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Elemental Sulphur Application Effects on Nutrient Availability and Sweet Maize (*Zea mays* L.) Response in a High pH Soil of Malaysia

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ABSTRACT

As plants grown in high pH soils usually suffer from nutrient deficiency, the present study was carried out to determine the influence of elemental sulphur as a soil acidulate on soil chemical properties and maize performance in a high pH soil of Malaysia. After 0, 20 and 40 days of soil incubation with different amounts of elemental sulphur (0, 0.5, 1 and 2 g S kg^{-1} of soil), maize plants were grown for 45 days under glasshouse conditions. Application of elemental sulphur at a rate of 0.5 g S kg^{-1} soil decreased soil pH value from the background level of 7.03 to 6.29 but significantly increased availability of Mn and Zn by 0.38% and 0.91%, respectively. This resulted in a 45.06% increase in total dry weight of maize. Further pH reduction due to the acidifying character of elemental sulphur at addition rates of 1 and 2 g kg^{-1} soil increased Mn and Zn availability, but significantly decreased maize performance. Overall, it can be concluded that when used in appropriate amounts, elemental sulphur can efficiently enhance soil fertility and maize performance by providing micronutrients for balanced fertilization.

Keywords: Mn and Zn, nutrient release, soil acidification.

INTRODUCTION

It is well known that the availability of essential nutrients in soil affect yield and yield components of crop (Ye *et al.* 2011). The availability of nutrients in soils depends on soil characteristics especially soil pH (Chien *et al.* 2011; Lindsay 1979; Shenker and Chen 2005; Wang *et al*. 2006). Fertilization and addition of acidifying amendments are common practices in high pH soils to enhance plant nutrient availability and improve plant performance. Elemental sulphur, as a soil amendment, is of special interest to increase plant nutrient availability in the soil system since it possesses a slow release acidifying characteristic and is readily available (Chien *et al*. 2011). The acidifying function of S originates from its microbial oxidation to sulphuric acid over time (Vidyalakshmi *et al.* 2009). However, according to some authors, application of elemental sulphur as a soil

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amendment does not have a significant effect on soil chemical properties such as acidity and plant nutrients availability (Sameni and Kasraian 2004; Shenker and Chen 2005; Skwierawska *et al*. 2012). Regardless of S rate, this can be due to both unsuccessful oxidation of applied sulphur as well as high carbonate content of the soil under investigation. At the same time, the successful oxidation of elemental sulphur and significant change in soil chemical properties and nutrient availability is well documented for some soils (Cui *et al.* 2004; Wang et al. 2006). Nonetheless, it is difficult to predict the response of plant nutrients to soil acidification; moreover, their interactions affect availability to crops as an over-abundance of one may result in deficiency of another.

Apart from low yield per unit area as a consequence of low nutrient availability in soils, the low nutrient content of agricultural products is the main reason for malnutrition in human beings (Mayer *et al.* 2008). Therefore any attempt to increase the nutrient concentration of agricultural products would help to achieve the goals of the General Assembly of the United Nations toward mitigating world health and poverty issues

Acidification of soil through elemental sulphur application may increase plant micronutrient availability and could serve as another option to improve plant production potential (Cui *et al.* 2004). This seems to be true especially for nutrients that are found in large amounts. The ability of Bintang Series soil to be oxidized by elemental S has been studied by Karimizarchi *et al.* (2013; 2014). They showed that Bintang Series soil can successfully oxidize elemental sulphur up to 1 g S kg^{-1} soil. While the oxidation of sulphur and its effect on Bintang Series soil has been documented, the release of plant micronutrients into the soil and its significance on plant performance needs to be quantified. Therefore, the present study was carried out to evaluate the effect of elemental S applied to Bintang Series soil on maize performance and soil chemical properties including pH and availability of selected plant nutrients.

MATERIALS AND METHODS

A pot experiment was conducted from 24^{th} of March to 15^{th} of June 2013 at Universiti Putra Malaysia to elucidate the effect of elemental sulphur application timing and application rates on plant nutrient availability and maize growth. A completely randomized block design with factorial treatment combination was used with the following factors: (i) application of elemental sulphur at four levels (0, 0.5, 1 and 2 g S per kg of soil) and (ii) application of elemental sulphur three times at 20-day intervals (0, 20 and 40 days before planting of maize). Each treatment was replicated four times and randomized in four rows.

Site Description and Soil Characterization

Soil samples were collected from the A horizon (0 - 20 cm) of Bintang Series soil located in Perlis, Malaysia (6° 31′ 01.61″ N and 100° 10′ 12.43″ E). The area, Bukit Bintang, is developed from limestone parent materials and is under natural vegetation (forest). Soil samples were air dried and ground to pass through 2.0

mm mesh size before use. Soil electrical conductivity and pH was measured in a soil water suspension (10 g soil to 25 ml deionized water) 24 h after shaking for 30 min on a reciprocal shaker. Total carbon, nitrogen and sulphur were determined by CHNS LECO analyzer. Soil mechanical analysis was done using the pipette method (Gee *et al.* 1986) and texture class was determined using the United States Department of Agriculture (USDA) soil textural triangle. Total micro and macronutrients were extracted by aqua regia digestion method using microwave oven (Chen and Ma 2001). Briefly, 0.50 g of soil sample was weighed into a 120 mL Teflon-PFA microwave digestion vessel. The samples were digested at 0.69 *106 Pa for 5.5 min, then filtered through Whatman no. 42 filter. Finally, solutions were made up to 100 mL with distilled water inside volumetric flasks. The concentration of all nutrients was determined by an inductively coupled plasma optical emission spectrometer (PerkinElmer Optima 8300). Titrimetric method was used for determination of total calcium carbonate (Bashour and Sayegh 2007). In this method, a given weight of soil is reacted with an excess of acid. The acid that is not used in the dissolution of carbonates is back titrated with sodium hydroxide solution.

Sweet maize (*Zea mays* L.) seeds, Masmadu, were provided by the Malaysian Agricultural and Development Research Institute (MARDI 2008). Seeds were germinated under laboratory conditions and transplanted into 30 cm (diameter) by 50 cm (height) plastic pots after 24 h. Each pot contained 10 kg soil and received three plants which were thinned to one within one week. Plants were grown for 45 days in the greenhouse located in Universiti Putra Malaysia (UPM). By weighing each pot, plants were irrigated daily to maintain 90% of soil field capacity moisture content. All plants were supplied with fertilizers based on MARDI's recommendation; 120 kg N ha^{-1} in the form of urea, 80 kg P_2O_5 in the form of triple superphosphate and 100 kg K_2O in the form of muriate of potash.

Plant Available Soil Nutrient Extraction and Determination

Plant micronutrients in the soil such as Fe, Mn, Zn and Cu were extracted by $CaCl_2$ as the un-buffered and neutral extracting solution (Jones 2001; Ye *et al.* 2011). The concentration of all nutrients was determined by an inductively coupled plasma optical emission spectrometer (ICP-OES), PerkinElmer, Optima 8300.

Statistical Analysis

The relationship between plant and soil properties was subjected to different regression models at a probability level of 0.05 with the help of Sigmaplot software. Using SAS 9.1, Anova analysis and Tukey's test at $\alpha = 0.05$ was employed to determine the significant differences among the treatments.

RESULTS AND DISCUSSION

Fertility Evaluation of Bintang Series Soil

The Bintang Series soil with a pH value of 7.5 (Table 1), developed on limestone materials, in Peninsular Malaysia, is low in organic matter and all extractable micronutrients including Fe, Mn, Zn and Cu. For instance, the available Cu extracted by Mehlich No.1 in Bintang Series soil (0.08 mg kg^{-1} of soil) is far below the recommended adequate range of 0.1 to 10 mg kg^{-1} of soil (Jones 2001). Additionally, as zinc concentration extracted by Mehlich No.1 is less than the optimum Zn level by a factor of 200, it is likely that plants grown in this soil would suffer from intensive zinc deficiency. Regarding the adequate range of Fe (2.5 to 5 mg kg^{-1}) reported by Jones (2001), our expectation is that plant growth would not be negatively affected due to the limited availability of Fe in Bintang Series soil. At the same time, available soil Mn (9 mg kg^{-1} of soil) is below the critical deficiency level of 10 mg kg^{-1}, and this would restrict plant production in this soil but not as much as copper and zinc would. As the Bintang Series soil comprises large amounts of Fe, Mn and Zn (Table 1), it appears that acidification of soil through elemental sulphur application may increase plant micronutrient availability and improve plant production potential. However, as total sulphur and Cu is very low in this soil, it appears that addition of soil amendments or fertilizers with high amounts of these nutrients is essential for successful plant production.

TABLE 1
Soil physico-chemical properties of Bintang series soil

Soil property	Unit	Value or concentration	Soil property	Unit	Value or concentration
pH	-	7.30	Silt	%	66.40
$CaCO_3$	%	Trace	Clay	%	24.60
C	%	1.75	Available P	mg kg^{-1}	1.6
N	%	0.12	Available Fe	mg kg^{-1}	3.20
S	%	0.004	Available Mn	mg kg^{-1}	9.00
C/N	-	14.58	Available Zn	mg kg^{-1}	0.16
C/S	-	437.50	Available Cu	mg kg^{-1}	0.08
CEC	$cmol_+ kg^{-1}$ soil	11.50	Sulfate	mg kg^{-1}	Trace
BS	%	56.00	Total Fe	%	2.81
FC	%	20.00	Total Mn	%	0.19
Texture	-	Silt loam	Total Zn	mg kg^{-1}	22
Sand	%	9	Total Cu	mg kg^{-1}	8.4

Soil pH

Our results found soil pH to be significantly affected by S rate, while application timing and its interaction with S rate was not significant (data not shown). With increasing S rate, soil pH decreased from the initial value of around 7.03 to 6.29, 5.26 and 3.94 at sulphur application rates of 0.5, 1 and 2 g kg^{-1}, respectively. *Figure*

1 shows the scatter diagram and regression line relating sulphur application rate to soil pH for 3 sulphur incubation times. The regression line slopes downward at a inclination of -1.52, which is consistent with the negative relationship anticipated between S rate and soil pH (Cui *et al*. 2004; Shenker and Chen 2005; Vidyalakshmi *et al*. 2009). While it reflected successful oxidation of elemental sulphur, this wide range of soil pH provided a good opportunity to assess the effects of soil pH, from alkaline to acidic, on plant nutrient release in the soil system and plant growth performance.

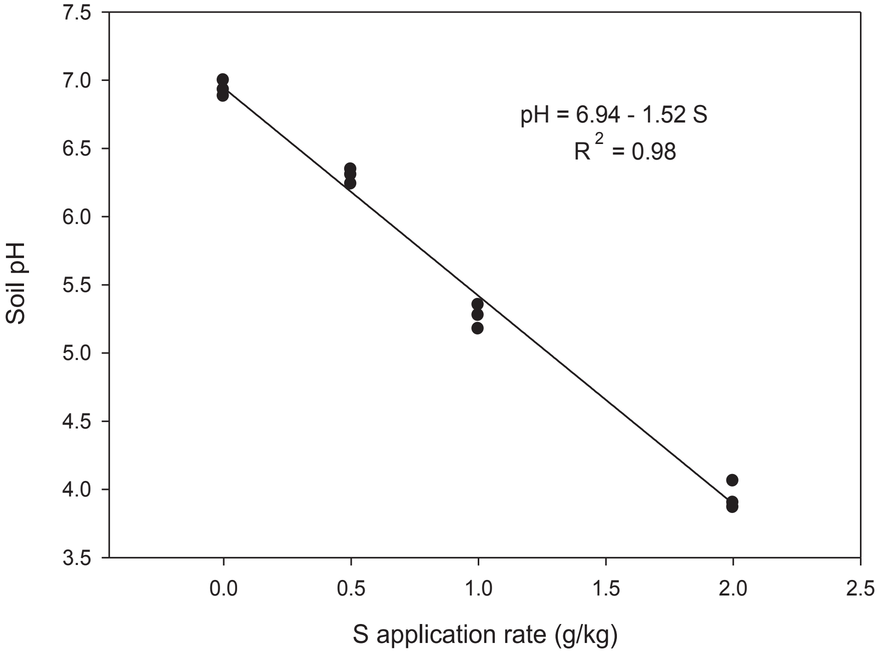

Figure 1: Soil pH changes in response to elemental sulphur application rate.

Soil Nutrient Composition and Release

Our results showed that application of elemental S up to 1 g kg^{-1} did not have significant effect on the availability of some micronutrients such as Fe and Cu (Table 2). Addition of elemental S at a rate of 2 g kg^{-1} increased Fe availability more than five fold, while Cu appeared in a detectable amount (0.132 mg kg^{-1}) only at maximum S rate. The significant and positive effect of S addition on availability of Mn started at S application rate of 0.5 g kg^{-1}. For instance, S application at 0.5 and 1 g kg^{-1} resulted in 0.38 and 1.40 % increase in Mn availability, respectively. It should be noted that the highest plant nutrients release was recorded at highest S rate with 3.86 % increase. The highest availability of Zn was 4.94 mg kg^{-1} at the highest S application rate, that is, 164-fold higher than without application of S (0.03 mg kg^{-1}).

TABLE 2
Availability of soil nutrients (mg kg^{-1}) in response to elemental sulphur application rate

Sulphur rate (g kg^{-1} soil)	Nutrient concentration (mg kg^{-1})			
	Fe	Mn	Zn	Cu
0	0.146 b†	1.61 d	0.030 c	Tr‡
0.5	0.163 b	7.26 c	0.20 c	Tr
1	0.214 b	26.67 b	1.47 b	Tr
2	0.887 a	73.41 a	4.94 a	0.132

Notes: †Means within column followed by the same letter are not significant at the 0.05 level, according to Tukey test. Values denote the means across incubation time.
‡Tr-traces

While our results showed plant nutrient availability from the soil to be significantly affected by the addition of sulphur (Table 2), there are also contrasting reports on the effect of elemental S on nutrient availability (Klikocka 2011; Safaa *et al*. 2013; Skwierawska *et al*. 2012). The effectiveness of elemental sulphur application on plant nutrient availability was not observed in some soils (Sameni and Kasraian 2004; Shenker and Chen 2005; Skwierawska *et al*. 2012). At the same time, the positive effect of elemental sulphur on plant nutrient availability that is in line with our results was reported by Cui *et al*. (2004). They reported 1.8 times increase in $CaCl_2$ extractable Zn with a 0.3 unit reduction in soil pH due to addition of 200 mmol S kg^{-1} of soil. As different soils may show different responses to soil acidification as an effective strategy for plant nutrient availability enhancement (Wang *et al*. 2006), it is necessary to find the optimum sulphur rate to obtain optimum pH for each specific soil in which nutrient availability increases, and concurrently, extreme soil acidification and its consequences such as nutrient toxicity for plants can be avoided.

As was anticipated, solubility and availability of nutrients in Bintang Series soil were differently affected by elemental sulphur rates (as soil amendment) under our investigation conditions. This is in line with the findings of Modaihsh *et al*. (1989) who reported that Cu responded least to S addition while Mn responded the most.

The considerable increase in release of soil nutrients with a big difference between rates of S (Table 2) can be attributed to the effect of elemental S to amend soil pH *(Figure 1)* and the release of plant nutrients from unavailable pools to soil solution. In line with our findings, it is well accepted that high concentrations of hydrogen ions may increase plant nutrient availability in soils by displacement of cations from exchangeable sites changing the oxidation state of nutrients, and increasing soil mineral weathering rate; high concentrations of hydrogen may also enhance nutrient uptake by plants (Lambers *et al.* 2008; Viani *et al*. 2014).

Maize Response to Sulphur Application Rate

Application of elemental sulphur had a significant effect on maize performance in Bintang Series soil; however, it showed insignificant response to S application timing. Additionally, the interaction of S application timing and S levels had no significant effect on maize biomass production (data not shown). In relation to the remedial effect of sulphur, the application of elemental sulphur at 0.5 and 1 g kg^{-1} significantly improved plant performance by 45.06 and 36.67 %, respectively. However, addition of 2 g S kg^{-1} significantly decreased total dry weight of maize by 38.34 % compared to the plants in control pots *(Figure 2)*.

The increase in maize performance can be attributed to an increase in soil nutrient availability (Table 2) due to a moderate reduction in soil pH *(Figure 1)*. This is further supported by plant analysis results (Table 3) where plant Zn and

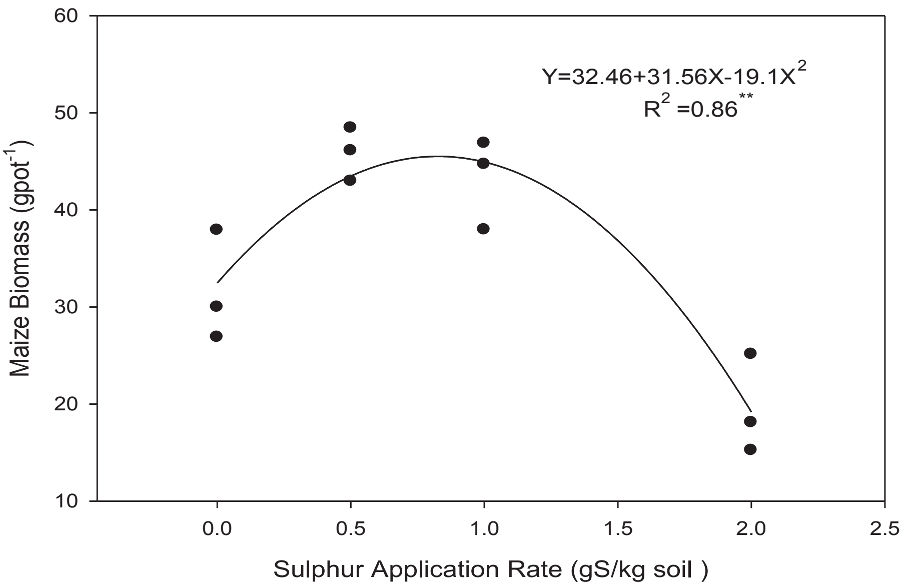

Figure 2: Maize response to elemental sulphur application rate.

Mn in untreated leaves were below the sufficiency range while they were in the sufficiency range in plants treated with 0.5 and 1 g S kg^{-1} soil (Table 3). Maize biomass reduction at the highest rate of S, 2 g kg^{-1}, may be attributed to both direct and indirect consequences of elemental S oxidation resulting in an increase in soil acidity and nutrient toxicity in plants under our study conditions. As can be seen from Table 3, the concentration of Mn and Zn at the highest sulphur application rate falls beyond the adequate range recommended by (Barker and Pilbeam 2007) while the concentration of Cu and P is in the less adequate range. The decreasing trend in P and Cu concentration in maize leaves (Table 3) can be attributed to the interaction of Cu with Zn and Mn and interaction of P with Ca in soil solution (Barker and Pilbeam 2007).

The relationship between elemental S rate and maize biomass followed a non- linear quadratic regression model with a R^2 value of 0.86 *(Figure 2)*. Based on the regression model, the rate of S for maximum biomass of maize was 0.83 g kg^{-1}. Considering a 10% decrease in yield as a critical level, the sufficiency range for S rate would be from 0.34 to 1.29 mg S kg^{-1}. The ability of elemental sulphur to enhance plant performance is of special interest and its diverse effects have been intensively studied (Motior *et al.* 2011; Ye *et al*. 2011; Zhao *et al.* 2008). For instance, Zhao *et al*. (2008) reported the positive effect of elemental sulphur application at a rate of 30 mg kg^{-1} on soybean performance in a fluvo-aquic soil with a pH of 7.5. However, application of sulphur did not improve sugarcane yield in histosols of the Everglades area with low micronutrient but high organic matter content (Ye *et al*. 2011).

TABLE 3
Concentration of nutrients in maize leaves in response to elemental sulphur application rate

Nutrient in leave	Elemental sulphur application rate (g S kg^{-1} soil)				
	0	0.5	1	2	Sufficiency range‡
N (%)	2.43 bc	2.28 b	2.5 b	2.8 a	2.5-3.2
P (%)	0.13 a	0.1 b	0.09 b	0.07 c	0.3-0.5
K (%)	2.1 b	2.00 b	2.1 b	2.7 a	2-3.5
Fe (mg kg^{-1})	61.24 a	69.95 a	64.56 a	63.35 a	50-300
Mn (mg kg^{-1})	35.86 d	81.69 c	199.68 b	691.72 a	50-160
Zn (mg kg^{-1})	63.43 c	103.63b	121.13 b	166.73 a	20-100
Cu (mg kg^{-1})	9.83 a	8.11 a	4.92 b	3.4 b	7-20

Notes: †Means within column followed by the same letter are not significant at the 0.05 level, according to Tukey test.

‡ Barker *et al*. (2007)

Maize Response to Soil pH

Our data showed that the maximum maize performance (45.81 g pot^{-1}) occurred at soil pH of 6.29 where 0.5 g S kg^{-1} soil was added. As maize performance at a pH of 5.26 was equal to 94.2 % of maize performance at a pH of 6.29, it appears that maximum production can be achieved at pH range of 6.29 to 5.26. This is because of the increase in soil nutrient availability as depicted in Table 2. As can be seen from Table 2, availability of all micro nutrients (Fe, Mn, and Zn) was significantly increased due to S addition. This is in agreement with the general opinion of improving plant performance with soil pH decrease from alkaline to slightly acidic conditions. While the decreasing trend of soil pH continued and reached the minimum of 3.93, a minimum biomass production of 19.47 g pot^{-1} was observed. At this soil pH, a significant reduction of 57.48 % in total dry weight of maize was observed. This negative effect of soil pH on plant performance can be due to the toxic level of plant nutrients as a result of an increase in solubility of soil minerals (Lambers et al. 2008; Viani *et al*. 2014). Maize response to soil pH followed the non-linear quadratic regression model *(Figure 3)*, with $R^2 = 0.79$**. The predicted maximum yield, 45.6 g pot^{-1}, was obtained by equating the first derivatives of the response equation to zero, solving for S, substituting the value of S into the response equation, and solving for Y.

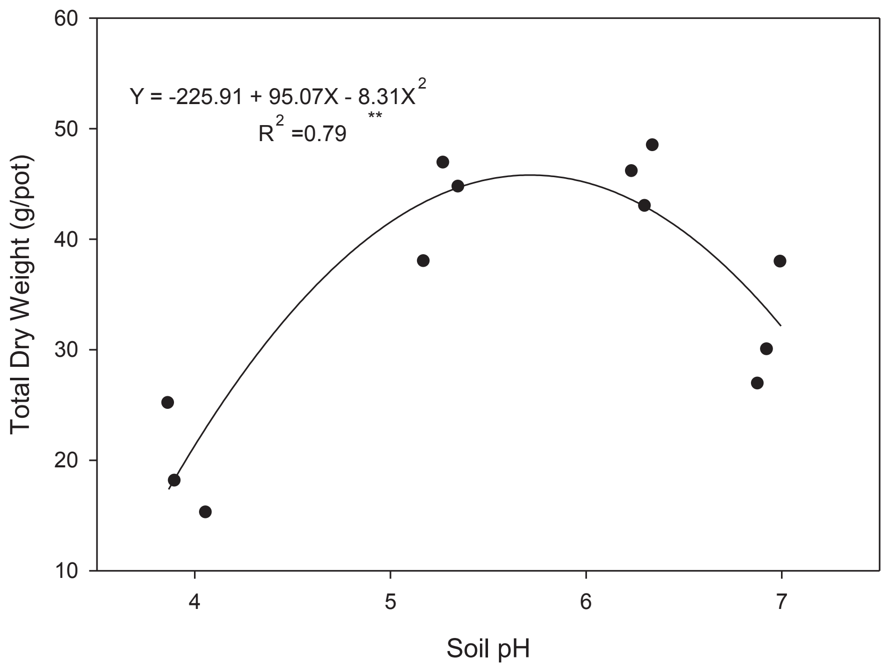

Figure 3: Maize response (total dry weight per pot) to soil pH.

CONCLUSION

The concentrations of Fe, Cu, Zinc and Mn in non-amended Bintang Series soil were far below the recommended adequate range and accounted for poor plant performance. The improved maize biomass for plants receiving elemental sulphur at 0.5 and 1 g S kg^{-1} soil was due to an increase in Fe, Zn and Mn concentrations at a sufficient level. This is attributed to the significant decrease in soil pH resulting from the acidifying effect of elemental sulphur. Additionally, the limited growth of maize treated with 2 g S kg^{-1} soil is attributed to the toxic level of Mn and Zn elements. Therefore, the utilization of elemental sulphur as a cost effective and readily available source of soil amendment at sufficient rates is recommended to address soil fertility problems of the Bintang Series soil. Overall, soil pH reduction is a suitable strategy to alleviate nutrient deficiency in high pH soils. As various soils have different responses to acidification and a specific optimum pH may exist, this pH value should be determined to avoid unnecessarily high soil acidification.

REFERENCES

Barker, A. V. and D. J. Pilbeam. 2007. *Handbook of plant nutrition.* New York: CRC press.

Bashour, I. I. and A.H. Sayegh. 2007. *Methods of Analysis for Soils of Arid and Semi-arid Regions*. Food and Agriculture Organization of the United Nations.

Chen, M. and L.Q. Ma. 2001. Comparison of three aqua regia digestion methods for twenty Florida soils. *Soil Science Society of America Journal.* 65(2): 491-499.

Chien, S. H, M.M. Gearhart and S. Villagarcía. 2011. Comparison of ammonium sulfate with other nitrogen and sulfur fertilizers in increasing crop production and minimizing environmental impact: a review. *Soil Science*. 176(7): 327-335.

Cui, Yanshan, Y.T. Dong, H.F. Li and Q.G. Wang. 2004. Effect of elemental sulphur on solubility of soil heavy metals and their uptake by maize. *Environment International*. 30(3): 323-328.

Gee, G. W., J.W. Bauder and A. Klute. 1986. *Particle-size Analysis. Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods*. Madison, Wisconsin: American Society of Agronomy Inc.

Jones, J.B. 2001. *Laboratory Guide for Conducting Soil Tests and Plant Analysis*. Washington, D.C.: CRC Press.

Karimizarchi, M., H. Aminuddin, M.Y. Khanif and O. Radziah. 2013. Elemental sulfur oxidation rate in a Malaysian high pH soil. In: *Soil Science Conference of Malaysia*. K. Wan Rasidah (eds). pp. 39-43. Pahang: Malaysian Society of Soil Science.

Karimizarchi, M., H. Aminuddin, M.Y. Khanif and O. Radziah. 2014. Incorporation and oxidation of elemental sulphur in high pH soils of Malaysia. *International Journal of soil science*. DOI:10. 3923/ijss.2014.

Klikocka, H. 2011. The effect of sulphur kind and dose on content and uptake of micro-nutrients by potato tubers (*Solanum tubersosum* L.). *Acta Scientiarum Polonorum Hortorum Cultus.* 10(2): 137-151.

Lambers, H., F.S. Chapin and T.L. Pons. 2008. *Plant Physiological Ecology.* New York: Edward Arnold Ltd.

Lindsay, W. L. 1979. *Chemical Equilibria in Soils*. New York: John Wiley and Sons Ltd.

MARDI. 2008. Jagung Improved Masmadu. Kuala Lumpur: Malaysian Agricultural Research and Development Institute, Serdang, Malaysia.

Mayer, J.E., W.H. Pfeiffer and P. Beyer. 2008. Biofortified crops to alleviate micronutrient malnutrition. *Current Opinion in Plant Biology.* 11(2): 166-170.

Modaihsh, A. S., W.A. Al-Mustafa and A.I. Metwally. 1989. Effect of elemental sulphur on chemical changes and nutrient availability in calcareous soils. *Plant and Soil*. 116(1): 95-101.

Motior, M. R., A.S. Abdou, F.H. Al Darwish, K.A. El-Tarabily, M.A. Awad, F. Golam and M. Sofian-Azirun. 2011. Influence of elemental sulfur on nutrient uptake, yield and quality of cucumber grown in sandy calcareous soil. *Australian Journal of Crop Science*. 5(12): 1610-1615.

Safaa, M M., S.M. Khaled and S. Hanan. 2013. Effect of elemental sulphur on solubility of soil nutrients and soil heavy metals and their uptake by maize plants. *Journal of American Science.* 9(12): 19-24.

Sameni, A.M. and A. Kasraian. 2004. Effect of agricultural sulfur on characteristics of different calcareous soils from dry regions of Iran. I. Disintegration rate of agricultural sulfur and its effects on chemical properties of the soils. *Communications in Soil Science and Plant Analysis.* 35(9-10): 1219-1234.

Shenker, M. and Y. Chen. 2005. Increasing iron availability to crops: Fertilizers, organo-fertilizers, and biological approaches. *Soil Science and Plant Nutrition*. 51(1):1-17.

Skwierawska, M., L. Zawartka, A. Skwierawski and A. Nogalska. 2012. The effect of different sulfur doses and forms on changes of soil heavy metals. *Plant, Soil and Environment-UZEI*. 58:135-140.

Viani, R.A.G., R.R. Rodriguesb, T.E. Dawsonc, H. Lambersd and R.S. Oliveira. 2014. Soil pH accounts for differences in species distribution and leaf nutrient concentrations of Brazilian woodland savannah and seasonally dry forest species. Perspectives in Plant Ecology, Evolution and Systematics. http://dx.doi.org/10.1016/j.ppees.2014.02.001.

Vidyalakshmi, R., R. Paranthaman and R. Bhakyaraj. 2009. Sulphur oxidizing bacteria and pulse nutrition - A review. *World Journal of Agricultural Sciences*. 5(3): 270-278.

Wang, A.S., J.S. Angle, R.L. Chaney, T.A. Delorme and R.D. Reeves. 2006. Soil pH effects on uptake of Cd and Zn by *Thlaspi caerulescens*. *Plant and Soil.* 281(1-2): 325-337.

Ye, R., A.L. Wright and J.M. McCray. 2011. Seasonal changes in nutrient availability for sulfur -amended everglades soils under sugarcane. *Journal of Plant Nutrition.* 34(14): 2095-2113.

Hao, Y., X. Xiao, D. Bi and F. Hu. 2008. Effects of sulfur fertilization on soybean root and leaf traits, and soil microbial activity. *Journal of Plant Nutrition*. 31(3): 473-483.