Mg-Rich Synthetic Gypsum Application on Soils in Malaysia to Sustain Agricultural Production: A Review

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ABSTRACT
Applying Mg-rich synthetic gypsum (MRSG) on acid sulfate soils results in a concomitant alleviation of Al\(^{3+}\) and/or Fe\(^{2+}\) toxicity and is known to increase soil pH and improve rice growth. In the case of the oil palm, S is required in sufficient quantities to produce oil in its fruitlets. For all intents and purposes, MRSG can be used as Mg- and/or Ca-fertiliser for oil palm and rubber as well as for sustainable rice cultivation on acidic soils. Greater use of MRSG which is locally available would reduce imports of fertiliser and at the same time sustain agricultural productivity. This is translated into foreign exchange savings as well as increased income for farming communities. As it is available in large quantities in Malaysia, MRSG utilisation would sustain agriculture in the country at a reasonable cost. In conclusion, application of MRSG on acidic soils in Malaysia does not contribute to environmental degradation. Instead, the MRSG supplies Ca, Mg and S that are needed in high amounts by crops to sustain growth and/or production. Thus, we can turn the otherwise cheap by-product of a chemical plant into a useful fertiliser that contributes to our economic growth.

Keyword: Agricultural production, Ca-Fertiliser, gypsum, Mg-fertiliser, soil ameliorant

INTRODUCTION
Words has been going round in the vicinity of Kuantan for years that human health would be negatively affected by a Lyanas rare earth processing plant located in nearby Gebeng town, Malaysia. People living near the chemical plant are divided between believing the stories propagated by opponents or proponents and the reality of the issue. The chemical plant in Gebeng is dedicated to the production of rare earth, which is essential for the development of high-end industries in the world. The production process of extracting the precious materials at the state-of-the-art chemical produces a by-product which can be useful for agriculture in the country. This is called Mg-Rich Synthetic Gypsum (MRSG).

The production of rare earth at Lyanas Chemical Plant in Gebeng, Pahang involves many steps. The process starts with lanthanide ore containing rare earth imported from Mount Weld in Australia. In the process of extracting the precious...
rare earth for the world market, two contrasting by-products are produced. After undergoing a series of chemical processes in the plant, a radioactive Water Leach Purification (WLP) residue is produced. This is followed by the production of Mg-Rich Synthetic Gypsum (MRSG), known as Neutralisation Underflow (NUF) residues, which is not radioactive (Figure 1). The final product of the process is the afore-mentioned rare earth which fetches a premier price at the marketplace.

Figure 1. A photograph showing MRSG being stored at Lynas chemical plant in Gebeng, Malaysia. (Courtesy of Lynas Malaysia Sdn Bhd)

Application of MRSG on land to enhance the growth of oil palm and sustain its yield does not result in environmental degradation. This was confirmed by the study of Abd Rahim et al. (2019) conducted over a period of three years on an oil palm plantation in Bera, Malaysia. While the land in the trial area benefitted via alleviation of soil acidity that affects crop growth, water quality in the channels and rivers in the surrounding areas remained intact. Thus, MRSG is not only is an excellent soil ameliorant, but also a source of Ca and Mg for crop growth.

This paper discusses the production of MRSG, physico-chemical properties and its utilisation for agriculture in Malaysia. The objectives are consistent with the Eleventh Malaysia Plan 2016-2020 initiatives which look at managing chemical plant wastes holistically. The initiative states that using wastes as a resource gives an economic value; hence, it should be diverted away from landfills towards more productive use. This article will be a useful reference for students in the field of agriculture as well as soil scientists and agronomists in Malaysia or even from the tropical Asia involved in the cultivation of oil palm, rice and rubber.

MRSG addition has been known to increase soil pH which in turn alleviates Al³⁺ toxicity in Malaysia if applied repeatedly at suitable rates (Ayanda et al., 2020). Therefore, the objectives of this paper are: (1) to discuss the effects of applying MRSG on acidic soils and to measure the growth/yield of oil palm, rice and rubber; and (2) to explain the impact of applying MRSG on land to alleviate soil acidity on the surrounding environment.
CHARACTERISATION OF Mg-RICH SYNTHETIC GYPSUM

Physical Properties of MRSG
A huge quantity of MRSG is now stored at the Lynas Chemical Plant in Gebeng, Malaysia (Figure 1). It is ready to be transported to any destination in the country for use in agriculture. Currently, the MRSG is left in the open and exposed to atmospheric conditions within the chemical plant compound. According to Mohd Firdaus et al. (2020), about 60% of the by-product is <1 mm in size and hydroscopic by nature (contains a moisture content of about 26.7%). The pH of the MRSG (existing in semi-powder form) is 9.28, while its EC is 7.03 (mS cm⁻¹). Table 1 shows the Mg and Ca content of the MRSG in comparison with those of China Kieserite and GML (Mohd Firdaus et al. 2020).

<table>
<thead>
<tr>
<th>Element</th>
<th>China Kieserite</th>
<th>GML</th>
<th>MRSG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Mg (mg kg⁻¹)</td>
<td>160,000±8,000</td>
<td>91,000±4,000</td>
<td>55,000±4,500</td>
</tr>
<tr>
<td>Total Ca (mg kg⁻¹)</td>
<td>25,000±3,000</td>
<td>190,000±8,000</td>
<td>240,000±17,000</td>
</tr>
</tbody>
</table>

Source: Mohd Firdaus et al. (2020)

The results of a recent test showed that the solubility rate of the fertilisers mentioned in Table 1 is in the order of: Kieserite > MRSG > GML (Shamshuddin et al. 2017a). This being the case, it is imperative to enhance the solubility of MRSG to be comparable with that of the China Kieserite. When applied on highly weathered acidic soils of the tropics, it is possible for MRSG to be dissolved completely in a matter of a few weeks, releasing Mg, Ca and S for crop uptake. As explained by Mohd Firdaus et al. (2020), the solubility of MRSG can be significantly accelerated if it is applied on soils in combination with elemental sulphur (S). This is because the oxidation of S in the soils would release acidity and increase the dissolution rate of the otherwise alkaline MRSG. However, this mechanism can only work well in soils under well drained conditions, but not for soils of waterlogged areas.

Mineralogical Composition of MRSG

XRD analysis
XRD analysis of the MRSG by Ayanda et al. (2020) showed that it contained high amounts of gypsum (45.4%), indicated by the d-spacing of 7.609 Å (2 theta 11.63) in the diffractogram (Figure 2). Some calcite was also present in the MRSG, indicated by the d-spacing at 3.036 Å (2 theta of 29.41); however, the XRD peak was too weak to be clearly seen on the diffractogram. Note that the analysis done by Golder Associates of Australia (courtesy of Lynas) found that the MRSG contained 73-74% gypsum, with fair amounts of magnesium hydroxide (17.1%),
calcium hydroxide (4.3%) and calcium carbonate (2.3%). It is the presence of Mg (OH)$_2$ and Ca (OH)$_2$ that makes MRSG alkaline in nature.

**Field Emission Electron Microscope analysis**
Dominance of gypsum in the MRSG is evidenced by the presence of the acicular-shaped mineral observed under Field Emission Scanning Electron Microscope (FESEM) as shown in Figure 3. The average chemical composition of the MRSG at any particular spot (e.g. at spectrum 1, 2 and 3) in the micrograph can be determined using the EDX attached to the FESEM. The presence of C was detected by FESEM-EDX, which is consistent with the presence of calcite confirmed by the XRD analysis (Figure 2).

**Chemical composition of the MRSG**
The MRSG discussed in this paper is alkaline in nature with a very high pH of 9.28 (Mohd Firdaus 2020). Hence, its application in oil palm and rubber plantations or even rice fields would have a positive impact on the chemical properties of the soils, especially in the alleviation of soil acidity. Besides, land application of MRSG would add other plant nutrients and/or beneficial elements into the highly weathered soils (Table 2). This is the known benefit of using the by-product in agriculture that farmers should know about.

The composition of the MRSG can be determined by FESEM-EDX. The chemical contents determined via this methodology (Figure 4) are at best the relative measurements normalised to 100%; thus, they are not absolute amounts as determined by ICP-OES. In this study, spectrum analysis was done to indicate
Ayanda et al. (2020) found Ca (20.99%) to be the most abundant element in the MRSG, followed by Mg (7.15%). The values of Ca and Mg in the MRSG were almost similar to that obtained by Shamshuddin and Ismail (1995) using GML on a Malaysian Ultisol. Besides, the MRSG contained some essential micronutrients (Mn, Zn and Cu), with small amounts of beneficial elements (Se and Si), but significant nevertheless (Table 2). The presence of Si was detected by ICP-OES, but not by the XRD analysis because it is believed to exist in the form of amorphous silica (SiO$_2$). Si, if present in sufficient amounts in oil palm tissues, can prevent certain diseases (Najihah et al. 2015).

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**TABLE 2**

<table>
<thead>
<tr>
<th>Micronutrient</th>
<th>Beneficial element</th>
<th>mg kg$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>Mn</td>
<td>1368</td>
</tr>
<tr>
<td>Zn</td>
<td>Cu</td>
<td>1175</td>
</tr>
<tr>
<td></td>
<td>Si</td>
<td>38.7</td>
</tr>
<tr>
<td></td>
<td>Se</td>
<td>127</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.4</td>
</tr>
</tbody>
</table>

Source: Ayanda et al. (2020)
USE OF MRSG IN AGRICULTURE

Mg-rich synthetic gypsum has been found to be a non-radioactive, non-toxic and non-hazardous by-product of the chemical plant producing rare earth. By utilising this special gypsum rich in Mg and Ca for agriculture, the Malaysian government will be able to value add to the economy and reduce the import of Mg- and Ca-fertilisers from other countries. On MRSG application to agricultural land, Mg and Ca will be released into the soils for uptake by crops to sustain growth and/or production.

![Figure 4. FESEM-EDX diffractogram of the MRSG](source: Abd Rahim et al. (2019))

A large area of arable land in Malaysia (>5 million ha) is cropped to oil palm with great success, with the rest of the area being utilised for the cultivation of rubber, cocoa and other food crops (Shamshuddin et al. 2018). According to Shamshuddin and Fauziah (2010), most of the soils in the areas under oil palm and rubber cultivation in the country are mainly highly weathered acidic Ultisols and Oxisols which have insufficient basic cations (especially Ca and Mg) required for crop growth. Therefore, fertiliser application is crucial to sustain the growth of the crops and eventually their yield.

It is normal practice in plantations in tropical Asia to apply kieserite (MgSO$_4$·H$_2$O) as the source of Mg to sustain oil palm growth/production. Applying kieserite would also add S into the soil system. S is required for oil production in the fruitlets. Another equally important source of S is dolomitic limestone [CaMg(CO$_3$)$_2$] (Sidhu et al. 2014), which is otherwise known as ground magnesium limestone (GML). GML dissolves to release Mg and Ca into the soil and is needed in high amounts by growing oil palm trees.

<table>
<thead>
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<th>Micronutrients</th>
<th>Beneficial elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>Mn</td>
</tr>
<tr>
<td>1368</td>
<td>1175</td>
</tr>
</tbody>
</table>

Source: Ayanda et al. (2020)

The composition of the MRSG can be determined by FESEM-EDX. The chemical contents determined via this methodology (Figure 4) are at best the relative measurements normalised to 100%; thus, they are not absolute amounts as determined by ICP-OES. In this study, spectrum analysis was done to indicate the presence of certain elements. However, detailed elemental composition of the MRSG was tabulated based on the ICP-OES analysis.
The way forward is to look for a cheaper substitute to replace the expensive kieserite or GML as a source of Mg and/or Ca because of their high cost of purchase. The industrial by-product MRSG has been found to have beneficial properties and offers potential as an alternative to kieserite or GML as a source of Mg-fertiliser for oil palm cultivation (Ayanda et al. 2020). There is also evidence to suggest that MRSG has the capacity to alleviate the problems of soil acidity (low pH stress) and Al³⁺ or even Fe²⁺ toxicity that significantly curtails rice production on acid sulfate soils in Malaysia and other Southeast Asian countries.

Using information from the recent studies conducted in the glasshouse and field, we believe that MRSG has a great potential in agriculture, particularly as Mg- and Ca-fertilisers or even as a soil conditioner. However, its utilisation on agricultural land is prohibited until and unless permission is granted by the Department of Environment (DoE), Ministry of Science in Putrajaya. Currently, MSRG is listed as a scheduled waste.

**Effects of MRSG Application on Oil Palm Growth and Production**

**Soil survey and soil characterisation**

Researchers from Universiti Putra Malaysia (UPM) and Universiti Kebangsaan Malaysia (UKM) collaborated on a study using MRSG for oil palm cultivation. MRSG is mainly composed of gypsum (CaSO₄·2H₂O), enriched with magnesium. This high pH by-product is known to be a good soil ameliorant and is regarded as a source of Ca and Mg for oil palm planted on highly weathered Malaysian soils (Shamshuddin et al. 2017a). A study by Abd Rahim et al. (2019) showed that MRSG is not harmful to the environment.

A soil survey was carried out on a 4-ha oil palm smallholding in Bera, Peninsular Malaysia to determine soil type distribution in the area. The condition of the 15-year-old palms and soil in the smallholding observed during the survey is as shown in Figure 5. Note that the soil is reddish in colour, indicative of the presence of high amounts of Fe in the form of hematite. But the major clay mineral in the clay fraction of the soil is kaolinite (Ayanda 2017).

The soil survey was carried out to collect samples for detailed physico-chemical analyses. Using the data obtained, the soil at the trial area was characterised and subsequently classified according to Soil Taxonomy (Soil Survey Staff, 2014). Following the Malaysian System of Soil Classification, the soil found at the trial site was identified as the Jempol Series (Shamshuddin et al. 2017a; Soil Survey Staff 2018).

**Glasshouse Study Using MRSG to Enhance Oil Palm Growth**

**Effects of treatments on the chemical properties of the soil**

The soil used for the glasshouse study was collected from the field experimental site at Bera, Malaysia (Figure 5). It was identified as the Jempol Series (Shamshuddin et al. 2017a) and taxonomically classified as the clayey, kaolinitic, isohyperthermic family of Typic Paleudults (Soil Survey Staff, 2014). The soil was acidic with a pH of <5; however, according to Goh et al. (2003), a pH level of <5 is still within
the suitable soil pH range for oil palm cultivation. Exchangeable magnesium in
the soil was 0.23 cmol$_c$ kg$^{-1}$ (Ayanda 2017). This is considered moderate for oil
palm growth and/or production. Available P in the soil was very low probably
due to immobilisation via specific adsorption by Fe and/or Al oxides, forming
insoluble Fe-P and/or Al-P compounds (Fageria and Baligar 2008); the Fe content
in the soil was very high (Figure 4).

The pKa of Al$^{3+}$ was 5; hence, soil solution pH will move towards 5 to
achieve the state of maximal equilibrium in the system. High organic matter
content as reflected by high nitrogen and carbon in the topsoil is thought to be
contributed by the felled fronds and empty fruit bunches previously laid down in
the inter-rows of the palms in the smallholding.

According to Ayanda et al. (2020), the exchangeable Mg in the soil of the
glasshouse study at harvest (month 9) indicated the level of Mg in soil treated
with MRSG to be comparable to that of the kieserite application (Table 3). The
original exchangeable Mg and Ca in the topsoil of the smallholding was 0.23 and
0.64 cmol$_c$/kg soil (Ayanda 2017), respectively, and these values are below the
sufficiency range for optimal oil palm growth (Shamshuddin et al. 2018). Mg
or even Ca required by oil palm can be supplied by GML application; however,
the standard practice of supplying Mg for oil palm consumption is via kieserite
application.

IPNI (2013) states that Ca is often neglected in oil palm nutrition since its
deficiency has been rarely reported by agronomists. This is due to the fact that in
the past, Ca was added to the soil through liming using GML. As the area of land
cultivated with oil palm is large, GML application has become a very expensive
practice. But the oil palm is known to be an acid-tolerant plant species (Auxtero
Effects of treatments on oil palm seedlings

The growth of oil palm seedlings in the glasshouse in terms of height, stem diameter, root length and root surface area were significantly enhanced by the addition of MRSG, giving results comparable to application of other sources of Mg-fertiliser (Table 4). For the vegetative growth of the oil palm seedlings, MRSG treatments gave comparable results to that of the kieserite (Ayanda et al. 2017) that can tolerate a pH of below 5. Raising soil pH to a higher level significantly enhances the growth of oil palm seedlings (Ayanda 2017). This is normally achieved through liming, which has been found to be expensive for oil palm cultivation. This is where MRSG could come in to alleviate the problem facing the oil palm industry. Adding MRSG as Mg-fertiliser would add a valuable amount of Ca into the soil. The presence of Ca results in a slight increase in soil pH, which is good for the growth of the oil palm. Thus, there is strong justification to raise the pH of Ultisols in Malaysia or Indonesia for oil palm cultivation to a higher level for the oil palm to perform even better.

In the glasshouse study, it was noted that applying MRSG on the soil resulted in a significant increase in soil pH, exchangeable Ca and exchangeable Mg (Table 3). Soil pH of the control treatment was almost 5, which is rather unusual for an Ultisol in Peninsular Malaysia (Shamshuddin et al. 2018). As such, there could be possible contamination of the control plots by running water (run-off) from the treated plots. Notwithstanding this, the results of the experiment showed that soil pH increased further with increasing rates of the MRSG treatment, with values exceeding 6 and a concomitant increase in exchangeable Ca and Mg. This means that applying MRSG somewhat improves soil fertility which is believed to have enhanced the growth of the oil palm seedlings planted under glasshouse conditions.

### Effects of treatments on oil palm seedlings

#### The growth of oil palm seedlings

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### TABLE 3

Soil pH and exchangeable Ca and Mg as affected by MRSG treatments

<table>
<thead>
<tr>
<th>Trt</th>
<th>Month 3</th>
<th>Month 6</th>
<th>Month 9</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pH (cmolc/kg)</td>
<td>Exch Ca</td>
<td>Exch Mg</td>
</tr>
<tr>
<td>T0</td>
<td>5.32&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.72&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.28&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>T1</td>
<td>6.02&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.86&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.39&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>T2</td>
<td>6.48&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.03&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.31&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>T3</td>
<td>6.18&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.36&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.34&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>T4</td>
<td>6.20&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.39&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.52&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>T5</td>
<td>6.76&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.61&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.71&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>T6</td>
<td>6.22&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.47&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.63&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Means followed by different letters within the same column are significantly different at **p<0.05**

**Notes**: T0 = Control (NPK only); T1 = NPK+ kieserite; T2 = NPK+GML; T3 = NPK+MRSG at the recommended rate; T4 = NPK+MRSG at half of the recommended rate; T5 = NPK+MRSG at double the recommended rate; T6 = NPK+MRSG equivalent to Ca in GML

**Source**: Ayanda (2017)
This is encouraging as it indicates the possibility of using MRSG to replace kieserite as an Mg source to sustain the growth of oil palm seedlings.

The content of Mg in frond 3 of the oil palm seedlings was within the sufficiency range for healthy growth (Table 5). In the case of Ca content, the values were higher than the sufficiency level for oil palm requirement. This is based on the standard requirement proposed by Von Uexkull and Fairhurst (1991) and Fairhurst and Hardter (2003). This indicates that, the higher the content of Mg and Ca in the soil due to application of MRSG, the higher the uptake by the oil palm seedlings in the glasshouse (Ayanda 2017).

Using the data obtained from the glasshouse experiment, more agronomic interpretations can be done. For instance, the height of oil palm seedlings was plotted against exchangeable Mg. It was found that there was no significant correlation between the height of oil palm seedlings and the level of exchangeable magnesium in the treated soil. However, when plant height was plotted against exchangeable Ca, a significant correlation was obtained. As explained by Ayanda et al. (2020), a possible explanation could be that Ca is the more limiting nutrient in the soil in comparison to Mg.

### TABLE 4
Effects of treatments on height and diameter of stem and root growth parameter of oil palm seedlings

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Height (cm)</th>
<th>Stem diameter (mm)</th>
<th>Root length cm/plant</th>
<th>Root surface area cm²/palm</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>131.05b</td>
<td>75.00d</td>
<td>18684b</td>
<td>3296.6c</td>
</tr>
<tr>
<td>T1</td>
<td>164.66a</td>
<td>82.10abc</td>
<td>21856a</td>
<td>3371.2bc</td>
</tr>
<tr>
<td>T2</td>
<td>161.57a</td>
<td>87.35a</td>
<td>23120a</td>
<td>3487.1bc</td>
</tr>
<tr>
<td>T3</td>
<td>166.01a</td>
<td>80.61bcd</td>
<td>22429a</td>
<td>3353.8c</td>
</tr>
<tr>
<td>T4</td>
<td>164.00a</td>
<td>84.40ab</td>
<td>21543a</td>
<td>3746.9ab</td>
</tr>
<tr>
<td>T5</td>
<td>172.83a</td>
<td>77.33cd</td>
<td>21924a</td>
<td>3936.4a</td>
</tr>
<tr>
<td>T6</td>
<td>163.83a</td>
<td>84.08ab</td>
<td>23615a</td>
<td>3650.9abc</td>
</tr>
</tbody>
</table>

Means followed by different letters within the same column are significantly different at p<0.05
*Source: Ayanda et al. (2020)*

### TABLE 5
Mg and Ca content in frond 3 of the oil palm seedlings

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Data from this study</th>
<th>Nutrient sufficiency level for oil palm*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium</td>
<td>0.29-0.45</td>
<td>0.30-0.42</td>
</tr>
<tr>
<td>Calcium</td>
<td>0.81-1.21</td>
<td>0.50-0.70</td>
</tr>
</tbody>
</table>

*Source: Ayanda et al. (2020)*
Relative height can be used as an indicator of oil palm seedling growth. The relative plant height (%) values were then calculated and subsequently plotted against exchangeable Ca in order to determine the critical level of exchangeable Ca to sustain oil palm growth (Figure 6). The critical level of exchangeable Ca value estimated in this way was 0.9 cmol$_c$/kg (value was taken at 90% relative plant height). This means that the topsoil exchangeable Ca of 0.64 cmol$_c$/kg observed in in plantations is insufficient for healthy oil palm growth. Oil palm agronomists are aware of this deficiency and that is why GML is applied. It has been known for a long time that Ultisols and Oxisols in Malaysia contain insufficient Ca and Mg to sustain crop production (Shamshuddin and Fauziah 2010; Shamshuddin et al. 2018).

As mentioned above, exchangeable Ca of more than 0.9 cmol$_c$/kg is rather uncommon for the Ultisols in Malaysia under continuous oil palm cultivation, as well as for the more weathered Oxisols endemic in the upland regions of the country. Note that about 70% of Malaysia is covered by these two soil orders. Therefore, exchangeable Ca level of the soil in the oil palm plantations has to be raised accordingly via agronomic means. Under normal circumstances, at this value of exchangeable Ca, soil pH would have been raised to above 5.

Stepwise regression analyses of soil pH, exchangeable calcium and exchangeable magnesium showed that a significant relationship exists between these variables and the height of oil palm seedlings, with $R^2$ equal to 0.9215 (Ayanda et al. 2020). This means that about 92% of the relationship can be explained by the regression line. Looking at plant height, it can be assumed that if soil pH, exchangeable Ca and exchangeable Mg are sufficiently increased, the growth of the oil palm seedlings would be significantly enhanced. It is believed that this can be done via the application of MRSG at appropriate rates and times.

Soil pH is found to be significantly correlated with height of oil palm seedlings (Figure 7). Stepwise regression analysis confirmed that soil pH is the most important factor contributing to the growth of oil palm seedlings in terms of height.
of height. This is consistent with the expected notion that oil palm growth is enhanced if soil pH is raised to a level above 5.

Stepwise regression analysis was also run on soil pH and exchangeable Ca and the correlation was found to be significantly positive. After MRSG application, exchangeable Ca in the soil was increased which in turn raised soil pH to the level dependent on the rate. This is another benefit of applying MRSG on highly weathered soils in Malaysia or even in the tropics where the pH is usually below 5.

We know that soil solution Al\(^{3+}\) will be precipitated as inert Al-hydroxides at a pH above 5 (Shamshuddin et al. 1991; Shamshuddin and Ismail 1995). For the topsoil of Jempol Series under investigation, even though the field soil pH was slightly below 5, the exchangeable Al was still high with a value of 1.41 cmol\(_c\)/kg. It follows that the increase in soil pH results in better growth of the oil palm seedlings under glasshouse conditions. The increase in soil pH after MRSG application was partly due to the addition of hydroxyl ions released by Mg and the presence of Ca hydroxides in it. The increase in soil pH was also promoted slightly by the reaction of some calcite, a liming agent found in MRSG.

**Field Trial Using MRSG to Sustain Oil Palm Growth and Production**

*Effects of treatments on soil properties*

Soil data in March 2016 (6 months after MRSG application) showed that there was no significant difference in exchangeable Mg or Ca between treatments over the period of the study (Table 6). Application of the MRSG on the soil produced results comparable to that of the kieserite in terms of supplying Mg to sustain oil palm growth. MRSG application also supplied Ca, which kieserite was unable to do so. Mg and Ca in the soil were sufficient for the healthy growth of the oil palm in the field due to MRSG application (Shamshuddin et al. 2017a).

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![Figure 7. Relationship between plant height and soil pH](source: Shamshuddin et al. (2017a))

\[
Y = 24.22x + 9.46 \\
R^2 = 0.89
\]
The respective soil pH at 12 and 18 months (Table 6) was 3.9 – 4.3 and 4.1 – 4.4, with no difference among treatments. It appeared to indicate a slight increase in soil pH with time. This can be regarded as an ameliorative impact of applying Ca containing MRSG on the soil. Any increase in soil pH resulting from MRSG application was partly due to: 1) The addition of hydroxyl ions released by Mg and Ca hydroxides present in it; and 2) By the reaction of calcite present in the MRSG. Continuous application of MRSG in the long run would possibly reduce soil acidity of the Ultisol even further. According to Auxtero and Shamsuddin (1991), the critical soil pH for healthy oil palm in Malaysia is 4.3 and in terms of pH consideration, this explains why oil palm plantations have been able to sustain growth and production. Based on the study of Shamshuddin et al. (1991), an increase in soil pH to a level above 5 would lower soil exchangeable Al, subsequent to which other nutrients will become more available in the soil for uptake by the oil palm.

The study further showed that after 18 months of experimental duration (Table 6), total soil C was 1.59–2.08%. Organic C in the soil was high, which was due to the proper soil/agronomic management in the field. Oil palm plantations in the country place cut fronds and empty fruit bunches in the inter-rows of the palms. When these materials are decomposed or mineralised, C and plant nutrients are returned to the soil, which eventually enhances soil fertility slightly. The CEC of the soil at 6 months of experimental duration was 9.59 – 14.43, while at 18 months it was observed to be 10.67 – 11.21 cmol/kg (Table 6) indicating that the CEC was within the range expected for a typical highly weathered Ultisol.

### TABLE 6
Effects of treatments on soil pH, exchangeable Mg, exchangeable Ca and CEC

<table>
<thead>
<tr>
<th>TR</th>
<th>Month 6</th>
<th>Month 12</th>
<th>Month 18</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pH</td>
<td>Mg</td>
<td>Ca</td>
</tr>
<tr>
<td>T0</td>
<td>- 0.46a</td>
<td>1.05a</td>
<td>9.59ab</td>
</tr>
<tr>
<td>T1</td>
<td>- 0.46a</td>
<td>1.03a</td>
<td>10.19a</td>
</tr>
<tr>
<td>T2</td>
<td>- 0.38a</td>
<td>1.15a</td>
<td>11.54a</td>
</tr>
<tr>
<td>T3</td>
<td>- 0.60a</td>
<td>1.52a</td>
<td>10.54a</td>
</tr>
<tr>
<td>T4</td>
<td>- 0.42a</td>
<td>0.98a</td>
<td>14.43a</td>
</tr>
</tbody>
</table>

Means followed by different letters within the same column are significantly different at $p \leq 0.05$

*Source: Shamshuddin et al. (2017); Ayanda et al. (2020)*
containing sufficient amounts of organic matter. Based on the afore-mentioned chemical attributes, the soil is in good condition for oil palm growth and/or production.

**Effects of treatments on oil palm growth and fruit bunch yield**

A significant difference was observed for Ca and Mg in frond 17 among treatments. The Ca and Mg level were within the sufficient range (NSR) for mature oil palm under production, based on the requirement levels proposed by Von Uexkull and Fairhurst (1991) and Fairhurst and Hardter (2003). The uptake of NPK by the oil palm was not significantly affected by the MRSG treatments indicating that MRSG application has a similar effect to that of kieserite or GML (control treatments) in terms of nutrient uptake. This finding shows that MRSG is as good as kieserite in terms of supplying Mg for the requirement of oil palm, although it may take a longer time to release the nutrient into the soil unlike in kieserite. MRSG is thus an excellent Mg-fertiliser as well as a source of Ca that is needed to sustain oil palm growth.

The Ca/Mg ratio in oil palm frond 17 of Malaysia is usually monitored by owners. The ratio in the leaves should be within 1.5-3.0 range (Fairhurst and Hardter 2003). Therefore, higher Ca is needed compared to that of the Mg to sustain oil palm growth/production. Note that the MRSG contains about 25% Ca and 5.5% Mg (Table 1). The respective Ca/Mg ratios for T0, T1, T2, T3 and T4 in this study were 2.4, 2.9, 2.9, 2.9 and 2.7. There was no Ca-Mg imbalance due to MRSG treatment. Thus, it can be assumed that treating the soil with MRSG or kieserite results in the same amount of Ca and Mg uptake by the oil palm.

The chemical composition of the oil palm tissue at month 6 showed no significant differences among treatments for all the parameters measured. However, Ca and Mg in the tissues were a bit lower than the sufficient range for normal oil palm growth. There was no significant difference in the number and weight of FFB among treatments. However, the means separation by month showed a significant yield increment towards the end of 2016. This is mainly due to the effect of increased rainfall occurring towards the end of the year (Shamshuddin *et al.* 2017a). This shows that oil palm requires adequate amounts of water for healthy growth and production of fruit bunches as mentioned by Corley and Tinker (2003).

A slight fluctuation in FFB harvested from January to August 2017 was observed between months. However, there were no significant differences in FFB yield between treatments for each month. This seems to indicate that T3 (MRSG treatment) produced higher FFB weight compared to that of the control treatments (T0 and T4) in January on MRSG application. It seemed to enhance growth of the oil palm leading to an increase in FFB weight. But it is admitted that this could be due to enhancement of soil fertility as shown by an increase in soil pH as well as Mg and/or Ca or it could even be due to the presence of extra micronutrients or essential elements (Table 2).
The FFB yield at month 18 showed no significant difference in FFB weight and number of fruitlets between MRSG and control treatments. MRSG treatment of Ultisols in the field gave comparable results to that of the kieserite in terms of weight of FFB and number of fruitlets in each fruit bunch.

Fruitlets for oil extraction rate (OER) were sampled about 2 years after the first MRSG application on the soil to ensure validity of the interpretation of the results obtained. The analysis of the OER showed no significant difference among treatments with values ranging from 16.3 to 22% (Table 7). The OER values due to MRSG treatments were comparable to those obtained by the commercial plantations in Malaysia. The data in Table 7 indicates that treating the Ultisol with MRSG produces higher OER compared to that of the kieserite or even GML. This is an important finding of the study.

As MRSG is a by-product of a chemical plant producing rare earth, it is much cheaper compared to GML. At present, the cost attached to it is due to the transportation of this material to the sites of application. Also, this by-product will be available in large quantities as long as the chemical plant producing rare earth in Malaysia is in operation.

The contribution of kieserite, GML and MRSG tested in the study towards the enhancement of soil fertility is summarised in Table 8. It is clear that MRSG is superior in terms of macronutrient and micronutrient supply to meet oil palm requirements compared to those provided by kieserite or GML. According to Shamshuddin and Ismail (1995), GML in Malaysia contains some Mn and Zn. Kieserite does not change soil pH, but both GML and MRSG do. MRSG contains S (which is required for oil production in the fruitlets); furthermore, it is cheaper than kieserite or GML. This being the case, as a fertiliser MRSG can be considered to be comparable or even better than kieserite (Table 8).

**TABLE 7**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Material</th>
<th>Rate (kg/palm)</th>
<th>OER (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>GML</td>
<td>1.25</td>
<td>16.3 a</td>
</tr>
<tr>
<td>T1</td>
<td>MRSG</td>
<td>1.10</td>
<td>17.1 a</td>
</tr>
<tr>
<td>T2</td>
<td>MRSG</td>
<td>1.45</td>
<td>22.0 a</td>
</tr>
<tr>
<td>T3</td>
<td>MRSG</td>
<td>2.40</td>
<td>18.6 a</td>
</tr>
<tr>
<td>T4</td>
<td>Kieserite</td>
<td>0.50</td>
<td>17.2 a</td>
</tr>
</tbody>
</table>

Means followed by different letters within the same column are significantly different at p<0.05

*Source: Shamshuddin et al. (2017a)*
TABLE 8
Key differences in chemical properties among tested fertilisers

<table>
<thead>
<tr>
<th>Fertiliser</th>
<th>Formula</th>
<th>Macronutrients</th>
<th>Micro/Essential nutrient</th>
<th>Change in pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kieserite</td>
<td>MgSO₄·H₂O</td>
<td>Mg, S</td>
<td>-</td>
<td>No change in pH</td>
</tr>
<tr>
<td>GML</td>
<td>Ca,Mg(CO₃)₂</td>
<td>Ca, Mg</td>
<td>Mn, Zn</td>
<td>Soil pH increase</td>
</tr>
<tr>
<td>MRSG</td>
<td>CaSO₄·2H₂O + Mg</td>
<td>Ca, Mg, S</td>
<td>Mn, Zn, Se</td>
<td>Soil pH increase</td>
</tr>
</tbody>
</table>

Source: Ayanda et al. (2020)

Effects of treatments on environment and palm oil quality
Abd Rahim et al. (2019) determined soil quality in the above-mentioned trial site using various indices. These were Biological Accumulation Coefficient (BAC), Geological Index (I-geo), Contamination Factor (CF) and Pollution Load Index (PLi). The results of the evaluation exercises showed that the BAC was low to moderate for As, Cd and Se, and was intensive for Zn. However, the intensive level obtained for Zn is probably not due to the result of applying MRSG as only a small amount of Zn was present in the MRSG used in the trial (Table 2).

Heavy metals and other elements of concern in the soil under investigation and surface water in the trial and surrounding areas were determined. The impact of applying MRSG on the surrounding environment using the data so obtained were also assessed by Abd Rahim et al. (2019) during the period of the field trial. The level of heavy metals present in the treated soil was lower than the values of the control soil. It is noted that there was no indication of an increase in heavy metal content in the soils treated with MRSG.

Further results of the assessment showed that the heavy metals contents and other elements of concern in the soil of the experimental plots were below the soil investigation level of Zarcinas et al. (2004) or the Eco-SSL of USEPA (2007). Heavy metals and other elements of concern in the surface water before and after MRSG application were below the bench mark value of the Ministry of Health Malaysia. Note that the drinking water standard of Malaysia is adopted from the World Health Organizations standard. The environmental risk analysis assessment by Abd. Rahim et al. (2019) shows clearly that the soil is not contaminated as evidenced by the low contamination factor with low pollution load index. This result indicates that MRSG is safe for application on agricultural land in Malaysia.

Heavy metal content and other elements of concern in the soil of the research plots in the study area were not affected by the application of MRSG, kieserite and GML, with no significant differences among treatments (Sahibin
et al., 2019). Both MRSG and kieserite treatments had produced comparable or similar results. This is good as MRSG can be promoted as Mg- and Ca-fertiliser.

The critical toxic concentration of La and Ce in soils throughout the world is unavailable at the moment. However, the mean concentration of the two rare earth elements in some common soils of Japan and China have been determined. The concentration in Japan is 18 and 40 mg/kg, while in the soils of China, it is 44 and 86 mg/kg (Sahibin et al., 2019). It is believed that their concentration in the soil under study due to MRSG application would not exceed the amount present in the soils of Japan or China. As for Sr in soils, no credible information is available in the literature.

The ultimate test on the impact of applying MRSG on soil cropped to oil palm is the quality of its oil. Palm oil quality was determined on oil palm fruitlets about 2 years after MRSG was first applied to ensure the credibility of the results (Shamshuddin et al. 2017a). The oil was analysed for the presence of common heavy metals (As, Cd, Pb, Zn, Mn, Ni, Cu and Fe) as well as the other metals of concern (Th, Cr and Hg). The latter could be harmful for human consumption, if present above the critical level.

The concentration of the said elements in the palm oil of the study was compared to those of the edible oils on sale at the marketplace. The results of the comparison did not show any indication of the accumulation of heavy metals and other elements of concern in the palm oil under investigation. It is also noted that the heavy metals found in the extracted oil were much lower than those found and/or reported by other researchers (Abd Rahim et al. 2019). Palm oil quality from palms grown on soil applied with MRSG is similar to that of oil from palms grown on soil applied with kieserite.

**SUSTAINING RICE PRODUCTION ON ACIDIC SOILS USING MRSG**

*Acidic Soils in the Kelantan Plains, Malaysia*

Some rice production in Malaysia is on soils with low pH, that is, the acid sulfate soils (Shamshuddin et al. 2014; Shamshuddin et al. 2017b). Hence, the rice plants are subjected not only to low pH stress, but also suffer from \(\text{Al}^{3+}\) and/or \(\text{Fe}^{2+}\) toxicity (Panhwar et al. 2014a; Panhwar et al. 2014b; Alia et al. 2017). Without alleviating the low pH stress as well as the toxicity caused by the two aforementioned acidic metals, rice yields have been < 2 t/ha/season in comparison to the national average of 4-5 t/ha/season. According to Elisa et al. (2014), using ground magnesium limestone as a liming agent to increase soil pH, rice yields comparable to that of the national average can be obtained. The soils could be further treated with GML in combination with a bio-fertiliser, fortified with beneficial microorganisms (Panhwar et al. 2014a). This agronomic practice has been tested by Panhwar et al. (2015) and Panhwar et al. (2016) on the acid sulfate soils in the Kelantan Plains, Malaysia.
The acid sulfate soils of the Kelantan Plains are notorious for being very acidic and containing high amounts of Fe (Shamshuddin 2006; Enio et al. 2011). On flooding the soils for rice cultivation, water in the fields would turn reddish in colour, indicating the presence of a high quantity of Fe (Figure 8). The pH of the water would be < 4 and the Al concentration would exceed the critical level of 20 µM. Note that the critical pH for the health growth of rice is 6 (Alia et al. 2015). The problem of soil acidity and Al$^{3+}$ and Fe$^{2+}$ toxicity in the area can be overcome by GML application. Based on the above discussion, we believe that the problem of soil acidity can be alleviated by MRSG application, albeit at a lower cost. On account of its proven ameliorative attributes, agronomists are now contemplating the use of MRSG to enhance rice production on the acid sulfate soils in the Muda Agricultural Development Authority (MADA), Kedah (Kedah-Perlis Plains). This area is regarded as the granary of the country as it is an important rice growing area.

Acidic Soils in the Kedah-Perlis Plains, Malaysia
Based on geological records, the Kedah-Perlis plains were once inundated by sea water when the sea level rose to its highest level some 4,300 years ago (Shamshuddin, 2017; Shamshuddin et al. 2017b). During that period of geological history, mineral pyrite (FeS$_2$) was formed and remained in the sediments where the MADA area is. That geological episode has left its fingerprint in affecting soil fertility negatively. During dry spells, the water table drops and exposes the pyrite which is subsequently oxidised to release acidity and toxic iron. The phenomenon has a negative impact on rice production in the long run. This seems to be the case in certain rice fields in Pendang, Kedah (under MADA’s jurisdiction). The

Figure 8. Rice fields in an acid sulfate area of the Kelantan Plains, Malaysia
Source: Shamshuddin (2006)
problem of high acidity and iron toxicity for rice production has to be rectified via agronomic means. Plans are underway to alleviate the low pH stress and Fe\(^{2+}\) toxicity of rice fields by using MRSG.

**USING MRSG FOR SUSTAINABLE RUBBER CULTIVATION**

It is reported that liming an acidic soil in Malaysia at a rate of 1 t GML/ha results in enhanced rubber growth (Shamshuddin and Fauziah 2010). This is probably due to the increased soil pH as well as additional Ca and Mg from the liming agent. The soil tested in the above study was an Oxisol at an advanced degree of weathering, known to have a low soil pH of <5 and insufficient Ca and Mg to sustain rubber growth (Shamshuddin et al. 2018). Due to liming, rubber in the research plots grew so fast that it could be tapped one year ahead of schedule. This indicates that liming using GML at specific rates helps improve rubber growth significantly. Latex flow was not in any way affected by GML application. The MRSG produced by Lynas Malaysia can be an important source of Ca and Mg for rubber requirement.

A glasshouse study is on-going in Malaysia to promote the use of MRSG to enhance the growth of rubber seedlings. However, the high Mg content in MRSG is a cause for concern when rubber trees in plantations mature and are ready for tapping. The subject of debate among rubber planters in the country for a long time is that the presence of high Mg in the mature rubber trees might have an adverse effect on latex flow. Latex tends to coagulate if Mg concentration is present above a certain critical level, which has yet to be determined. It is one of the objectives of the study to determine the said critical concentration of Mg in the trees so that latex flow after tapping is not curtailed via coagulation. Research is being carried out to determine the critical rate of MRSG application in the field. This is to ensure that rubber roots only take up the required amount of Mg present in the soil for growth and latex production. Notwithstanding this concern, Mg is a macronutrient that is needed in sufficient quantities to sustain rubber growth and/or latex production.

Despite this reservation, MRSG can be an alternative source of Ca and Mg for the rubber tree to sustain growth, just like it does for oil palm (Ayanda et al. 2020). Applying MRSG would raise soil pH to the level required for positive rubber growth in the long run. The research hopes to identify a suitable rate of MRSG application that helps enhance rubber growth, yet is able to sustain latex flow at the expected level. The ultimate aim is to extend the results of the glasshouse study to rubber cultivation in the plantations.

**USING MRSG TO SUSTAIN AGRICULTURE IN SOUTHEAST ASIA**

Based on the results of our review, we have come to the conclusion that MRSG has a great potential as Mg- and/or Ca-fertiliser to sustain the production of oil palm, rubber and rice planted on soils under tropical environment. The countries in Southeast Asia have almost similar soil types – Ultisols, Oxisols, Inceptisols
and Entisols. The first 2 soil orders are cropped to oil palm and rubber. Many of the soils in the last 2 soil orders belong to acid sulfate soils where rice is grown. Beside Malaysia, other Southeast Asian countries producing the crops mentioned above include Indonesia, Thailand, Vietnam and the Philippines (Shamshuddin 2006; Shamshuddin et al. 2014). MRSG can be promoted to these countries for sustainable production of the crops.

In Indonesia, it is almost certain that most of the oil palm and rubber are grown on the highly weathered soils of Sumatra and Kalimantan (Shamshuddin et al. 2018). The soils planted with these crops are similar in their physico-chemical properties to those of Malaysia. On the other hand, Anda et al. (2009) mention in their study that rice is grown in some areas with mixed success on the acid sulfate soils of Kalimantan, not far from Banjarmasin, Indonesia.

The acid sulfate soils in the Bangkok Plains (Thailand), Mekong Delta (Vietnam) or in some islands of the Philippines are in dire need of alleviation of soil acidity as well as Al\(^{3+}\) or Fe\(^{2+}\) toxicity to sustain rice production (Shamshuddin et al. 2014). Liming materials at these places can be costly or even unavailable. Thus, the problem facing rice production can be alleviated via the application of MRSG at a reasonable cost for the farmer.

**CONCLUSION**

Our studies show that application of Mg-rich synthetic gypsum on land supplies sufficient amounts of Ca and Mg to highly weathered soils lacking these macronutrients, with a concomitant increase in soil pH that enhances oil palm and rubber growth. Also, of equal importance, our study shows that land application of MRSG does not result in environmental degradation. For oil palm plantations in the tropics, application of MRSG provides the necessary S for oil production in the fruitlets. We also know that rice production on acid sulfate soils in Southeast Asia is often limited by low pH stress and Al\(^{3+}\) and/or Fe\(^{2+}\) toxicity. These agronomic problems can be alleviated cheaply and/or effectively via the application of MRSG at suitable rates and times.

To sustain agricultural production in the long run, MRSG, a cheap chemical plant waste produced in Malaysia offers a viable alternative to GML and kieserite which are imported. We know that MRSG is available in large quantities in the country (Malaysia) and is more cost effective than that of the GML. In turning to MRSG, the nation’s fertiliser import could be reduced, yet agricultural productivity is expected to be sustained. This effectively translates into increased farmers’ income and foreign exchange savings.

**ACKNOWLEDGEMENTS**

The authors would like to acknowledge the financial and technical support provided by Lynas Malaysia Sdn Bhd and Universiti Putra Malaysia without which it would not have been possible to obtain adequate data for this paper.
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