmol_c$/kg for GPR per t/ha for Batu Anam and Durian soils, respectively (Table 4). Kieserite and gypsum had been shown to have a significant effect on neutralising aluminium in Batu Anam soil (Table 5). Unlimed Batu Anam soil, which had the lowest pH, contained the highest exchangeable Al and Al saturation (Table 4); most of the exchange sites were saturated with Al. As soil pH was increased from 4.4 to 6.5 with the application of GML, the amount of exchangeable Al decreased by 100% from 5.17 to 0.00 $cmol_c$/kg of soil; a corresponding increase in exchangeable Ca and Mg was obtained from 0.57 to 5.40 and 0.10 to 2.13 $cmol_c$/kg of soil, respectively. For $MgCO_3$, as soil pH increased from 4.4 to 5.0, the amount of exchangeable Al decreased by 80.7% from 5.17 to 1.00 $cmol_c$/kg of soil; a consequent increase in exchangeable Mg was also obtained from 0.10 to 1.86 $cmol_c$/kg of soil. There was a slightly increase in Ca from 0.57 to 0.95 $cmol_c$/kg of soil. For GPR, as the soil pH increased from 4.4 to 4.7, the amount of exchangeable Al decreased by 77.4% from 5.17 to 1.17 $cmol_c$/kg of soil; a resultant increase in exchangeable Ca from 0.57 to 4.43 $cmol_c$/kg of soil was also obtained (Table 4). Lime is the most dominant and most effective practice to replenish the soil cation pool. Lime increases soil pH, Ca concentration, CEC, and base saturation, simultaneously lowering the Al concentration. All of these chemical changes, provided they are within a favourable range, improve grain yield and crop sustainability (Fageria and Baligar 2003).

TABLE 3

Summary of the statistical analysis of variance (ANOVA) for the comparison of GML, $MgCO_3$ and GPR amendments

Factors & Interactions	Parameters					
	Al	Al Saturation	Soil pH	Ca	Mg	Ca /Mg
Soil (S)	*	n.s.	*	*	*	*
Amendments (A)	*	*	*	*	*	*
Rates (R)	*	*	*	*	*	*
S X A	*	n.s.	*	n.s.	*	*
S X R	*	n.s.	*	*	n.s.	*
A X R	*	n.s.	*	*	*	*
S X A X R	n.s.	n.s.	n.s.	*	*	*
Linear contrast	*	*	*	*	*	*
Quadratic contrast	*	*	*	*	*	*

*significant at $p \leq 0.05$

n.s. not significant $p > 0.05$

There was a significant difference in Al saturation amelioration among amendments and rates (Table 3). The three amendments were effective in neutralising Al saturation. The amelioration of Al saturation for Batu Anam and Durian soils were 13.1 and 13.0% for GML, 9.9 and 9.8% for GPR, and 9.2 and 9.4% for $MgCO_3$ per ton applied (Table 4). Values of Al saturation can be used as an index for lime application rate, a rate that varies from soil to soil and among crop species as well as within cultivars of the same species. In the lowland acid soils of Brazil, a relationship has been found between Al saturation and the relative grain yield of common bean. With increasing Al saturation, there was a quadratic decrease in the grain yield (Fageria and Baligar 2003).

A close relationship ($P < 0.05$) was found between soil pH and exchangeable Al concentration and Al saturation with the trends being different among amendments. In the case of $MgC0_3$ and GPR, increasing soil pH linearly decreased exchangeable Al, and for GML increasing soil pH exponentially decreased exchangeable Al (Fig. 1). Similar results for GML were reported by Caires *et al.* (2008). According to Sikora (2002), a 0.1 unit increase in soil pH caused a 10.3 mg/kg reduction in 1 N KCl extractable Al for the Copper Basin soil. Although the PR liming effect may only increase pH a few tenths of a unit, the reduction in soluble Al could result in a significant improvement for plants growing in very acidic soils.

Exchangeable Ca and Mg

There was a significant difference in exchangeable calcium among soils, amendments, and rates, and the interaction between amendments and rates (Table 3). The interaction between amendments x rates may be described using the linear polynomial contrast with GML rising to 0.82 and 0.78 $cmol_c$/kg and GPR increasing Ca to 0.61 and 0.79 cmolc/kg, per ton applied for Batu Anam and Durian soils, respectively (Table 4). Gypsum showed a significant increase in exchangeable Ca raising 1.76 and 1.71 $cmol_c$/kg of soil per ton applied on Batu Anam and Durian Soils.

There was a significant difference in exchangeable magnesium among means of soils, amendments, and rates, and their respective interactions (Table 3). The best response was achieved in Batu Anam soil. The interaction between amendments and rates, described by the linear polynomial contrast, was as follows: kieserite raised Mg content to 1.23 and 1.03 cmolc/kg of soil; GML increased Mg to 0.34 and 0.27 $cmol_c$/kg of soil and $MgCO_3$ increased to 0.28 and 0.24 $cmol_c$/kg of soil per ton applied for Batu Anam and Durian soils, respectively (Tables 4 and 5). Total Mg contents were observed to increase exponentially with higher GML rates. However, exchangeable Mg contents improved quadratically only, implying that at a high rate of GML, a large proportion of the soil Mg content remains in non-exchangeable form. This might be attributed to the poorer chemical reactivity of magnesium carbonate compared to calcium carbonate in soil. Therefore, more time is required for the Mg nutrient in GML to reach its maximum effectiveness (Goh *et al.* 1998). Heming and Hollis (1995) reported that the kieserite, calcined

Table 4
Effect of GML, $MgCO_3$ and GR amendments on soil pH, exchangeable Al, Al saturation, Ca, Mg and Ca/Mg and available P on Batu Anam and Durian soil series

Soil	Amendment	Rate t ha^{-1}	Soil pH	Al (cmol$_c$/kg)	Al saturation %	Ca (cmol$_c$/kg)	Mg (cmol$_c$/kg)	Ca : Mg	P mg kg^{-1}
Batu Anam	**$MgCO_3$**	0	4.40	5.17	78.90	0.57	0.10	7.55	
		2.2	4.58	3.70	63.13	0.73	0.38	2.09	
		3.5	4.66	2.47	50.63	0.68	0.67	1.03	
		4.8	4.83	1.80	40.53	0.72	1.11	0.65	
		6.1	5.00	1.00	21.23	0.95	1.86	0.51	
		Equation	y= 0.097x+4.373	y= -0.694x+5.113	y= -9.229x+81.27	y= 0.051x+0.560	y= 0.278x-0.093	y=-1.116x+6.042	
		R^2	0.98	0.99	0.98	0.73	0.91	0.78	
Durian	**$MgCO_3$**	0.0	3.97	3.42	77.23	0.24	0.11	2.98	
		2.2	4.33	3.06	75.23	0.11	0.21	0.88	
		3.5	4.43	2.26	64.67	0.08	0.52	0.15	
		4.8	4.53	1.26	40.60	0.14	1.09	0.12	
		6.1	4.66	0.67	21.83	0.11	1.54	0.07	
		Equation	y= 0.109x+4.022	y= -0.481x+3.721	y= -9.419x+86.92	y= -0.017x+0.191	y=0.244x-0.112	y=-0.470x+2.389	
		R^2	0.96	0.94	0.85	0.41	0.88	0.80	
Batu Anam	**GML**	0.0	4.40	5.17	78.90	0.57	0.10	7.55	
		2.2	4.91	1.40	28.37	2.45	0.47	5.23	
		3.5	5.25	0.33	6.07	3.61	0.95	3.81	
		4.8	5.90	0.00	0.33	4.64	1.53	3.03	
		6.1	6.46	0.00	0.13	5.40	2.13	2.55	
		Equation	y=0.339x+4.263	y=-0.838x+4.14	y = -13.11x+ 65.94	y=0.806x+0.677	y=0.338x+0.075	y=-0.841x+7.203	
		R^2	0.96	0.81	0.85	0.99	0.96	0.96	
Durian	**GML**	0.0	3.97	3.42	77.23	0.24	0.11	2.98	
		2.2	4.59	1.00	30.87	1.21	0.40	3.28	
		3.5	5.05	0.27	7.90	2.12	0.67	3.30	
		4.8	5.44	0.03	0.47	3.44	1.21	2.83	
		6.1	5.89	0.00	0.03	4.99	1.78	2.79	
		Equation	y=0.316+3.942	y=-0.556x+2.77	y=-12.98x+66.05	y=0.776x-0.157	y=0.273x-0.067	y=-0.046x+3.187	
		R^2	1.00	0.82	0.88	0.96	0.93	0.20	
Batu Anam	**GPR**	0.0	4.40	5.17	78.90	0.57	0.10	7.55	6.00
		2.2	4.44	2.93	41.33	3.26	0.05	57.44	26.30
		3.5	4.54	2.03	29.97	3.63	0.06	61.10	48.40
		4.8	4.62	1.40	21.83	4.17	0.07	58.71	72.50
		6.1	4.67	1.17	18.17	4.43	0.08	55.33	96.20
		Equation	y=0.048x+4.376	y=-0.664x+4.726	y=-9896x+70.62	y=0.612x+1.197	y=-0.002x+0.083	y=7.269x+24.09	y=15.08x+0.232
		R^2	0.96	0.93	0.90	0.87	0.11	0.57	0.97
Durian	**GPR**	0.0	3.97	3.42	77.23	0.24	0.11	2.98	5.97
		2.2	4.27	2.93	56.17	1.60	0.08	19.28	46.43
		3.5	4.34	2.71	42.60	2.88	0.10	30.70	47.09
		4.8	4.44	1.98	28.80	4.11	0.11	36.98	73.01
		6.1	4.48	1.31	18.87	4.83	0.11	43.66	97.53
		Equation	y=0.082x+4.027	y=-0.342x+3.599	y=-9.764x+76.88	y=0.787x+0.140	y=0.001x+0.095	y=6.766x+4.446	y=14.23x+7.132
		R^2	0.92	0.94	1.00	0.99	0.13	0.99	0.96

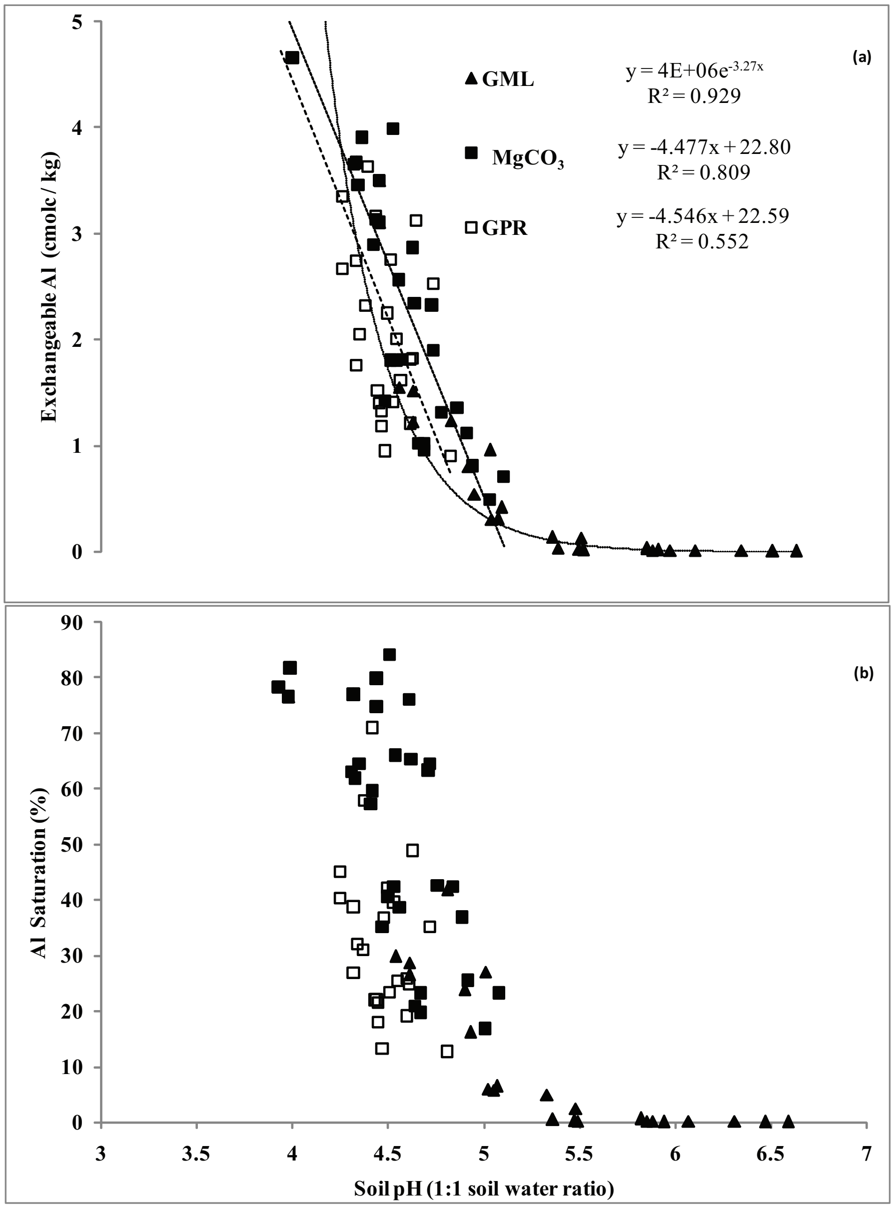

Fig. 1. Relationship between soil pH (1:1 soil to water ratio) and exchangeable Al and Al saturation in Batu Anam and Durian soils for GML, $MgCO_3$, and GPR amendments

magnesite and magnesian limestone had some effect within 12 months with soil Mg being raised by at least one index value. Kieserite and calcined magnesite powder gave a similar increase in extractable Mg, but granular calcined magnesite was less effective in all soils.

TABLE 5
Kieserite effects on soil pH, Mg and exchangeable Al, and Gypsum effects on soil pH, Ca and exchangeable Al on Batu Anam and Durian soils

Soil	Rate	Kieserite			Gypsum		
		Soil pH (H_2O)	Mg	Al	Soil pH (H_2O)	Ca	Al
	t ha^{-1}		($cmol_c$/kg)			($cmol_c$/kg)	
Batu Anam	0.0	3.97	0.10	5.16	3.97	0.57	5.16
	2.2	3.81	1.13	3.73	3.80	4.00	4.75
	3.5	3.76	2.59	4.05	3.76	5.94	4.77
	4.8	3.76	5.43	3.77	3.73	8.28	4.52
	6.1	3.76	9.01	4.04	3.74	11.55	4.10
	Equation	y=-0.033x+3.92	y=1.238x+0.632	y = -0.1681x+4.70	y=-0.038x+3.92	y=1.762x+0.26	y=-0.157x+5.17
	R^2	0.73*	0.86*	0.30*	0.79*	0.97*	0.35*
Durian	0.0	4.40	0.11	3.42	4.40	0.24	3.42
	2.2	4.06	1.69	3.09	4.11	3.03	3.29
	3.5	4.01	3.10	2.94	4.02	5.38	2.96
	4.8	4.01	4.82	3.06	4.00	7.41	2.94
	6.1	4.03	6.35	2.75	3.98	10.88	2.83
	Equation	y=-0.058x+4.29	y=1.036x+0.1941	y=-0.095x+3.36	y=-0.067x+4.32	y=1.715x+0.255	y=-0.103x+3.42
	R^2	0.55*	0.95*	0.09^{ns}	0.74*	0.90*	0.12^{ns}

* - significant at $p \leq 0.05$
n.s. - not significant $p > 0.05$

Available Phosphorus

A positive response on available P was obtained by GPR. For every ton of GPR applied, the level of available P increased to 15.08 and 14.23 mg/kg (Table 4). This value qualifies as an optimum level for the maintenance of oil palm crop (Munevar *et al.* 2001; Fairhurst et al. 2005). A similar increase in available P was reported by Munevar et al (2005) in which 25.0 mg/kg of available P was obtained with the application of 1.43 ton/ha of phosphate rock # 3 (Enmienda Fosfórica # 3) from Colombia.

Economic Analysis

The economic analysis of the various amendments on aluminium amelioration was done according to the price of the materials provided by Agro-Export of Colombia and Mejisulfatos Colombian Fertilizer Company on May 2008 (Table 6).

The GML gave more benefits in contrast with the other sources evaluated, because it has the capacity to highly increase soil pH and reduce a major quantity of exchangeable Al, resulting in a low Al saturation value. Additionally, it supplied sufficient levels of Ca and Mg, and was able to maintain a balanced Ca/Mg ratio in the soil. Economically, use of GML as an amendment, allows for Al to be neutralised and soil pH increased at a low cost (USD 118.50 per $cmol_c$/kg) compared to GPR (USD 232.36 per $cmol_c$/kg).

TABLE 6
Amendments effect on exchangeable Al, price of the amendment and the cost per ha per cmolc/kg of Al neutralised for Batu Anam soil

Amendments	Al^{3+} (cmolc/kg) neutralized / t $CaCO_3$	Price per t $ USD	Cost per Al^{3+} ($cmol_c$/kg) neutralized
$MgCO_3$	0.69	469.91	681.03
GML	0.84	99.54	118.50
GPR	0.66	153.36	232.36

CONCLUSIONS AND RECOMMENDATIONS

The GML gave the best agronomic and economic efficiency in neutralising soil acidity in Ultisols such as Batu Anam and Durian soils as it increased soil pH, Ca, Mg, and neutralised the major proportion of exchangeable Al and Al saturation, and maintained the Ca/Mg balance ratio. $MgCO_3$ and GPR gave a similar effect on soil pH, exchangeable Al, and Al saturation. However, both provided an additional effect in improving the level of Mg for $MgCO_3$, and Ca and P for GPR. The level of Mg and P attained from 1 ton/ha is probably enough to achieve the optimum level for oil palm maintenance. Kieserite provided an increased proportion of Mg and was capable of neutralising Al in Batu Anam soil. The amendments evaluated showed variable effects on acid soil parameters. Therefore, a combination of different sources must be used to obtain an adequate balance of the nutrients which assures greater efficiency of nutrient availability to the plants.

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