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Can the Acidic Ultisols in Peninsular Malaysia Be Alleviated by Biochar Treatment for Corn Cultivation?

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ABSTRACT

Arable land in Peninsular Malaysia is dominated by highly weathered infertile soils which are taxonomically classified as Ultisols. The production of non-acid tolerant sweet corn on these acidic Ultisols is known to be negatively affected by soil acidity and/or Al^{3+} toxicity. However, to some extent, corn is able to defend itself against Al^{3+} toxicity and/or H^+ stress. For Al^{3+} toxicity problem, the defence mechanism is along this line. The positively-charged Al^{3+} is attracted to the negatively-charged root surface of the sweet corn. When the Al^{3+} touches the surface of the root, the corn plant reacts instantly to release oxalic acid that chelates the Al^{3+}. By this mechanism some of the Al^{3+} at the solution-root interface will be deactivated by the organic acid and rendered unavailable for uptake by corn. The chelation of Al^{3+} occurring in soil solution by this mechanism is a crucial step to help sustain the production of corn growing on the Ultisols. For sustainable corn production, the pH of the Ultisols has to be raised to a level above 5.3 by liming or other agronomic means. In the final analysis, Al^{3+} activity in the soil solution is less than the critical level of 10 µM. The low productivity of the Ultisols can be overcome by applying EFB-biochar at a rate of 10 t biochar/ha, which is an economically viable agronomic practice.

Keyword: Acid Soils, Al toxicity, biochar treatment, corn production, oxalic acid.

INTRODUCTION

As soils in the upland areas of the tropics are mostly highly weathered, they usually contain limited amounts of basic cations. In Peninsular Malaysia, like everywhere else on the globe, the profiles of the soils are deep and the soils are leached, with their soil solutions low in basic plant nutrients (K, Ca, Mg), but high in Al concentration (Tessens and Shamshuddin 1983; Shamshuddin *et al*. 1991; Ismail *et al*. 1993; Anda *et al*. 2008; Shamshuddin and Fauziah 2010). The base saturation of the soils is usually < 35%, while Al saturation is high (>50%) which limits the growth of Al-sensitive crops such as cocoa and corn. The low fertility of the soils is usually alleviated by ground magnesium limestone (GML) application.

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Mainly classified as Ultisols (Soil Survey Staff 2014), the highly weathered soils are very widespread in South-east Asia (Malaysia, Indonesia, Thailand, Cambodia, the Philippines and Vietnam), Africa (Democratic Republic of Congo, Nigeria, Ivory Coast, Liberia and Ghana) and South America (Brazil, Colombia, and Ecuador). The area occupied by Ultisols in the tropics is 749 million ha (Fageria and Baligar 2008).

Corn is one of the most important cereal crops grown worldwide to feed the increasing population. In the tropics, it has been known for many years that low pH stress and/or Al^{3+} toxicity are the two most important factors limiting its production. Lehmann *et al.* (2003) had shown that the fertility of acidic soils can be ameliorated by biochar application. The critical Al concentration for the growth of acid tolerant corn species is 22 µM, while the critical soil solution pH is 4.3 (Shamshuddin *et al*. 1991). However, the normal concentration of Al in the soil solution of Ultisols in Peninsular Malaysia is much higher than 22 µM. This paper explains how biochar produced from oil palm empty fruit bunches (EFB) can be used to sustain corn production on Ultisols.

The objectives of this paper are:

1) To explain how EFB-biochar is able to sustain the growth of a non-acid tolerant sweet corn planted on an Ultisol in Peninsular Malaysia; and

2) To determine the mechanisms by which the sweet corn defends itself against Al^{3+} toxicity and/or low pH stress.

Mineralogy and Chemical Properties of Ultisols

Ultisols occurring in Peninsular Malaysia are leached and highly weathered. According to Tessens and Shamshuddin (1983) and Shamshuddin and Fauziah (2010), the clay fraction of the soils is dominated by kaolinite, gibbsite, goethite and hematite; the last two minerals are known as variable charge minerals (Uehara and Gillman 1981). Due to their low cation exchange capacity (CEC) of less than 10 cmol/kg, added basic cations (K, Ca and Mg) via fertilisation or liming are easily lost via leaching under a tropical environment. With the low productivity contributed by low pH stress and/or Al^{3+} toxicity, the soils have to be adequately limed (using GML) to sustain corn production (Shamshuddin *et al*. 1991; Ismail and Shamshuddin 1993). Based on the results of past research (Glaser *et al*. 2002) the low productivity of Ultisols can also be alleviated by application of biochar at an appropriate rate and time.

Charge Manipulation in Soils

Colloids (minerals) in weathered tropical soils can be classified into permanent and variable charge colloids (Uehara and Gillman 1981). Charges occurring on permanent charge colloids are derived from isomorphic substitution (Tessens and Zauyah 1982), which do not change with the change in pH and/or the concentration of the ambient solution (e.g. mica, smectite, vermiculite, chlorite). On the other hand, charges on the oxides/hydroxides and broken edges of kaolinite change with pH and/or concentration, and are thus classified as variable charge colloids. At low pH, the colloids are net positively-charged, while at high pH, they are net negatively-charged.

The charges existing on the surfaces of minerals in soils can be presented as follows:

$$\text{Total charge } (Q_T) = \text{Permanent charge } (Q_P) + \text{Variable charge } (Q_V) \quad (1)$$

Variable charge (Q_V) is described by the Guoy-Chapman Equation (Wann and Uehara 1978):

$$Q_V = [(2nDkT)/\pi]\sinh 1.15z(pH_0\text{-}pH) \quad (2)$$

where n is the electrolyte concentration, D is the dielectric constants, z is the valency, T is the temperature and pH_0 is the pH value where the amounts of positive and negative charges are equal (Uehara and Gillman 1980).

Equation 2 implies that one can increase the charge in a soil by lowering its pH0 or by increasing the pH. In reality, the pH0 of highly weathered tropical soils (Tessens and Shamshuddin 1983; Shamshuddin 2011) is not far from their pH and thus charges contributed by variable charge colloids are small, but significant in relation to the total charge, which is also small.

What happens when the soils are mixed with soil amendments, such as adding organic matter (e.g. biochar) or being limed with ground magnesium limestone (GML) that increases soil pH (Shamshuddin *et al*. 1991)? We know that when soil pH is increased, negative charge (CEC) on the exchange complex increases accordingly (Shamshuddin and Fauziah 2010; Shamshuddin 2011; Shamshuddin *et al.* 2018). This phenomenon will eventually enhance the productivity of highly weathered soils.

According to Zulkifli and Shamshuddin (1985), adding or mixing a soil having variable charge minerals with palm oil mill effluents (POME) lowered its pH_0. Based on the afore-mentioned Guoy-Chapman equation, lowering pH0 results in an increase in soil negative charge. We therefore can assume that the CEC of variable soils can be increased by applying EFB-biochar.

Soil and Biochar under Investigation

The pH of the Ultisol used for the experiment was < 5, with expected high exchangeable Al present in the soil of not less than 1.5 $cmol_c$/kg. The soil of the above-mentioned study was Bungor Series, belonging to the clayey, kaolinitic, isohyperthermic family of Typic Paleudult (Tessens and Shamshuddin 1983). The topsoil (0-20 cm depth) was sampled and collected from Universiti Putra Malaysia farm in Serdang, Malaysia. The concentration of Al in the soil solution was believed to have exceeded the critical level for the healthy growth of corn.

The feedstock of the biochar production was oil palm empty fruit bunch (EFB). It was produced via slow pyrolysis of the EFB (size 2-5 mm, moisture content of 5%) in the absence of O_2 at a temperature of 300-350° C. It had a pH of about 9, with ash content of 25% (Rabileh *et al.* 2015). Total C in the biochar was 50% and its CEC was 60 $cmol_c$/kg. Based on its chemical properties, the biochar is capable of alleviating the problem related to soil acidity and/or Al^{3+} toxicity when applied onto an Ultisol at an appropriate rate and time.

Effects of Biochar Application on Soil Solution Attributes

The pH of the soil solution (extracted at field capacity) was plotted against biochar rate (Figure 1). The effect of applying biochar in combination with 2 GML/ha is also presented for purposes of comparison. Soil solution pH was positively correlated with the rate of biochar irrespective of whether it was applied alone or in combination with 2 t GML/ha (Rabileh *et al*. 2015).The rate of biochar required to raise the pH to >5 was about 10 t/ha, which is affordable by the farming communities in the country, considering the positive ameliorative impact of its application on acidic Ultisols. This finding is consistent with that of Glaser *et al.* (2002).

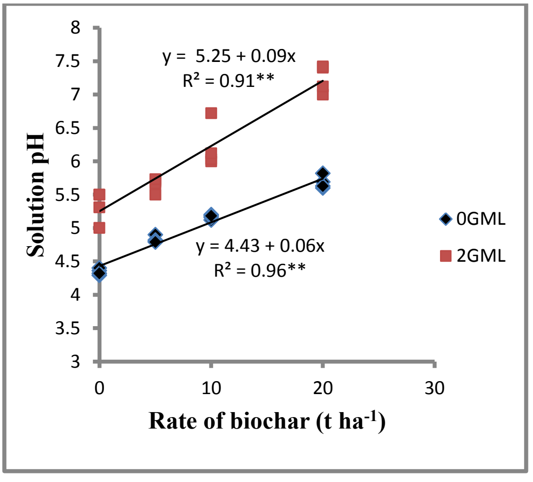

Figure 1. Relationship between soil solution pH and biochar rate with or without GML (Rabileh *et al.* 2015)

Figure 1 shows that soil solution pH increased with the biochar rate, with the trend being similar to that of lime application. Since the soil is dominated by variable change minerals in the clay fraction, its CEC would increase in tandem with the pH increase (Shamshuddin and Fauziah 2010). Any increase in soil solution pH to a level above 5, results in the precipitation of Al^{3+} as Al-hydroxides. The phenomenon in a way can be considered as an improvement to soil productivity.

Using data available from the experiment, the critical pH for the good growth of sweet corn was determined. It was done by plotting the graph of the relative corn root length against soil solution pH. The 10% drop in relative root length corresponded to a pH of 5.3 (Figure 2); this value is termed as the critical pH for the healthy growth of the corn under investigation. The rate of biochar to raise soil solution pH to that level was estimated to be about 10 t biochar/ha (Figure 1). When soil solution pH reached 5.3, Al^{3+} will be precipitated as amorphous Al-hydroxides, which is inert (Shamshuddin and Ismail 1995); therefore, the soil environment is no longer toxic to corn roots.

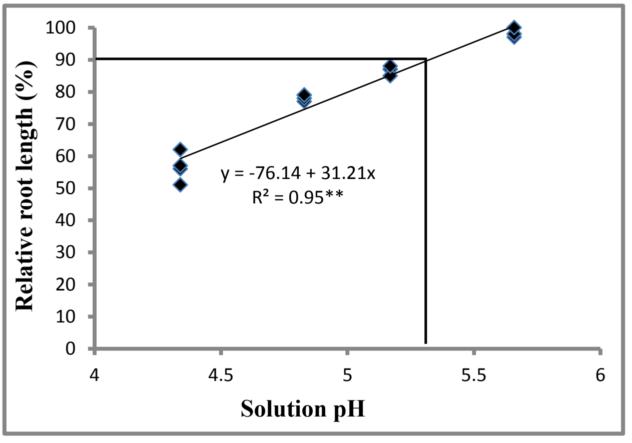

Figure 2. Relationship between relative root length and soil solution pH (Rabileh et al. 2015)

The critical Al^{3+} activity for the growth of sweet corn was estimated by a similar method as that of the critical pH and the value so determined was about 10 µM (Figure 3). Note that the corn under investigation was not an acid tolerant species. The critical level obtained cannot be compared to that of the corn studied by Shamshuddin *et al*. (1991), which was reported in terms of Al concentration. However, we can assume that the sweet corn tested in the study was sensitive to Al^{3+} toxicity. We believe or expect Al^{3+} activity in the Ultisols under normal circumstances in Peninsular Malaysia to be much more than 10 µM. So using EFB-biochar to alleviate Al^{3+} toxicity prevailing in the Ultisols of the humid tropics is timely and justified, with the recommended rate being10 t/ha or thereabouts. The amelioration of Al^{3+} toxicity by biochar application is somewhat similar to what has already been studied and/or explained by Hue *et al*. (1986).

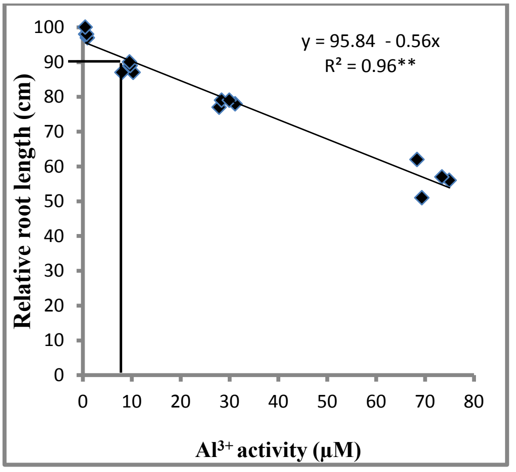

Figure 3. Relationship between relative root length and Al3+ activity (Rabileh et al. 2015)

Effects of Biochar Application on Solution

It is generally believed that even a non-acid tolerant plant species can, to a certain extent, be able to defend itself against soil acidity and/or Al^{3+} toxicity. The mechanism of defence against the said problem can also be explained via a nutrient solution experiment. The results of such a study are given in Figure 4. It was found that the root length of corn grown in the nutrient solution was negatively correlated with Al concentration. Likewise, corn root surface area was negatively correlated with Al concentration. The critical Al concentration and critical pH can also be estimated using the methods mentioned earlier in this paper (Figure 5). Note that the estimated values were not far apart from that reported by the previous experiment (Rabileh *et al.* 2015).

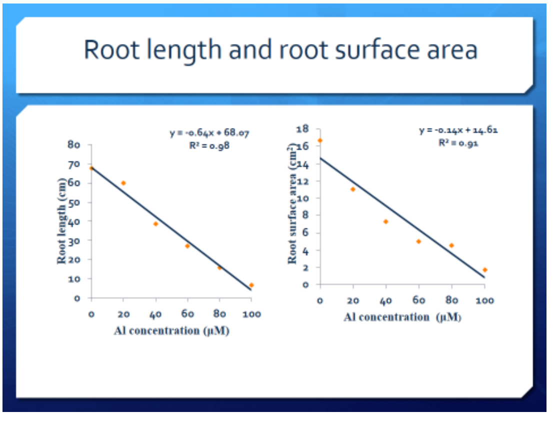

Figure 4. Relationship between root length and Al concentration (left) and root surface area and Al concentration (right)

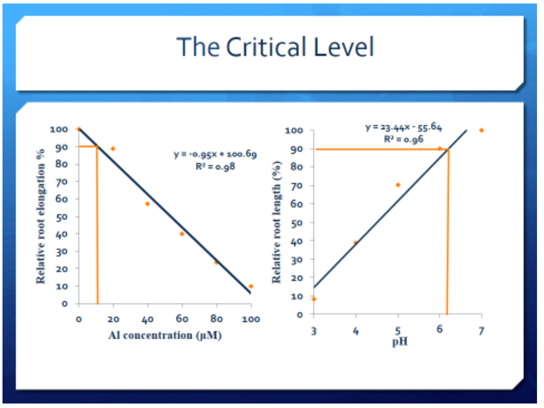

Figure 5. Determination of the critical Al concentration (left) and critical pH (right)

How corn grown on an Ultisol defends itself against Al^{3+} toxicity is explained in Figure 6. In the presence of Al^{3+} ion, the roots of corn react instantly to excrete oxalic acid, which then chelates the Al^{3+}, rendering it inactive. Likewise, the oxalic acid excreted by the roots of corn is able to help deactivate H^+ activity. In the end, the amount of Al^{3+} and/or H^+ concentrating at and/or around the root rhizosphere is reduced. As seen in Figure 6, the higher the Al^{3+} or H^+ in the solution, the higher the oxalic acid excreted by the corn roots.

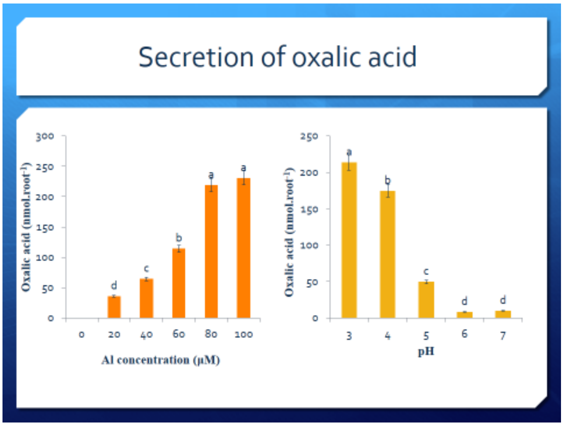

Figure 6. Secretion oxalic acid by corn root

The following is an alternative explanation on how the secretion of oxalic acid by corn roots reduces the H^+ stress that enhances corn growth (Shamshudin *et al.* 2015). Organic acids (in this case, oxalic acid) are weak acids with pKa value of 4-5. When the solution pH is changed to 3, the corn roots immediately release oxalic acid (Figure 6). The pKa of oxalic acid is above 3 and therefore instead of releasing, it consumes proton, resulting in a slight increase in pH at the solution-root interface. The hydrolysis of oxalic acid is described as follows:

$$H_2C_2O_4 + H_2O \rightarrow HC_2O_4^- + H_3O^+, \text{ pKa} > 4$$

When the oxalic acid is released by the corn roots, the solution pH will be re-adjusted so that it will approach its pKa value. Hence, the reaction is in the reverse order. In this way, the corn under study would suffer less H+ stress compared to that without.

The mechanism of how corn defends itself against Al^{3+} toxicity can further be explained by Figure 7, which has already been used by Shamshuddin *et al*. (2015) to show how rice root excreted organics acids that chelated Al^{3+}. We know that the cells of plant root (including corn) are negatively-charged (Yang *et al*. 2009). Hence, the positively-charged Al^{3+} present in the soil solution of the Ultisol under investigation are attracted to the corn root (Figure 7).

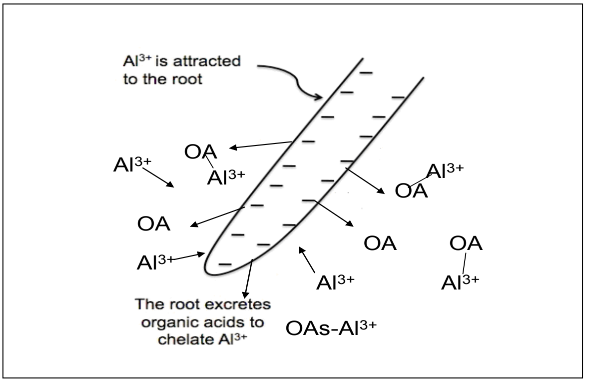

Figure 7. Chelation of Al^{3+} by organic acids in corn root.

When Al^{3+} touches the root of the corn, the plant reacts instantly to release oxalic acid (Figure 6; Figure 7). In the end, some of the Al^{3+} will be chelated by the organic acids and render unavailable for uptake by corn via its roots. The deactivation of Al^{3+} by this mechanism is a crucial step to sustain not only the production of corn growing on the acidic Peninsular Malaysian Ultisols, but also those found elsewhere in the tropics.

CONCLUSION

The growth of non-acid tolerant sweet corn planted on Ultisols in Peninsular Malaysia is affected negatively by soil acidity and/or Al^{3+} toxicity. The critical pH for the healthy growth of the corn is 5.3, while the critical Al^{3+} activity is10 µM. However, the Ultisols in Peninsular Malaysia mostly have a soil pH that is below 5 and Al^{3+} activity much higher than the said critical level. To some extent, corn grown on acidic Ultisols is able to defend itself against Al^{3+} toxicity. Under stress, its roots excrete oxalic acid that chelates Al3+, rendering it inactive. One of the ways to overcome the problem of sweet corn production on the Ultisols in the country is to apply biochar at an appropriate rate. Based on this study, the recommended rate is 10 t EFB-biochar/ha.

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