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Mg-rich Synthetic Gypsum or Basalt as an Alternative Source of Ameliorant to Manage Soil Acidity for Plantation Tree Crops

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The rubber and oil palm in Malaysia are mainly cultivated on acidic Ultisols and Oxisols, which occupy about 70 per cent of the country's land surface. The pH of the soils varies from 4 to 5; however, the crops can withstand this level of soil acidity. This is not the case for cocoa, which grows best if the pH is greater than 5, at which Al^{3+}, Fe^{2+} and Mn^{2+} toxic to its roots are mostly precipitated as inert hydroxides; the respective pKa of the ions are 5, 4.58 and 6. Long-term application of ammonium sulphate on soils in Malaysian plantations can result in increased soil acidity due to nitrification of NH_4^+ released by the N-fertiliser. Thus, in the long run, soil pH can be lowered to the level that affects the growth and production of the crops. For oil palm, soil pH should be maintained at the level greater than 4.3. Treating Ultisols and Oxisols cropped to cocoa, rubber or even oil palm with ground magnesium limestone (GML), Mg-rich synthetic gypsum (MRSG) and ground basalt increases their pH, with the level dependent on the amount applied. Besides increasing soil pH, application of the ameliorants (MRSG or basalt) increases Ca, Mg and even S in the soils that translate into enhanced crop growth and eventually their production is sustained.

Keywords*: Acidic soils, cocoa, oil palm, rubber, soil ameliorant.*

The well-drained regions of the tropics are dominated by highly weathered soils, which are classified as Ultisols and Oxisols. Ultisols as defined by the USDA Soil Taxonomy (Soil Survey Staff, 2014) are soils having argillic diagnostic horizon (usually referred to as Bt horizon). On the other hand, soils having oxic diagnostic horizon (usually referred to as Bo horizon) are classified as Oxisols. Global distribution of the two soils is summarised in *Table 1* (Fageria & Baligar, 2008). Distribution of Ultisols and Oxisols is indicated in the global soil map produced by the United States Department of Agriculture, Washington, DC. It seems that the two soil orders are very extensive in Southeast Asia, especially

TABLE 1
GLOBAL DISTRIBUTION OF ULTISOLS AND OXISOLS

	Global area		*Tropical region*	
Order	*Total*	*Percent of total*	*Total*	*Percent of total*
Ultisols	1347	9.3	749	20.4
Oxisols	840	5.8	833	23.0

Source: Fageria and Baligar (2008)

Malaysia. In Malaysia, Ultisols are more common than Oxisols; however, this is not the case for the tropical regions of Brazil and certain African countries.

Ultisols and Oxisols in Malaysia, mainly located in the upland regions, are developed on igneous, sedimentary and metamorphic rocks of varying compositions (Tessens & Shamshuddin, 1983; Paramananthan, 2000). According to IBSRAM (International Board for Soils Research and Management) (1985), about 70 per cent of Malaysia's land surface are occupied by these soils. It seems that tropical countries located along the Equator have similar climatic regimes and soil types that are suitable for rubber and oil palm or even cocoa cultivation.

Exposed to the tropical environment for a long period of time (since late Pleistocene), rocks in the upland regions of Malaysia are weathered to form highly leached, acidic Ultisols and Oxisols (Tessens & Shamshuddin, 1983; Shamshuddin & Fauziah, 2010). The soils are mainly utilised for oil palm and rubber cultivation, with some areas reserved for cocoa. Important characteristics of Ultisols and Oxisols in Malaysia are summarised in *Table 2*.

Ultisols and Oxisols in Malaysia are sporadically distributed in the undulating areas of the upland regions. High temperature and high rainfall evenly distributed throughout the country is conducive for rubber and oil palm cultivation, and also for cocoa if the rainfall is not too high. Based on crop suitability evaluation, rubber and oil palm are allowed to be planted on sloping land less than 25 degrees. However, cultivating the crops on sloping land requires adequate soil erosion protection to sustain production; hence, land conservation practices has to be put in place at all time (Khalid & Tarmizi, 2008; Shamshuddin *et al*., 2018).

Long-term application of certain types of ammonium fertilisers on Ultisols or Oxisols results in increased soil acidity that affects crop productivity. However, soil acidity increase in the plantations can, to a certain extent, be ameliorated by the hydrolysis of Ca^{2+} coming from dissolution of phosphate rocks that produces some hydroxyls. It is reported that to increase soil pH to a higher level to sustain corn production on Malaysian Ultisols, ground magnesium limestone (GML) is applied at the appropriate rate and time (Shamshuddin *et al*., 1991). According to Shamshuddin and Fauziah (2010), the ameliorative impact of applying GML at 4 tonnes per hectare on Ultisols and Oxisols in the country could last at least four years.

Agronomic management by the Malaysian plantation owners in the past to sustain rubber and oil palm growth and production had been successful. There is no doubt that the agro-system put in place is sustainable in the long run. However, recent research conducted in Malaysia had come up with alternative

TABLE 2
COMMON CHARACTERISTICS OF ULTISOLS AND OXISOLS IN MALAYSIA

Soil	*Diagnostic horizon*	*Soil pH*	*Minerals**	*CEC $cmol_c$ /kg clay*	*Colour*
Ultisols	Bt	4.0-4.5	kn, gb, gt	>16	Yellowish
Oxisols	Bo	4.5-5.0	kn, gb, gt, ht	<16	Reddish

* kn = kaolinite; gb = gibbsite; gt = goethite; ht = hematite

agronomic practices of managing soil acidity, using equally effective ameliorants available in the country at affordable cost.

The need for continuous application of N-fertilisers to sustain rubber growth and/or production has been explained in detail by Wan Noordin and Shafar Jefri (2017), with the source of N coming from either ammonium sulphate or urea. Application of N-fertilisers is considered to be one of the major reasons for acidification of agricultural system (George *et al.*, 2012). Wong *et al.* (2020) found that the pH of soils formed on sedimentary rocks in Peninsular Malaysia cropped to oil palm were usually in the strongly acidic range that may affect its growth. According to the researchers, this condition could only be ascribed to the application of ammonium sulphate that produces soil acidity. This notion is consistent with the results of a study conducted in rubber plantations of Nigeria; the age of the rubber ranged from 7 to 41 years old (Oku *et al.*, 2012). The topsoil (0-15 cm) pH in the rubber plantations was strongly acidic (4.0-4.4). Based on a study conducted in Thailand (Damrongrak *et al.*, 2015), liming soils of this nature with dolomite enhanced rubber growth.

The pH of Malaysian Ultisols can be raised to the required level to sustain oil palm growth/ production by Mg-rich synthetic gypsum (MRSG) application (Ayanda *et al.*, 2020). According to Ayanda *et al.* (2020), the MRSG with pH higher than 7 contained the following: Mg (7.1%), Ca (20.9%), K (49 mg/kg) and P (234 mg/kg). (*Note:* MRSG is a by-product of chemical plant located in Pahang, Malaysia, which is not radioactive but rich in Mg, Ca and S). Sahibin *et al.* (2019) found that MRSG was safe for application in oil palm plantations. For Oxisols, it is believed that ground basalt is equally effective as an ameliorant in alleviation of their acidity problems (Anda *et al.*, 2009; Anda *et al.*, 2015).

The objectives of this paper are:

i) To elucidate the physico-chemical characteristics of Ultisols and Oxisols in Malaysia; and
ii) To explain the impact of applying ground basalt, MRSG or GML on chemical properties of the soils and the growth/ production of cocoa, rubber and oil palm.

CHARACTERISTICS OF ULTISOLS AND OXISOLS

Physico-chemical properties and mineralogical composition

Ultisols and Oxisols are taxonomically classified on the basis of the presence of Bt and Bo diagnostic horizons, respectively. The soils are characterised by their low soil pH (4 - 5), with lower values for Ultisols than those of the Oxisols (Tessens & Shamshuddin, 1983; Shamshuddin & Fauziah, 2010). Basic cations (Ca, Mg and K) are low in both soils; and, insufficient to sustain crop growth and/or production (Paramananthan, 2000; Soil Survey Staff, 2018). The clay fraction of the soils are dominated by kaolinite and sesquioxides (i.e. gibbsite, goethite and hematite). The CEC (cation exchange capacity) of the soils is low with values less than 10 $cmol_c$ per kilogramme (Tessens & Shamshuddin, 1983, Shamshuddin & Fauziah, 2010); however, it can be increased, to a certain extent, by increasing soil pH *via* agronomic means. This is especially true for soils having high amount of oxides of Fe (Shamshuddin & Ismail, 1995; Shamshuddin, 2011).

Charging phenomena in the soils

For soils of both orders, their clay fraction is dominated by kaolinite and gibbsite, goethite and hematite; goethite and hematite are variable-charged minerals (Shamshuddin, 2011) – i.e. their CEC increases with increasing soil pH. Thus, the CEC of Ultisols and Oxisols in Malaysia or anywhere else in the world can be increased somewhat by application of GML as well as any other soil ameliorants (MRSG or ground basalt) that are able to raise soil pH (Shamshuddin & Fauziah; 2010; Shamshuddin *et al.*, 2018).

Based on a study by Shamshuddin and Ismail (1995), application of gypsum ($CaSO_4.2H_2O$) into an Oxisol (Prang Series) slightly increased its pH, resulting from adsorption of SO_4^{2-} onto oxides of Fe (*Figure 1*). There is also a concomitant increase in the CEC due to SO_4^{2-} adsorption. As such, this phenomenon would slightly enhance soil fertility that eventually improves the productivity of Oxisols.

Generation of soil acidity

The inherent acidity in Ultisols and Oxisols comes from various sources. Most of the soil acidity could have come from the hydrolysis of the Al^{3+}, Fe^{3+} and Fe^{2+} existing in their soil solutions. Chemical reactions in the soil solutions can be depicted as follows:

$$Al^{3+}.6H_2O + H_2O \rightarrow Al(OH)^{2+}.5H_2O + H_3O^+, \text{ pKa } 5.0 \quad \text{(equation 1)}$$

$$Fe^{3+}.6H_2O + H_2O \rightarrow Fe(OH)^{2+}.5H_2O + H_3O^+, \text{ pKa } 3.0 \quad \text{(equation 2)}$$

$$Fe^{2+}.6H_2O + H_2O \rightarrow Fe\ (OH)^{+}.5H_2O + H_3O^+, \text{ pKa } 4.58 \quad \text{(equation 3)}$$

As mentioned above, the pH of the highly weathered soils is 4 to 5. Hence, the chemical equilibrium is thus controlled by the hydrolysis of Al^{3+} and Fe^{2+} (equations 1 and 3). The hydrolysis of Fe^{3+} is only significant if the soil pH is about 3 (equation 2). This is rather uncommon for Ultisols and Oxisols in Malaysia. This could only be due to extremely bad agronomic practices that significantly increases soil acidity. It can be assumed that Al^{3+} and/or Fe^{2+} but not Fe^{3+} cause toxicity to the roots of crops. As such, the former have to be eliminated from the soil solutions to sustain crop growth/production in the long run. Besides, soil pH is lowered by application of ammonium sulphate (Fageria *et al.*, 2010).

Soil pH can also be raised to the level greater than 5 by application of GML, ground basalt or MRSG at the appropriate rate based on various studies (Shamshuddin *et al.*, 1991; Anda *et al.*, 2009; Ayanda *et al.*, 2020,

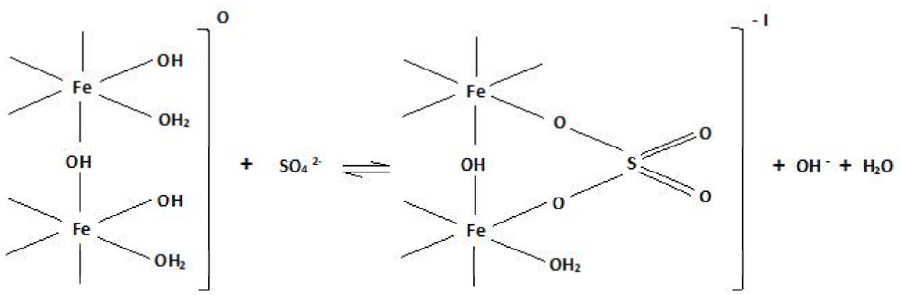

Figure 1 Increase in soil pH and generation of negative charge on oxides/hydroxides of Fe due to gypsum application
Source: Shamshuddin and Ismail (1995)

respectively). At the soil pH level of greater than 5, Al^{3+} will be precipitated as amorphous Al-hydroxides, while Fe^{2+} will be changed to inert Fe $(OH)_2$. Both precipitates are not harmful to the roots of the plantation crops growing in the fields.

Precipitation of toxic metals due to liming

When GML is applied into soils in plantations for certain agronomic reasons, the first reaction that takes place is dissolution (equation 4). The carbonate so released by the dissolution of the dolomitic limestone (GML) is hydrolysed to release hydroxyls, resulting in pH increase (equation 5). Some of the available hydroxyls will react with Al^{3+} in the soil solution to precipitate inert Al-hydroxides (equation 6). Likewise, Fe^{2+} will be precipitated as its inert form (Fe-hydroxides). In this way, the toxic Al^{3+} and/or Fe^{2+} that negatively affect crop roots are eliminated from the soil solutions.

$$(Ca, Mg)(CO_3)_2 \rightarrow Ca^{2+} + Mg^{2+} + CO_3^{2-} \quad \text{(equation 4)}$$

$$CO_3^{2-} + H_2O \rightarrow HCO_3^{-} + OH^{-} \quad \text{(equation 5)}$$

$$Al^{3+} + 3OH^{-} \rightarrow Al(OH)_3 \quad \text{(equation 6)}$$

Mg and Ca so released by the dissolution of the GML are available for crop uptake. According to Alva *et al.* (1986), Ca^{2+} is able to slightly reduce the effect of Al^{3+} toxicity.

COCOA GROWTH AND PRODUCTION

Shamshuddin and Fauziah (2010) stated that low pH and highly weathered Malaysian soils (such as Ultisols and Oxisols) contained variable concentration of Mn in their soil solutions, with Oxisols usually having the most. It is reported that cocoa grown on Oxisols in Malaysia is subjected to Mn^{2+} toxicity (Anda, 2006). Besides, cocoa grown on Oxisols suffers from low pH stress and Al^{3+} toxicity. The critical Al^{3+} activities to sustain cocoa growth and production is 10 µM (Shamshuddin *et al.*, 2004). According to Auxtero and Shamshuddin (1991), the critical Al^{3+} activities for oil palm healthy growth was 100 µM. This means that cocoa is 10 times more sensitive to Al^{3+} toxicity compared to that of the oil palm. Thus, cocoa will not grow well on Oxisols in Malaysia without alleviating Al^{3+} and/or Mn^{2+} toxicities.

The pKa of Mn^{2+} is 6 (De Coninck, 1978). So, if soil solution pH goes up above 6, Mn^{2+} is precipitated as $Mn(OH)_2$, which is inert. However, it is too costly to apply GML on Ultisols or Oxisols to raise soil pH to 6. If we raise soil pH to 5.2, it is already good enough to eliminate Fe^{2+} (the pKa is 4.58) and Al^{3+} (the pKa is 5) toxicities; however, only part of the Mn^{2+} toxicity is alleviated. This notion is consistent with the results of a study conducted by Ismail *et al*. (1993) who analysed soil solutions extracted from Bungor Series (Ultisol) and Prang Series (Oxisols) treated with GML at 2 tonnes per hectare. The relationship between soil solution Al (µM) and Mn (µM) with pH are given below (Shamshuddin & Fauziah, 2010):

$$Al = 1.09 \times 10^{6} \exp(-2.40x) \quad \text{(equation 7)}$$
$$R = 0.79$$

$$Mn = 1.88 \times 10^{4} \exp(-1.69x) \quad \text{(equation 8)}$$
$$R = 0.75$$

To get soil solution pH to 5, apply GML at the rate of 2 tonnes per hectare (Shamshuddin & Fauziah, 2010). The ameliorative impact of applying GML at this rate could last more than four years. Using equation 7, we can determine what happens to Al in the soil solution after applying 2 tonnes GML per hectare. When pH goes above 5, Al no longer becomes a threat to crop as its concentration in the solutions is minimal (equation 1).

As shown in equation 8, Mn in the soil solution decreases exponentially with increasing soil solution pH. When pH goes above 5, soil solution Mn concentration is less than 5 µM (Shamshuddin & Fauziah, 2010); a level believed to be no longer toxic to cocoa.

Panhwar *et al*. (2014) proved that Al^{3+} and Fe^{2+} in soil solution can in part be inactivated by organic acids (*via* chelation) released by bio-fertiliser, fortified with phosphate-solubilising bacteria (PSB). Likewise, Mn^{2+} can be inactivated by the same mechanism. If GML is applied on Oxisols in combination with the said bio-fertiliser, we only need to raise soil pH to 5.2 to get rid of all toxicities caused by the three metals. The bio-fertiliser, using organic matter as filler, contains PSB that help produce organic acids; besides, the PSB increase soil solution pH. In this way, the fertility of the highly weathered soils is enhanced. This is translated into good cocoa growth and eventually increases cocoa pod yield.

Another agronomic practice that helps improve soil fertility to sustain cocoa production on an Oxisol is applying ground basalt at the appropriate rate. Application of basalt dust on agricultural land in Australia is also known to enhance soil fertility considerably and that sustains sugarcane production for many years (Gillman *et al*., 2001; Gillman *et al.*, 2002). The dissolution of Mg-olivine (forsterite) present in basalt is shown by the following reaction (De Coninck, 1978):

$$4Mg^{2+} + SiO_4^{4-} + 4\ H_2O \rightarrow 4Mg^{2+} + Si(OH)_4 + 4OH^- \qquad \text{(equation 9)}$$

This reaction produces hydroxyls that increases soil pH to the level dependent on the rate of basalt applied (*Figure 2*). (Note that this is a laboratory experiment intended to prove that it takes a long time for ground basalt to completely disintegrate and dissolve under moist condition in a soil) (Anda, 2006; Anda *et al*., 2009). The real amount of ground basalt needed to sustain cocoa production is relatively small. In practice, ground basalt is recommended to be applied at specific sites in the plantations, e.g. in the planting holes or within the weeded circle of each plant where cocoa roots concentrate.

As shown in *Figure 2,* the disintegration and dissolution of basalt in Oxisols takes a long time (equation 9). According to Anda (2006), under field conditions, ground basalt was still observed in the soil two years after application. It should be noted that basalt contains not only Si and Mg, but also some other macronutrients (Ca, K and S). S is a macronutrient needed by crops, and some soils contain insufficient amount of S. Besides increasing soil pH, basalt is a kind of slow-release fertiliser that helps sustain cocoa production in the long run. It has been confirmed by Anda *et al*. (2013) that basalt application in the field increased soil solution Si. The presence of sufficient Si in the plant system may possibly prevent the outbreak of a cocoa disease. A study in Indonesia by Wijaya *et al.* (2009) indicated that the pods on cocoa trees treated with Si was not attacked by borers. This may be attributed to them having Si that resulted in being harder than they otherwise were; thus, the pods were difficult to penetrate.

An experiment was conducted at the Malaysian Cocoa Board (MCB) Experimental Station in Temerloh, Malaysia, to prove that the above-mentioned notion is for real (Anda, 2006; Anda *et al*., 2015). The soil at the MCB experimental Station is Segamat Series which is classified as an Oxisol. Cocoa plants on soil treated with ground basalt started to bear fruits

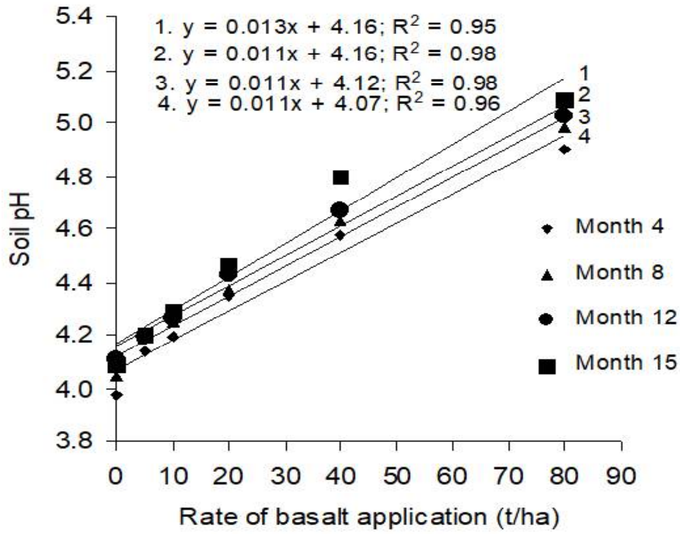

Figure 2 Changes in pH of an Oxisol (Segamat Series) with increasing rate of basalt application
Source: Anda *et al.* (2009)

after 24 months. This proves yet again that applying ground basalt to sustain cocoa production is a feasible agronomic practice. [*Note*: Basalt dust (with size slightly bigger that 2 mm) is available in large quantity from a quarry in Segamat, Johor, which only costs RM35 per tonne. The good thing about this basalt source is that it contains insignificant amount of heavy metals, almost similar in composition to that used by Anda *et al.* (2015), which was obtained from Australia].

RUBBER GROWTH AND PRODUCTION

The trial on rubber cultivated on an Oxisol (Prang Series) was initiated in mid 1986 in Malaysia. The pH of the Prang Series in the area before treatment was below 5. The results showed that due to application of 1 tonne of GML per hectare, rubber growth was significantly enhanced. At the end of the trial (of 4 years), soil pH of the treated plots was found to have increased slightly. Rubber in the treated plots could be tapped 12 months ahead of the normal time (Shamshuddin & Fauziah, 2010). GML applied at this level did not have an adverse effect on latex flow. It is generally believed that high Mg uptake by mature rubber could cause latex coagulation that may reduce yield.

Soil acidity increase because of the long-term N-fertiliser application in rubber plantations is consistent with the results of a study by the Rubber Research Institute of India (Joseph, 2012). This is validated by Jessy *et al.* (2012) who compared soil pH in 2 500 rubber smallholdings in rubber growing regions of India during the 1979-1984 and 2003-2008 periods. Comparison of the same sites over the years showed significant decline in soil pH.

According to Joseph (2012), soil pH in some rubber plantations in India was lowered to a level slightly above 3 due to long-term ammonium sulphate application, which affected latex production significantly. Thus, lime application was recommended to alleviate soil acidity problem so that the growth and production of rubber could be sustained. This notion is consistent with the result of a study conducted in Thailand by Damrongrak *et al.* (2015).

What happens to the chemical properties of Oxisols planted with rubber if MRSG is applied on them? As shown in *Figure 1*, SO_4^{2-} released by MRSG will be adsorbed by goethite and/or hematite present in the soils, resulting in a slight increase of soil pH. Besides, the CEC of the Oxisols will be raised because goethite and hematite are variable-charged minerals – i.e. their CEC increases with increasing soil pH (Shamshuddin, 2011; Shamshuddin & Fauziah, 2010). As such, MRSG is a good soil ameliorant for rubber cultivation (i.e. young rubber).

A study by Ayanda *et al*. (2021) confirmed that the MRSG had pH higher than 7. Besides, it contained high amounts of Mg, Ca and S with some micronutrients, but no heavy metals of concern were detected. Unpublished results (Ayanda, 2021 - pers. comm.) indicated that the rubber seedlings responded positively to Mg-rich synthetic gypsum application. However, MRSG is not yet recommended to be applied on soils having mature rubber as it has high Mg content. More studies need to be conducted on MRSG application for mature rubber.

Application of ground basalt can likewise help enhance rubber seedlings at nursery stage. This notion was confirmed by Shafar Jefri (2017) who used basalt dust taken from a quarry in Segamat, Malaysia. Basalt dust used in the experiment contained CaO (9.3%), MgO (4.2%), K_2O (3.8%), P_2O_5 (0.63%) and SO_3 (0.06%). Based on the data from a field trial on a soil developed from granite (Rengam Series) at Kampung Chepor in Perak, Malaysia (classified as an Ultisol), Shafar Jefri (2017) concluded that soil fertility was significantly enhanced by ground basalt application. Young rubber in the research plots responded positively to the addition of ground basalt in the planting holes.

The recommended rate (Shafar Jefri, 2017), to be applied in the planting hole of each rubber seedling is 179 g per plant. As such, ground basalt is a potential source of macronutrients for rubber cultivation. More agronomic trials in the field are necessary to determine conclusively if ground basalt can really enhance and/or sustain latex production in the long run. In one hectare of a plantation, up to 400 of rubber seedlings can be planted; therefore, only a small amount of ground basalt is needed. This is considered a sustainable agronomic practice, considering its ameliorative impact that is expected to last over many years.

In Malaysia, for rubber cultivation the fertilisers generally used was a combination of ammonium sulphate, rock phosphate, muriate of potash and kieserite. The calcium in the rock phosphate counteracted the acidifying effect of ammonium sulphate. However, with continued use of phosphate and with replanting with time there is the build-up of P in soil. Already currently in some mature areas the application of phosphate has been reduced or eliminated. With time, the chances of increased soil acidity could be high. Basalt is a potential to address the problem of soil acidity or even nutrient deficiency.

OIL PALM GROWTH AND PRODUCTION

The Department of Agriculture (DOA) Malaysia insists that agricultural production in the country has to be run on sustainable basis, following good agricultural practices as outlined by MyGAP (Malaysian Good Agricultural Practices) (DOA, 2005). Palm oil production in the country is sustainable. Malaysia being number two in the world in terms of palm oil production, the land area cropped to oil palm is huge, currently occupying more than 5 million hectares. Most of the oil palm in the country are grown on the highly weathered Ultisols and Oxisols.

Suitable soil pH to sustain oil palm growth

Oil palm can withstand a moderately low pH stress – in other words, it is an acid-tolerant plant species. The critical soil pH to sustain oil palm growth is 4.3 (Auxtero & Shamshuddin, 1991). Oil palm growing in the fields having soil pH less than 4.3 will suffer from low pH stress. When soil pH is raised to the level greater than 5, oil palm is no longer affected by excessive amount of H^+ under this condition, nor does it suffer from Al^{3+} (the pKa is 5) and/or Fe^{2+} (the pKa is 4.58) toxicity. This is because the two ions will be precipitated as inert hydroxides.

Nutrient requirement of oil palm

Oil palm needs sufficient and continuous supply of major nutrients (NPK) to sustain its growth and production. Besides, it needs sufficient Mg, Ca and S; S is needed by oil palm for oil production in its fruitlets. Usually, N-fertiliser applied for oil palm cultivation is ammonium sulphate. After the fertiliser is applied on soils, S in it is made available for oil palm uptake. Mg is needed in high amount for the process of photosynthesis, which is usually supplied *via* kieserite ($MgSO_4.H_2O$) application, which can also supply S for oil palm requirement. Alternatively, Mg can be added into the soil *via* application of MRSG, but at a much lower cost than that of kieserite.

Nitrification of NH_4^+ ions

Application of ammonium sulphate in the long run would lower soil pH significantly. The acidity is produced according to the following chemical reaction (Miller & Donahue, 1990):

$$NH_4^+ + O_2 \rightarrow NO_2^- + 2H^+ + H_2O \quad \text{(equation 10)}$$

The expected drop of soil pH in oil palm plantations due to long-term ammonium sulphate application should be curtailed or stopped *via* agronomic means. This is to make sure that soil pH remains above the critical level of 4.3 to keep oil palm growth/production going.

Mineralisation of organic matter

Mineralisation of fresh organic matter in a soil increases its pH due to release of some NH_3 at the early stage of the process (Hoyt & Turner, 1975). This happens in oil palm plantations where cut-fronds are laid down and left to rot between oil palm rows. On dissolution of the NH_3 in water, some hydroxyls are produced that increases soil pH slightly. But the alkalinity so produced is unable or insufficient to offset the acidity released by above-mentioned nitrification of ammonium ions present in the N-fertiliser (equation 10).

Due to the high cost of applying kieserite (for Mg) or GML (for Mg and Ca) for oil palm cultivation, a cheaper substitute should be looked into. Mg-rich synthetic gypsum, an industrial by-product, is found to have beneficial properties that makes it a potential alternative. MRSG with pH greater than 7 contains high amounts of Mg, Ca and S, with some calcium carbonate (Ayanda *et al.*, 2021). Its application on an Ultisol cropped to oil palm in Bera, Malaysia, sustains the growth, giving comparable result to that of kieserite or GML (Ayanda *et al.*, 2020). Continuous MRSG application would eventually reduce soil acidity prevalent in the tropical regions of the world where oil palm is mostly cultivated. Based on a nursery study, soil pH increase due to MRSG application enhanced the growth of oil palm seedlings. This is indicated by the increase of oil palm seedlings height with increasing soil pH (*Figure 3*).

The alkalinity present in the MRSG can, to a certain extent, offset the acidity generated by the nitrification of N-fertiliser. In a study conducted on an Ultisol at Bera, Malaysia, application of MRSG in an oil palm plantation did not result in soil or water pollution; besides, the quality of palm oil produced remains intact (Sahibin *et al.*, 2019).

Ayanda *et al.* (2020) showed conclusively that soil pH increased with increasing rate of the MRSG treatment, with a concomitant increase in exchangeable Ca and Mg. Applying MRSG at an appropriate rate improves soil fertility that enhances the growth of the oil palm seedlings. This means that oil palm grows better at soil pH greater than 5 than that at lower pH, where it may suffer from low pH stress and/or Al^{3+} toxicity. The height of the oil palm seedlings in the nursery increased with increasing exchangeable Ca (*Figure 4*).

According to Ayanda *et al.* (2020), the estimated critical exchangeable Ca for healthy oil palm growth is 0.9 $cmol_c$ per kilogramme. Exchangeable Ca of more than 0.9 $cmol_c$ per kilogramme is rather uncommon in Ultisols and Oxisols in Malaysia under continuous oil palm cultivation. As such, exchangeable Ca level of the soil in oil palm plantation has to be raised *via* agronomic means.

Using stepwise regression analyses of the soil pH, exchangeable Ca and exchangeable Mg it was shown that a significant relationship existed between these variables and the height of oil palm seedlings (Ayanda *et al.*, 2020). Soil pH is the most important factor controlling the growth of the oil palm seedlings based on its height. Further results showed that soil pH was positively correlated with exchangeable Ca, which means that as Ca in the soil increased, soil pH was raised to the level dependent on the rate of the MRSG applied.

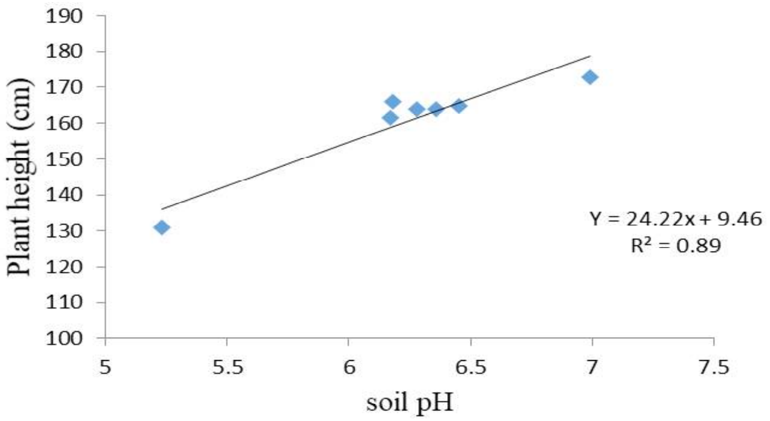

Figure 3 Relationship between oil palm plant height and soil pH
Source: Shamshuddin *et al.* (2018)

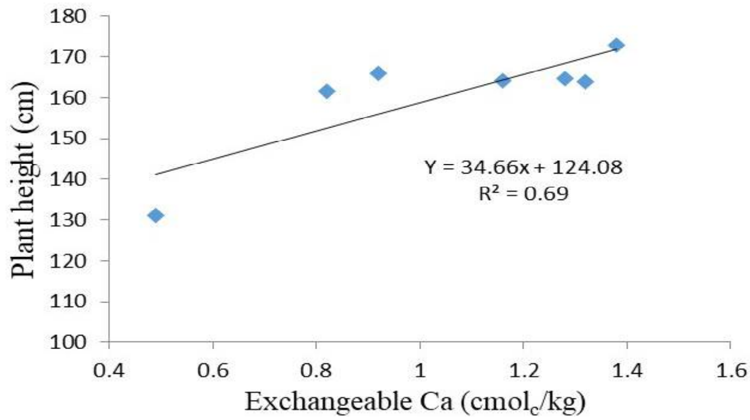

Figure 4 Relationship between plant height and exchangeable calcium
Source: Shamshuddin *et al.* (2018)

Najihah *et al.* (2015) reported that Si taken up by oil palm is able to prevent basal stem rot disease caused by *Ganoderma*. It is believed that Si is usually absorbed by plant roots in the form of Si $(OH)_4$. This silicic acid can be made available by dissolution of ground basalt applied onto acidic soils (equation 9). The chemistry of ground basalt dissolution in Oxisol has been explicitly explained by Shamshuddin *et al.* (2018). Slow dissolution of ground basalt in acidic but highly weathered soils existing under tropical environment will supply some nutrients (Ca, Mg, K, P and S) required by oil palm to help sustain its growth/production.

CONCLUSION

Ultisols and Oxisols are widespread in the well-drained upland regions of the humid tropics, especially Malaysia. With proper agronomic practice, the soils can productively be utilised for cocoa, rubber and oil palm cultivation. However, there are various obstacles and challenges faced by growers to sustain their crop production in the long run. Besides having to add fertilisers to the soils so that the necessary nutrients are sufficient to sustain growth and/ or production, growers have to take care of problems related to generation of soil acidity or toxicity to crop roots caused by Al^{3+}, Fe^{2+} and Mn^{2+}. The said problems can be eliminated *via* application of appropriate ameliorants to raise soil pH to the required level.

Among the agronomic options deemed appropriate for consideration by the estate management are application of ground magnesium limestone, Mg-rich synthetic gypsum or ground basalt at the pre-determined rate and time. The choice of the soil ameliorant to be considered should be based on its efficacy, availability and cost. For cocoa, it is advisable to increase soil pH to a level more than 5 using one of the ameliorants so as to eliminate low pH stress and toxicity caused by the mentioned acid metals. Oil palm and rubber can withstand a certain level of soil acidity and toxicity related to Al^{3+} and Fe^{2+}. Soil pH should be maintained at more than 4.3 throughout the productive life of oil palm to sustain its growth and production using MRSG or basalt, and these are alternatives to the traditional ground magnesium limestone.

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