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Improving the Productivity of Acid Sulfate Soils for Rice Cultivation using Limestone, Basalt, Organic Fertilizer and/or their Combinations

(Meningkatkan Produktiviti Tanah Asid Sulfat Tanaman Padi menggunakan Batu Kapur, Basalt, Baja Organik dan/atau Gabungannya)

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ABSTRACT

Acid sulfate soils are generally not suitable for the crop production unless they are efficiently improved. A study was conducted to improve the productivity of acid sulfate soils for rice cultivation using ground magnesium limestone (GML), basalt and organic fertilizer. The study was conducted on rice in laboratory, glasshouse and field. The pH of acid sulfate soils was low and exchangeable Al was very high which affected rice growth. The application of GML and basalt increased soil pH and reduced Al toxicity. GML required to ameliorate the soils for rice cultivation was 4 t ha^{-1}. Basalt in combination with organic fertilizer was a good soil amendment, but required to be applied a few months ahead of rice cultivation. Due to GML or basalt application, rice plants grew well even though water pH was below 5. The highest rice yield obtained was 4.0 t ha^{-1} season^{-1} for Sulfaquepts and it was 7.5 t ha^{-1} season^{-1} for Sulfosaprists. In general, the application of GML or basalt in combination with organic fertilizer improved the productivity of acid sulfate soils and consequently enhanced rice yield.

Keywords: Acid sulfate soil; aluminum toxicity; iron toxicity; rice production; soil amendments

ABSTRAK

Asid tanah sulfat secara amnya tidak sesuai untuk pengeluaran tanaman kecuali ditambah baik secara cekap. Suatu kajian telah dijalankan untuk meningkatkan produktiviti tanah sulfat asid untuk penanaman padi menggunakan batu kapur magnesium (GML), basalt dan baja organik. Kajian telah dijalankan ke atas tanaman padi di dalam makmal, rumah kaca dan lapangan. pH tanah adalah rendah dan pertukaran Al yang sangat tinggi memberi kesan kepada pertumbuhan padi. Aplikasi GML dan basalt ini meningkatkan pH tanah dan mengurangkan ketoksikan Al. GML yang diperlukan untuk memperbaiki tanah bagi penanaman padi adalah 4 t ha^{-1}. Gabungan basalt dengan baja organik adalah baik untuk memperbaiki keadaan tanah tetapi perlu diletakkan beberapa bulan lebih awal sebelum padi ditanam. Penggunaan GML dan basalt menyebabkan tanaman padi menbesar dengan baik walaupun pH air adalah di bawah 5. Untuk Sulfaquepts, hasil padi tertinggi yang diperoleh ialah 4.0 t ha^{-1} musim^{-1} manakala bagi Sulfosaprists adalah 7.5 t ha^{-1} musim^{-1}. Pada amnya, aplikasi GML atau basalt bersama baja organik akan meningkatkan produktiviti tanah asid sulfat sekaligus meningkatkan hasil padi.

Kata kunci: Ketoksikan aluminium; ketoksikan ferum; penambahbaikan tanah; pengeluaran padi; tanah asid sulfat

INTRODUCTION

The demand for the consumption of rice worldwide is increasing over the years (Yap 2012). Therefore, we need to produce more rice than ever before. Rice production can be increased by increasing the area planted to rice or increasing the yield per unit area. With no expansion in area and slowing down in yield increase, the growth of rice production has fallen below market demand. Farmers have to depend partly on the productivity of marginal soils in the world for their rice supply.

One of the soils targeted for rice cultivation in the future is acid sulfate soil. Acid sulfate soil occupies almost 50 million ha worldwide, including Southeast Asia, Australia, West Africa and Scandinavia (Ljung et al. 2009). In Malaysia, this kind of soils was estimated to cover about 0.5 million ha area with 110000 ha in the Malay Peninsular (Poon & Bloomfield 1977). Around 20000 ha were being used for rice cultivation in Peninsular Malaysia. This soil occurs exclusively in the coastal plains (Enio et al. 2011; Muhrizal et al. 2006; Shamshuddin et al. 1995). The soil is characterized by the presence of pyrite (FeS_2), which produces high acidity when the soil is opened up for development. Consequently, high amount of Al was released into the environment (Shamshuddin et al. 2004), affecting rice growth (Ting et al. 1993).

Acid sulfate soils that have been reclaimed were used for the cultivation of rice and oil palm with mixed success. These soils were degraded by way of low pH and high exchangeable Al. The soils were also low in Cu, Zn and B (Liew et al. 2010). Unless they are properly ameliorated, the soils are not suitable for agriculture. The methods used to ameliorate the soils are by applying ground magnesium limestone (GML) and ground basalt or submerging the soils. Liming raises soil pH so as to precipitate Al as inert Al-hydroxides, thereby reducing its toxicity (Shamshuddin et al. 2010). Besides increasing pH, GML can supply Ca and Mg. According to Ting et al. (1993), rice could achieve a yield of 4.5 t ha^{-1} $season^{-1}$ due to annual GML application of 2 t ha^{-1}. Likewise, ground basalt application can ameliorate acidic soils that lead to yield increase (Shamshuddin & Fauziah 2010).

Organic matter can remove Al from solution in acid sulfate soils via chelation (Muhrizal et al. 2003). When acid sulfate soil is flooded for rice cultivation, pH increases, but its value is still below 5.0. The rate of pH increase depends on the quality of the organic matter applied (Muhrizal et al. 2006). Below pH5.0, Al^{3+} is present in the water at toxic level. Applying GML in combination with organic fertilizer can produce high yield of rice (Suswanto et al. 2007). Application of lime, basalt, organic fertilizer and their combinations at appropriate rate is able to ameliorate acid sulfate soil infertility for rice production (Shazana et al. 2013). The objective of this study was to increase the productivity of acid sulfate soils for the rice cultivation using ground magnesium limestone, ground basalt, organic fertilizer and/or their combinations.

Materials and Methods

This study was conducted in laboratory, glasshouse and in the field. For the laboratory experiment, soil and water were taken from a paddy field in Merbok, Kedah, Malaysia. The soil was Merbok Series, classified as Typic Sulfaquepts. The soil for the glasshouse experiment was taken from Kelantan Plains, Malaysia which belongs to Parit Botak Series (Typic Sulfaquepts). The field trial was carried out at the Kelantan Plains, Malaysia on soils classified as Typic Sulfosaprists. The rice variety MR219 was used for this study.

Laboratory Experiment

The laboratory experiment was conducted in two phases. Firstly, the rice seeds were soaked in a hormone-based chemical (Zappa™). Three pre-soaked seeds were transferred into test tubes containing 0.5 mM $CaCl_2$ solution with various concentrations of Al (0, 10, 20, 30, 40 and 50 µM) using $AlCl_3$. Another set of experiment was conducted using acid water containing high concentration of Al and usually this concentration of Al is found in a paddy field in Merbok, Kedah. The pre-soaked seeds were exposed to 100 mL of the acid water. The pH of the water was adjusted to various levels at pH 3.0, 4.0, 5.0, 6.0 and 7.0 using 0.01 M HCl or 0.01 M NaOH. The seedlings were grown for 7 days. The root morphology of rice seedlings was determined using a root scanner.

Glasshouse Experiment

Moist acid sulfate soils from the field were mixed with amendments. The treatments were: T_1 = control; T_2 = 4 t GML ha^{-1}; T_3 = 4 t ground basalt ha^{-1}; T_4 = 0.25 t organic fertilizer ha^{-1} and T_5 = 4 t ground basal + 0.25 t organic fertilizer ha^{-1}. All treatments received standard fertilizer rates recommended for rice production in Peninsular Malaysia: 120 kg N, 18 kg P and 90 kg K ha^{-1} using urea, triple super phosphate and muriate of potash, respectively. The soils were kept moist and mixed with the amendments for 3 weeks before the transplanting. Water in the pots was sampled at regular interval in order to determine pH, Al, Fe and other chemical properties. During harvesting, yield components were recorded. Roots were examined under scanning electron microscope.

Some roots were especially selected from the control treatment and that treated with ground basalt. They were observed under scanning electron microscope (JEOL JSM-7600F, field emission scanning microscope, Japan). The element composition (Al, Fe, Si, K and Mg) was determined using energy dispersive X-ray (EDX) attached to the electron microscope.

Field Trial

The treatments for the field trial were; T_1 = 0 t GML ha^{-1} (control), T_2 = 2 t GML ha^{-1}, T_3 = 4 t GML ha^{-1}, T_4 = 6 t GML ha^{-1}, T_5 = 8 t GML ha^{-1}, T_6 = 4 t GML + 0.25 t JITU ha^{-1} (sugar cane-based organic fertilizer) and T_7 = 4 t GML + 0.25 t FMP ha^{-1}. Two successive crops of rice were planted during the main season. GML was applied once and the seedlings were transplanted two weeks later, just before irrigation. Standard fertilizer rates were applied as above mentioned, additionally NPK Blue (12:12:17+TE) and NPK Green (15:15:15+TE) were added.

Soil Analyses

The pH of soil and soil standing water was determined by a pH meter. Exchangeable Ca, Mg, and K in the NH_4OAc extract were determined by atomic absorption spectrometry (AAS). Exchangeable Al was extracted by 1 M KCl and determined by AAS. Organic carbon was determined by Walkley-Black method, while available P was determined by the method of Bray and Kurtz (1945).

Statistical Analysis

Statistical analysis for means comparison was carried out by the Tukey's test (HSD) and/or LSD using SAS version 9.2 (SAS Institute, Inc., Cary, N.C., USA).

Results Laboratory Experiment

Effects of Al and pH on the Root Length, Surface Area of Rice Seedlings

The pH of water was 3.7 and the Al concentration was 878 µM. The root length of rice seedlings was affected by the presence of high Al concentration in the water (Figure 1). Relative root length and root surface area was negatively correlated with Al concentration. The equation representing the relationship is given by (1) and (2), respectively.

$$Y= -1.33x+17.92 \ (R^2 = 0.83) \quad (1)$$

$$Y= -0.11x + 1.45 \ (R^2 = 0.95) \quad (2)$$

Relative root length and pH showed positive correlation (Figure 2), shown by (3). Similar trend was found for root surface area which is shown by (4).

$$Y = 4.792x + 1.233 \ (R^2 = 0.90) \quad (3)$$

$$Y = 0.38x + 0.18 \ (R^2 = 0.93) \quad (4)$$

GLASSHOUSE EXPERIMENT

The experimental soil was very acidic, consistent with the presence of jarosite in the soil profile. The exchangeable Al was high (3.35 $cmol_c\ kg^{-1}$) in the topsoil and the value increased with depth (Table 1). On the other hand, basic cations were low, but the organic carbon was very high.

CHANGES OF SOLUTION PH AND AL CONCENTRATION WITH TIME

After applying the treatments, initially water pH increased to a value higher than 6.0 for all treatments. This was due to the consumption of proton during the reduction process. After that, the pH decreased to 4.0, except for the GML treatment. Al concentration in the water did not change much during the first 10 days of submergence.

Soil pH was below 3.5 except for the soil treated with 4 t GML ha^{-1}, indicating that the soil was still acidic although it was treated with ground basalt (Table 2). Basalt takes time to disintegrate and dissolve completely in the soil. The low soil pH is consistent with the high exchangeable Al. Exchangeable Al in the control treatment was 4.18 $cmol_c\ kg^{-1}$ soil, which was far too high for normal rice growth. On the other hand, basic cations were low, but available P was within the sufficiency ranges for rice growth.

EFFECTS OF TREATMENT ON THE GROWTH YIELD OF RICE

The rice yield for the control treatment was less than 1 t ha^{-1} (Table 3). Treating the soil with basalt improved the soil fertility that gave yield of 4.41 t ha^{-1}. The highest yield of 4.7 t ha^{-1} was obtained by treating the soil with basalt in combination with organic fertilizer.

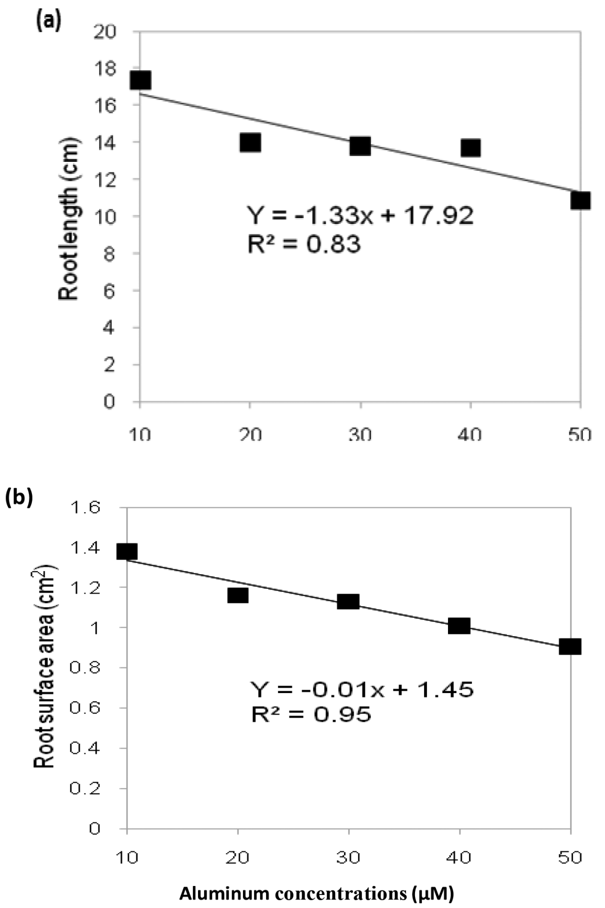

FIGURE 1. Relationship between root length (a) and root surface area with Al (b)

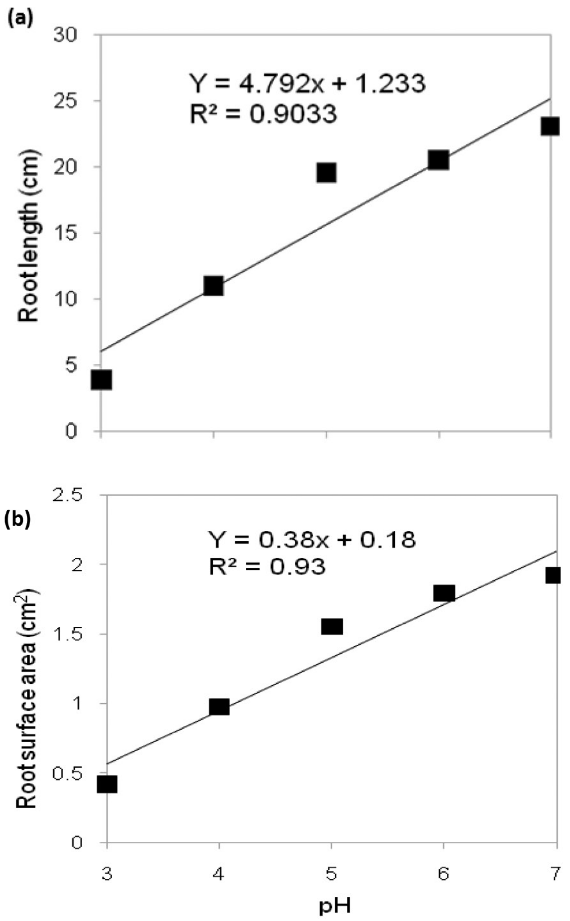

FIGURE 2. Relationship between root length (a) and root surface area with pH (b)

TABLE 1. Chemical properties of the soils for glasshouse study

Depth (cm)	Soil pH (air-dried 1:2.5)	OC (%)	Al	Ca	Mg	K
			($cmol_c$ kg^{-1})			
0-15	4.2	21.5	3.35	0.27	0.13	0.88
15-30	4.0	-	4.81	0.36	0.18	0.86
30-45	3.7	-	8.74	0.32	0.47	1.23
45-60	3.3	-	8.76	0.31	0.54	1.09
60-75	2.5	-	32.43	0.07	0.37	0.76

OC = organic carbon

TABLE 2. Chemical properties of the soil at harvest (glasshouse study)

Treatments	pH	Exchangeable cations				Available P
		Ca	Mg	K	Al	
		($cmol_c$ kg^{-1})				
Control	3.26 [b]	0.15 [b]	0.82 [b]	0.15 [a]	4.18 [a]	16.28 [a]
4 t GML ha^{-1}	4.37 [a]	3.10 [a]	4.30 [a]	0.08 [b]	0.69 [c]	13.60 [a]
4 t GB ha^{-1}	3.34 [b]	0.27 [b]	1.71 [b]	0.09 [ab]	3.19 [b]	14.28 [a]
0.25 t OF ha^{-1}	3.18 [b]	0.11 [b]	0.38 [b]	0.09 [ab]	4.01 [a]	16.55 [a]
4t GB + 0.25 t OF ha^{-1}	3.49 [b]	0.37 [b]	1.97 [b]	0.07 [b]	2.92 [b]	15.73 [a]
HSD	<0.01	<0.01	<0.01	0.02	<0.01	0.27

GML = Ground magnesium limestone, GB = ground basalt and OF = organic fertilizer
Means followed by the same letter within a column are not significantly different (HSD p>0.05)

TABLE 3. Rice yield data after harvesting at glasshouse study

Treatments	Yield component				
	Grain yield (t ha^{-1})	Panicle number (10^4 ha^{-1})	Spikelet number ($panicle^{-1}$)	Filled spikelet (%)	1000 grain weight (g)
Control	0.47 [c]	252 [b]	58.25 [c]	74.58 [c]	20.10 [c]
4 t GML ha^{-1}	4.21 [a]	760 [a]	116.75 [a]	94.87 [a]	20.40 [b]
4 t GB ha^{-1}	4.41 [a]	784 [a]	99.75 [b]	93.26 [a]	23.68 [a]
0.25 t OF ha^{-1}	1.20 [b]	704 [a]	65.00 [c]	80.99 [b]	20.33 [bc]
4t GB + 0.25 t OF ha^{-1}	4.70 [a]	796 [a]	109.75 [a]	93.53 [a]	23.55 [a]
$HSD_{0.05}$	<0.01	<0.01	<0.01	<0.01	<0.01

GML = Ground magnesium limestone, GB = ground basalt and OF = organic fertilizer
Means followed by the same letter within a column are not significantly different (HSD p>0.05)

RELATIONSHIP BETWEEN RICE YIELD AND AL IN THE ROOT

Al accumulated in the rice roots and affected its growth by damaging the cells, which was reflected by the poor yield. As the Al in the roots increased, rice yield decreased (Figure 3).

ROOT STUDY USING SEM

The Al concentration in the roots at spectrum 1 was 1.06% (Figure 4(a)). Treating the soil with basalt at 4 t ha^{-1} reduced the Al concentration to 0.86% at spectrum 3 (Figure 4(b)). Less Al had been taken up by the rice plants as a result of ground basalt treatment. Rice grew better and produced more yield (Table 3).

Iron was taken up by the roots in the control treatment, but it was not detected in the roots of basalt treated rice plants. Water pH increased due to basalt application. The increase in pH probably resulted in the precipitation of Fe as Fe-hydroxides.

The dissolution of basalt under acidic condition had released SiO_4^{4-} into the solution, which was subsequently hydrolyzed to release OH^- and monosilicic acid (H_4SiO_4), which is the form taken up by rice. It can be shown that as a result of basalt application, more Si had been taken up by the rice plant. In the control treatment, Si concentration was 1.46% as compared to 2.14% for the basalt treatment (Figure 4).

FIELD TRIALS

THE INITIAL SOIL CHEMICAL PROPERTIES

The initial chemical characteristics of the soil are given in Table 4. The topsoil pH was low and coincided with the

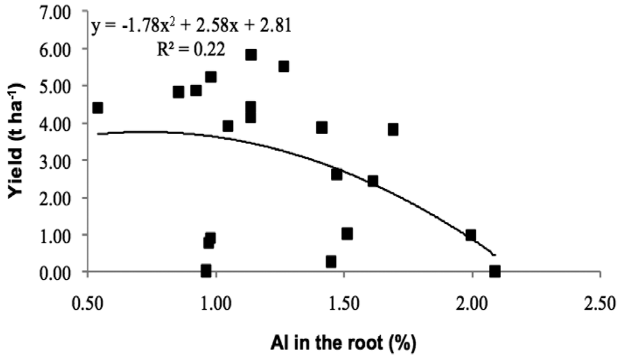

FIGURE 3. Relationship between rice yield and Al in the root

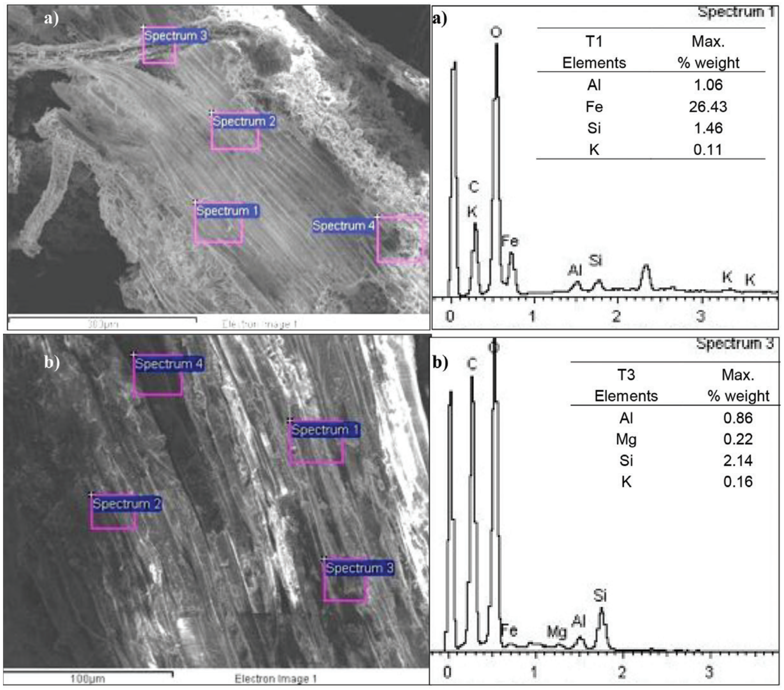

FIGURE 4. SEM micrographs of the root (a) which is an X-ray spectrum 1 (control); (b) which is an X-ray spectrum 3 (basalt treatment)

TABLE 4. Chemical properties of the field soil before applying treatments

Depth (cm)	pH		Al	Ca	Mg	K	OC (%)
	air-dried soil (1:2.5)	fresh soil (1:2.5)	-------------- ($cmol_c\ kg^{-1}$) --------------				
0-15	4.1	4.7	4.46	0.36	0.18	1.21	10.4
15-30	4.0	4.5	4.84	0.22	0.14	1.30	-
30-45	3.6	4.4	8.29	0.20	0.52	1.81	-
45-60	2.9	3.9	12.54	0.08	0.33	0.61	-
60-75	2.5	4.1	15.10	0.05	0.15	0.13	-

OC = organic carbon

presence of jarositic mottles in the soil. The low pH was consistent with the presence of high exchangeable, Al, especially at depth below 45 cm, which was the sulfuric layer. The exchangeable Ca and Mg were very low. The topsoil exchangeable Ca and Mg of the untreated soil ranged at 0.05-0.36 and 0.14-0.52 $cmol_c\ kg^{-1}$ in the soil, respectively, while the organic carbon was 10.4% at surface soil.

THE EFFECTS OF TREATMENT ON SOIL PH AND EXCHANGEABLE CATIONS

Flood occurred twice during the experimental period. Soil analysis carried out on the soil samples after the first rice harvest showed unexpected results. In the second season, the lowest pH with a value of 3.95 was reported for the control. The highest pH of 4.52 was reported in 8 t GML ha^{-1} treatment (Table 5). Consistent with the lowest pH, the control treatment had the highest value of exchangeable Al (12.75 $cmol_c\ kg^{-1}$). As a result of the GML application, soil pH slowly but surely increased, culminating in the 8 t GML ha^{-1}. In this treatment, the exchangeable Ca and Mg were the highest in the trials, having values of 3.74 and 1.10 $cmol_c\ kg^{-1}$ soil, respectively.

The soil pH was highly correlated with exchangeable Ca (Figure 5). Soil pH increased significantly following reduction in exchangeable Al (Figure 6). There was no correlation found between rice yield and Ca/Al ratio. However, there was an excellent correlation found between pH and Ca/Al ratio (Figure 7).

RICE YIELD IN THE FIRST AND SECOND SEASON

The effect of the flood is clearly seen in the erratic values of the rice yield (Table 6). There seemed to be no real difference in rice yield between treatments. The highest rice yield for the second season was 7.5 t ha^{-1} obtained in 4 t GML + 0.25 t ha^{-1} organic fertilizer (Table 6). This yield is comparable with the yield of rice grown on normal soils. There was indication that applying 2 t GML ha^{-1} is not enough to ameliorate the soil for rice cultivation. As Table 5 shows, for this treatment, the pH was still low (3.99) and Al was very high (10.22 $cmol_c\ kg^{-1}$ soil).

DISCUSSION

The study showed that the pH of water in the paddy field was very low (3.7), the suitable water pH for growing rice is 6.0. Rice plants were able to detoxify Al by excreting organic acids that chelated the Al in the water. In the current study, Al concentration in the water was >800 μM. The high Al concentration indicates negative correlation with

TABLE 5. Top soil pH and exchangeable cations after harvest

Treatment	pH water 1:2.5	Al	Ca	Mg	K
		----------------------($cmol_c\ kg^{-1}$)----------------------			
Control	3.95^{e}	12.75^{a}	1.58^{e}	0.48^{f}	0.41^{a}
2 t GML ha^{-1}	3.99^{e}	10.22^{ab}	1.99^{de}	0.57^{e}	0.24^{bc}
4 t GML ha^{-1}	4.06^{de}	9.45^{ab}	2.22^{cd}	0.70^{d}	0.15^{d}
6 t GML ha^{-1}	4.35^{b}	3.13^{c}	2.81^{b}	0.93^{b}	0.19^{bcd}
8 t GML ha^{-1}	4.52^{a}	2.37^{c}	3.74^{a}	1.10^{a}	0.17^{cd}
4 t GML + 0.25 t JITU ha^{-1}	4.21^{bc}	8.79^{ab}	2.57^{bc}	0.79^{c}	0.27^{b}
4 t GML + 0.25 t FMP ha^{-1}	4.16^{cd}	7.46^{bc}	2.47^{bc}	0.78^{cd}	0.21^{bcd}
$LSD_{0.05}$	0.14	5.15	0.47	0.08	0.08

GML = Ground magnesium limestone, JITU = sugarcane based organic fertilizer and FMP = fused magnesium phosphate
Means followed by the same letter within a column are not significantly different (HSD *p*>0.05)

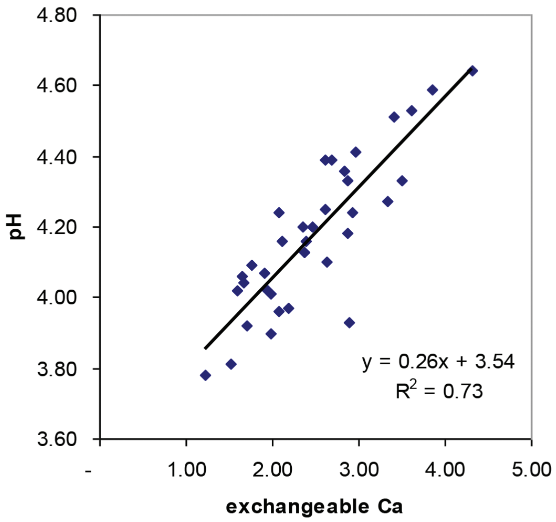

FIGURE 5. Relationship between exchangeable Ca and pH

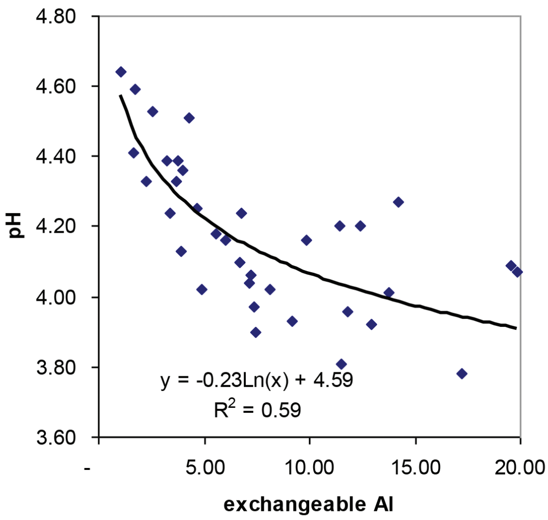

FIGURE 6. Relationship between exchangeable Al and pH

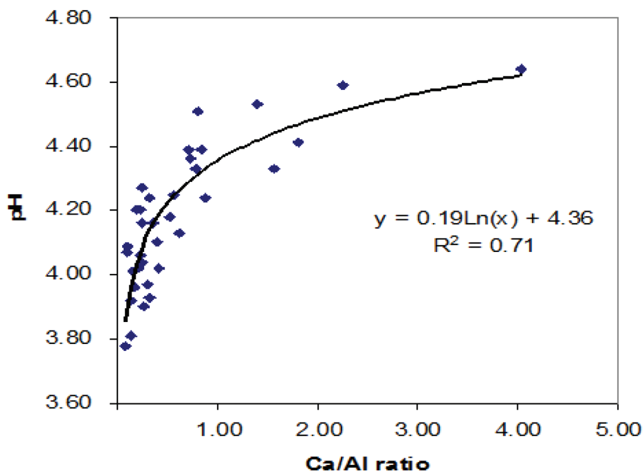

FIGURE 7. Relationship between Ca/Al ratio and pH

TABLE 6. The rice yield (field) at harvest

Treatment	First harvest ($t\ ha^{-1}$)	Second harvest ($t\ ha^{-1}$)
Control	4.5^{ab}	5.1^{bc}
2 t GML ha^{-1}	5.0^{a}	4.5^{c}
4 t GML ha^{-1}	3.5^{bc}	6.3^{ab}
6 t GML ha^{-1}	4.4^{abc}	6.6^{ab}
8 t GML ha^{-1}	4.2^{abc}	7.2^{a}
4 t GML + 0.25 t JITU ha^{-1}	3.7^{bc}	7.5^{a}
4 t GML + 0.25 t FMP ha^{-1}	3.1^{c}	6.8^{ab}
$LSD_{0.05}$	1.4	2.0

GML = Ground magnesium limestone, JITU = sugarcane based organic fertilizer and FMP = fused magnesium phosphate
Means followed by the same letter within a column are not significantly different (HSD p>0.05)

pH and Al concentration. This result is consistent with the finding of Horst et al. (2009) who established that Al inhibited plant root elongation.

Reduction in root length resulted in the decrease of nutrient uptake. The uptake of Ca and Mg is reduced by Al toxicity (Ridolfi & Garrec 2000). This is because Al affects the growth of cells in the roots elongation zone (Sasaki et al. 1997). The Al concentration equivalent to 90% relative yield is 15 μM. This value is considered as the critical level of Al concentration for rice growth. Rice variety MR219 is less tolerant to Al toxicity than that reported by Dent (1986). Al concentration in the water of acid sulfate area cropped to rice (even after lime is applied) is above that value.

The critical pH value for rice is 6.0. Under condition prevailing in acid sulfate soils, this level of pH can only be achieved by applying lime at high rate (>4 t ha^{-1}). It is known that applying GML at 4 t ha^{-1} before rice planting only manage to raise the pH to 4.5. Liming alone will not solve the problem of Al^{3+} toxicity and H^+ stress in these soils entirely. We have to use other means, such as application of organic matter, to chelate some Al. When water pH was raised to above 5.0, Al started to precipitate as inert Al-hydroxides (Shamshuddin & Auxtero 1991; Shamshuddin & Ismail 1995). If this happens, the growth stress for rice would have been gradually diminishing, depending on how high the increase in pH. If pH was raised to 5.2, Al in the solution was minimal (Ismail et al. 1993) and it is no longer becoming a threat to the growing rice plants in the field.

The decrease in root surface area due to high Al concentration can be explained by the deficiency of Ca and Mg as reported by Ridolfi and Garrec (2000). Excess Al decreases water uptake and movement in rice plant that affects its growth (Ohki 1986). For better absorption of nutrients, the root surface area of rice seedlings needs to be increased.

The acid sulfate soils under study contain high exchangeable Al with low cations. The soil pH was changed to a higher value by the applications of various amendments. Addition of 4 t GML ha^{-1} showed better results than the application of other amendments, but still pH did not increase to a value above 5. On the other hand, Al level was reduced reasonably, indicating the better efficiency of GML as compared to the basalt application. This might be due to the slow dissolution of basalt in the soil. Similar results were found by Shamshuddin et al. (1991) in their earlier study. Significantly higher yields were observed for the GML amended soil compared to other treatments because GML treatment resulted in higher pH and lower Al concentrations in the soil. On the other hand, uptake of Si was known to reduce the incident of rice blast disease (Abed-Ashtiani et al. 2012). Therefore, basalt application for long term in rice production would be a good agronomic practice to adopt.

The pH of topsoil of the field study was low, coinciding with the presence of jarositic mottles in the soil. The low pH was consistent with the presence of high exchangeable Al, especially at depth, which was the sulfuric layer. On the contrary, in the Kelantan Plains, the exchangeable Ca and Mg were very low (Soo 1975). The topsoil exchangeable Ca and Mg in the untreated soil was lower than the required level for rice growth (Dobermann & Fairhurst 2000; Palhares 2000). Ca was able to reduce the toxic effect of Al (Alva et al. 1986; Shamshuddin et al. 1991). High exchangeable Al in soil is usually associated with low pH. The highest pH coincides with the lowest Al in the soil. In the water, Al concentration would certainly exceed the critical level of 15 μM. This study suggested that GML application at the rate of 4 t ha^{-1} would be enough to mitigate the problem of Al toxicity in acid sulfate soils for rice cultivation.

The alleviation of Al toxicity would be shown by the increase in rice yield. The presence of extra Mg could also contribute to the alleviation of Al toxicity as had been shown by Shamshuddin et al. (1991) for maize. Acid-extractable Fe in the soils was slightly above the critical level. Adding organic fertilizer into a flooded acid sulfate soil would intensify the reducing condition, resulting in the release of Fe^{2+}, which is toxic to rice plants (Tran & Vo 2004). The GML applied together with organic fertilizer gave the highest rice yield. On the contrary, high quality organic matter, like organic fertilizer used in the current study, would hasten the reduction of Fe^{3+} to Fe^{2+} that would result in quicker pH increase (Muhrizal et al. 2006).

Addition of GML would increase soil pH accordingly, with concomitant addition of Ca and Mg into the soil. For second season of the trial, soil pH increased linearly with increasing exchangeable Ca (Figure 5; $R^2 = 0.73$).

GML ameliorated in the soil according to the following reactions:

$$(Ca, Mg)(CO_3)_2 \rightarrow Ca^{2+} + Mg^{2+} + CO_3^{2-} \quad (5)$$

$$CO_3^{2-} + H_2O \rightarrow HCO_3^- + OH^- \quad (6)$$

$$Al^{3+} + 3OH^- \rightarrow Al\,(OH)_3 \quad (7)$$

The GML dissolved readily on applying it into the acidic soil, releasing Ca and Mg (5). Subsequently, hydrolysis of CO_3^- (6) would produce hydroxyls that neutralized Al by forming inert Al-hydroxides (7).

Basalt dissolves according to the following equation (de Coninck 1978):

$$4Mg^{2+} + 4SiO_4^{4-} + 4\,H_2O \rightarrow 4Mg^{2+} + Si\,(OH)_4 + 4OH^-$$

The hydrolysis of silicate produces high amount of hydroxyls. However, it takes time for ground basalt to dissolve completely even under acid sulfate soil condition (Shazana et al. 2013). Thus, basalt should be applied way ahead of seeding/transplanting. Basalt dissolution releases silicic acid, the form of Si that rice plant can take up (Bokhtiar et al. 2010). Basalt treatment increased rice yield significantly. This is consistent with the findings of Nagabovanalli et al. (2009). There was no correlation between rice yield and Ca/Al ratio. However, there was an excellent correlation between pH and Ca/Al ratio. Ca is able to detoxify Al to certain extent (Alva et al. 1986). Hence, Ca/Al ratio can be used as an index of soil acidity (Shamshuddin et al. 1991).

Conclusion

Rice grows well if water pH is 6.0 and Al concentration is <15 μM. However, water pH in the paddy field where acid sulfate soils occur is less than 4 and Al concentration exceeds 800 μM. However, rice has a mechanism to defend itself against Al toxicity. To alleviate soil acidity and Al toxicity, GML or basalt can be applied at the rate of 4 t ha^{-1}. Basalt should be applied a few months ahead of seeding/ transplanting as it takes time to dissolve completely. It is even better to apply basalt in combination with organic fertilizer. Basalt application can result in rice plants taking more Si that eventually improves rice growth. Properly amended, acid sulfate soils can be productively used for rice production.

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