



Shear strength and root length density analyses of Entisols treated with palm oil mill effluent sludge

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Abstract

*The underutilized and improper management of wastewater such as palm oil mill effluent sludge (POME) sludge might create pollution and give a negative impact towards the environment. This study was aimed to evaluate the effect of shear strength parameter and root length density of maize on Entisols applied with POME sludge as a soil amendment. The maize was planted on Rasau soil series (Entisols) amended with different POME sludge treatment systems from various ponds (mixing, anaerobic, facultative, algae, and dumping). Standard direct shear box test was used to identify the cohesion (c) and angle of internal friction (ϕ) after application of treatments. The bulk density, porosity, moisture content, organic matter, root length and root density of *Zea mays* L. (Hibrimas) applied with POME sludge from dumping pond (DP), aglae pond (ALP) and facultative pond (FP) were significantly difference against the control treatment. The positive effect of root length and root length density (RLD) treated with POME sludge from the dumping pond was 26% and 38% compared to the other treatments. The results highlighted that roots enhanced soil shear strength by reducing the cohesion and increased the angle of internal friction component. The shear strength analysis showed that high shear strength of normal stress at 500.72 kN/m² was measured from the dumping pond's POME sludge treatment after maize harvesting. The POME sludge from the DP, ALP and FP was ameliorating some nutrients deficiencies for the plant growth and improved the root length density. In conclusion, the POME sludge from the DP indicated the high shear strength and root length densitie due to the adequate nutrients for roots distribution and maize growth.*

Keywords: Shear strength, root length density, Entisols, POME sludge

Introduction

Maintaining and replenishing organic matter into the soil is important to sustain the productivity of the soil in the tropical climate. Generally, Malaysia had produced about half of organic waste from oil palm industry, which has not been fully utilized. According to Embrandiri *et al.*, (2013) palm oil mill effluent (POME), palm kernel cake, decanter cake, empty fruit bunch and palm kernel shell were potential to be processed and used as an organic matter amendment for land application. Recently, some studies were using decanter cake with lady's finger (Embrandiri *et al.*, 2013), tannery sludge with capsicum plants (Silva *et al.*, 2010), cowpea (Silva *et al.*, 2013) and olive mill waste with lettuce and chicory (Kelepesi and Tzortzakis, 2009) as their organic matter materials for soil amendment. Unfortunately, only a few studies were focused on POME sludge as a soil amendment for the plant growth. According to Khairuddin *et al.*, (2016), the treated POME sludge was identified equally balance with C, N, and macronutrients (P, K, Ca,

Mg, S, Na). Mostly, these elements were vital for soil improvement and productivity of the crops. Moreover, heavy metal content in POME sludge was in accordance with the standard from WHO/FAO that is safe for human consumption.

The influence of soil physical condition on plant growth associated with agricultural practices has been emphasized and preferably more on the roots against the stability of the soil. Climate also played an important role in influencing the physiological aspect of plant establishment such as roots (Terzaghi and Peck, 1967). The roots reinforced the soil through the mechanical and hydrological mechanism and also stabilized the soil water content from exceeding the field capacity (FC) (Normaniza and Barakbah, 2006). Root absorbs and circulates water to the atmosphere rather than percolating deep into the soil profile. Plant roots play an important role in resisting the shallow landslip and topsoil erosion of slopes by raising soil shear strength. The method to determine the soil

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strength was obtained using the direct shear test analysis. Shear strength of a soil mass is the internal resistance per unit area that the soil mass can offer to resist failure and slide along any plane inside it. The presence of roots would result in an overall increase of the soil strength. This arises from the combined effects of soil reinforcement by a mass of roots (Mohamad Nordin *et al.*, 2011) and soil moisture depletion by evapotranspiration (Ali and Osman, 2008). Other factors, which affect the soil strength was soil moisture content, particle size distribution (soil texture), and the mineralogical content of the different soil series.

The shear strength of the soil was a measure of its cohesiveness and resistance to shearing forces exerted by gravity, moving fluids and mechanical loads. Its strength was derived from the frictional resistance met by soil constituent particles when they were forced to slide over one another or to move out of interlocking positions, the extent to which stresses or forces were absorbed by solid-to-solid contact among the particles, cohesive forces related to chemical bonding of clay minerals, and surface tension forces within the moisture films in unsaturated soils. The objectives of this study were to determine the effect of root length density and shear strength of Entisols amended with palm oil mill effluent (POME) sludge.

Materials and Methods

Study site

The field experiment is located at Research Farm in the Universiti Teknologi MARA Pahang, Jengka Campus, Pahang, Malaysia (3.7562 °N, 102.5611 °E) for a period of Feb 2015 until June 2016. It was a tropical climate with the average temperature of 31°C, rainfall at 2300 mm per annum and relative humidity was 60-80%. The POME sludge samples were taken from palm oil mill, Felda Jengka 8, Bandar Tun Abdul Razak Jengka, Pahang, Malaysia from the treatment ponds system; mixing (MP), anaerobic (ANP), facultative (FP), algae (ALP), and dumping pond (DP)). POME treatment system was differentiated based on the Hydraulic Retention Time (HRT): cooling ponds (1 day), mixing ponds (2 days), anaerobic ponds (45 days), facultative ponds (20 days), algae ponds (7 days) and dumping pond (more than 6 months) after discharged from palm oil mill. The hydraulic retention time (HRT) was also reflected to the decomposition rate and characteristics of the POME sludge. According to Khairuddin *et al.*, (2016), millions of tonnes of POME sludge was discharged into the dumping pond for maintenance purposes. Figure 1 shows the POME sludge samples collected from the treatment ponds. Physically, they were blackish, textured and smelly. The DP sludge (A) was blackish in color and less smelly. Furthermore, less moisture and dark brownish color was

shown in ALP sludge (B), ANP sludge (C), and FP sludge (D). Lastly, POME sludge from MP sludge (E) was shown to be oily and of dark yellowish color compared to the other sludge.

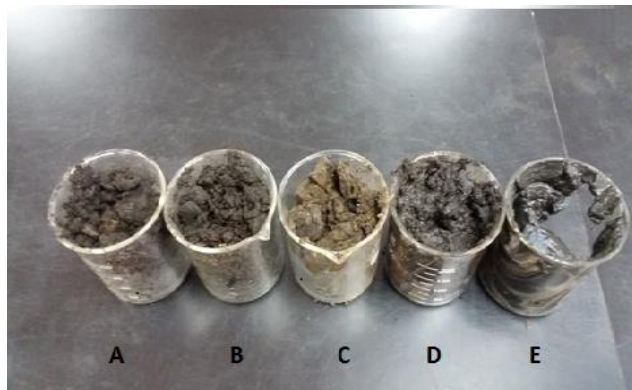


Figure 1: The POME sludge samples from DP (A), ALP (B), FP (C), ANP (D), and MP (E)

Experimental design

The experiment was set-up in the field using polybags in randomized completely block design (RCBD) with three replications. Maize was planted in the polybags of 16 cm X 20 cm. The different POME sludge from mixing, cooling, anaerobic, facultative, algae and dumping ponds were used as soil amendment. 30% of w/w of POME sludge was applied and uniformly mixed with soil for each of the treatment. Rasau soil series (Entisols) was selected due to deficient organic matter content, pH, CEC and a characteristic of weakly developed profiles. In this study, *a Zea may L. (Hibridmas variety)* was planted to investigate the root growth performance. POME sludge was applied once and mixed with Rasau soil for each polybag. Drip irrigation system was used for watering the maize twice a day per plant. The maize was harvested after 75 days of planting (DAP).

Selected soil physicochemical properties

Soil and POME sludge samples were analyzed for selected soil physicochemical properties (bulk density, soil porosity, moisture content and organic matter). The bulk density (Eqn. 1) was measured using a core method (Blake and Hartge, 1986). Indeed, the sample was also used to determine the field moisture content (Eqn. 2) (Teh and Talib, 2006). Usually, the measurement of bulk density and moisture content allows total porosity (Eqn. 3) (Teh and Talib, 2006) to be measured, respectively. Organic matter in the soil was determined using CNS analyzer (LECO CNS-2000) (Kowalenko, 2001) as under: Bulk density p_b ($g\ cm^{-3}$) was measured



$$P_b = \frac{W_b - W_r}{\frac{\pi h d^2}{4}} \quad (1)$$

Where W_b is the soil and core after oven-drying (g); W_r is the weight of the core ring (g); h is the core ring height or depth (cm); and d is the core ring diameter (cm)

Soil water content q_w , expressed on a dry mass basis;

$$\theta_w = \frac{W_a - W_b}{W_b - W_r} \quad (2)$$

where W_a is the weight of the soil and core ring before oven-drying (g)

Soil porosity e ;

$$e = 1 - \frac{P_b}{P_p} \quad (3)$$

where p_p is the particle density (g cm^{-3}). For most mineral soils, particle density is 2.65 g cm^{-3}

Shear strength analysis

Soil shear strength or shear stress at failure was determined by the direct shear box test (Head, 1982). Briefly, 25-cm thick intact soil samples (20 cm x 20 cm x 100 cm) were cut at 25-cm intervals in each wooden box and the edges carefully trimmed. The sample was packed in a metal shear box following the procedure described by (Head, 1982). The sample was then placed in the shear box. Half of the shear box was carefully separated using spacing screws to set a gap slightly larger than the largest soil grains present. Clamping the loading head in place using the setscrews was done for that purpose and then the separation screws were taken out. The normal load needs to reflect the applied vertical load plus the weight of the load block and top half of shear box. Shear deformation dial gauge was attached and both vertical and horizontal gauges were set to zero. The angle of internal friction was determined by placing the soil in a rigid metal box, square in plan, consisting of two horizontal halves. During the shearing process, the relative displacement of the two portions of the specimen and the applied shearing force were both measured so that a load/displacement curve could be plotted. The vertical movement of the top surface of the specimen, which indicates changes in volume, was also measured and enabled changes in density and void ratio to be determined during shear. This shear box test was the standard quick test carried out in a 60 mm square shear box, which has been the most common size used in the UK and the USA (Head, 1982).

Horizontal (shear) loading was then started and readings of horizontal load shear displacement, and vertical (volume-change) displacements were taken. The speed of

0.025 mm/min was used at regular intervals (every 30 seconds), readings of the load dial, the vertical movement dial and the time were recorded. Normal stress of 100 kN m^{-2} , 200 kN m^{-2} and 300 kN m^{-2} were used for every layer of the soil profile samples. Shearing was continued until the maximum stress or peak point has been clearly defined, that is until at least four consecutive readings indicate a decrease or equal to load. If a peak was not observed, shearing should continue until the full length of travel of the box had been reached. A set of three specimens was usual but additional specimens were tested when required. A plot of the Mohr-Coulomb failure envelope is used to determine the shear parameters; cohesion (c) and internal angle of friction (ϕ) as outlined in Section 3 (Head, 1982). Given the linear relationship between shear strength, and c and ϕ , evaluation of roots of shear properties was limited to shear strength. The coulomb envelope was the relationship between maximum shear stress related to normal stress from shear box tests (Tan, 2003). In soil, for practical purposes, this linear relationship holds good and it represents the most widely accepted criterion of failure. The shear stress at failure, τ_f , against the corresponding normal stress, σ_n , for each specimen was plotted. This line is the failure envelope or the Coulomb envelope. The angle of inclination ϕ of the failure envelope to the horizontal axis was measured to the nearest $\frac{1}{2}^\circ$. The cohesion intercept c (kN m^{-2}) on the vertical axis was identified after the graph has been plotted (Head, 1982).

Shear strength is a key determinant of slope stability and soil detachment during erosion processes. Therefore, the current study used the Mohr-Coulomb failure criterion as a framework for evaluating the effect of nutrient and lime application on root-induced shear strength properties. According to the limit equilibrium theory, the safety factor (F_s) is used to evaluate slope stability and soil susceptibility to detachment. F_s is the ratio of stresses resisting failure to the stresses required to bring the slope into a state of limiting equilibrium along a given failure surface (Eqn. 4) (Ali and Osman, 2008).

$$F_s = \frac{s}{\tau} \quad (4)$$

where s is the shear strength of the soil and τ is shear stress acting along the failure surface. According to the Mohr-Coulomb (1776, 1900) failure criterion, the total shear strength or shear stress of earth material at failure consists of cohesion and friction components (Eqn. 5) (Morgan, 1996):

$$s = c + \sigma_n \tan \phi \quad (5)$$

where s is a shear strength or shear stress at failure (kN m^{-2}), c is cohesion (kN m^{-2}), σ_n is the total stress normal to the

shear plane (kN m^{-2}), and ϕ and $\tan\phi$ are the angle and coefficient of internal friction of the material, respectively. Roots permeated earth materials behave like composite materials, in which elastic roots of high tensile strength are embedded in a relatively elastic soil matrix. Overall, roots contribute additional apparent cohesion (c_r), but have negligible influence on the frictional component of soil shear strength. Slope failures are associated with saturated conditions and excessive build-up of pore-water pressure (Abernethy and Rutherford, 2000). When pore water pressure is significant, the total normal stress (σ_n) is replaced by effective stress ($\sigma_n - \mu$) [11]. Accounting for the effects of both roots and pore-water pressure on shear strength (s) yields (Eqn. 6) (Ali and Osman, 2008):

$$s = c' + c_r + (\sigma_n - \mu)\tan\phi' \quad (6)$$

where, c' and ϕ' denotes effective stress parameters

Root length density

Root data were collected from a field site. After that, the root was separated from the soil by vigorously rinsing at low pressure with water out of the polybags. The roots were extracted, cleaned and spreading it on a plate. The roots were scanned for root length density using root scanner analysis (WinRhizo Pro, Régent Instruments, Québec, Canada) (Shang *et al.*, 2016). Root length density (RLD) was calculated in each core as the total root length divided by the volume of each core (calculated as a cylinder). A total of root length, the volume of the root, and an average diameter of the roots are important characteristics to be considered when describing and comparing the roots system.

Statistical analysis

A statistical analysis was conducted using SAS 9.4 statistical package (SAS, 2007). Analysis of variance (ANOVA) was done to test the treatments effect while means separation was used using LSD test at $P \leq 0.05$.

Results and Discussion

Selected soil physicochemical properties

The soil amended with different POME sludge (mixing, cooling, anaerobic, and facultative, algae and dumping ponds) was analyzed to determine the bulk density, porosity, moisture content and organic matter content. Figure 2 shows a significant difference of POME sludge's bulk density from the different treatment ponds. In general, the highest bulk density for each treatment was control (C) (1.44 g cm^{-3}), MP (1.27 g cm^{-3}), ANP (1.26 g

cm^{-3}), FP (1.22 g cm^{-3}), and ALP (1.19 g cm^{-3}). The lowest bulk density was in DP treatment (1.02 g cm^{-3}). The bulk density showed that there was significant difference between control and DP treatments. However, there was no significant difference in ANP, FP, and ALP. This trend may be attributed to the high value of organic matter content in the POME sludge as compared to the control (Figure 2). According to USDA (2008), loose soil, porous, and high organic matter content correlated to low bulk density. Moreover, Khaleel *et al.*, (1981) clarified that the effect of organic matter on bulk density of soil was similar with the finding in this experiment. Soil bulk density is a basic soil property that correlates to soil compaction, which is influenced by soil physical and chemical characteristics such as soil texture, the amount of organic matter in the soil, constituent of minerals, and porosity (Chaudhari *et al.*, 2013).

The soil porosity result was presented in Figure 2. Porosity increased significantly in C (45%) and DP (61%), respectively, whereas no significant difference was reported in MP (52%), ANP (52%), FP (53%) and ALP (54%). Therefore, a POME sludge treatment with low bulk density was correlated to high soil porosity. The increase of soil porosity might reduce the soil compaction and improve the soil structure. According to Pagliai *et al.*, (1993), a soil structure might improve with the increases of soil porosity. Soil porosity is formed due to the penetration and movement of roots and soil organisms. The roots and soil organisms create more pores for soil aeration and water storage in the soil. High bulk density correlated to low volume of porosity which depends on soil texture and structure (Kumari *et al.*, 2014). Water can be held tighter in smaller pores than in large ones, so fine soils can hold more water than the coarse soils (Ball, 2001).

The moisture content characteristics of soil treated with POME sludge are presented in Figure 2. The DP sample was the highest (16.44%) followed by ALP (14.81%), FP (13.40%) and the lowest was control treatment (11.01%). However, there was no significant difference between ANP (13.48%) and MP (12.68%). This might indicate that moisture content of the soil was contributed by the organic matter content. Using POME sludge from DP, ALP and FP recorded high organic matter content that may be attributed to the water-holding capacity of the soil. According to Bláhová *et al.*, (2013), water can act as binding agent among the soil and with organic matter, it may influence the structural stability and strength of the soil.

The organic matter of the POME sludge in DP treatment was 2.68%, whereas for ALP, FP, ANP and MP were 2.65, 2.32, 2.32 and 2.01% reduction in each treatment as compared to the control (1.15%). Figure 2



shows that there was significant difference between the DP, MP and the control treatment, respectively. POME sludge increased organic matter content, decreased the bulk density and provided more nutrients to the soil. According to Pascual, *et al.*, (1997), organic amendments showed a greater effect in decreasing the C: N ratio. Hao *et al.*, (2008), stated that the application of organic amendments generally elevates the soil organic matter and microbial biomass contents to a much greater extent. Therefore, it was proven in this study that all the POME sludge treatments contain high organic matter compared to the control treatment. Indirectly, it could also assist in producing high yield as well as better growth of the plant.

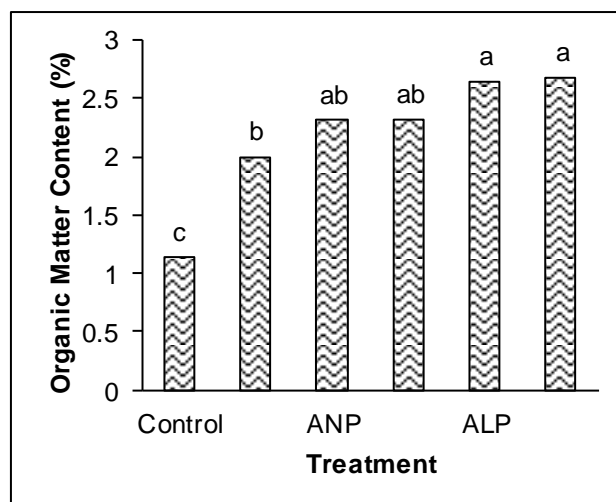
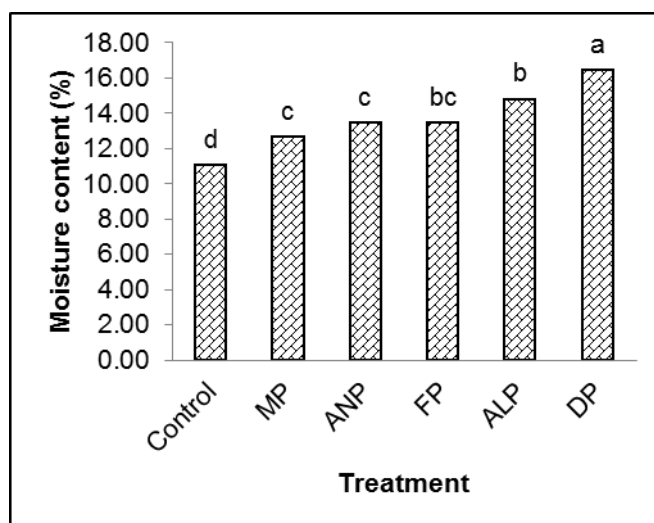
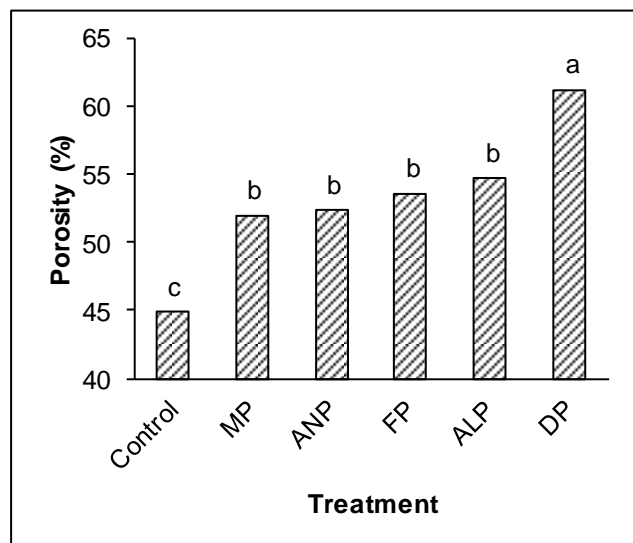
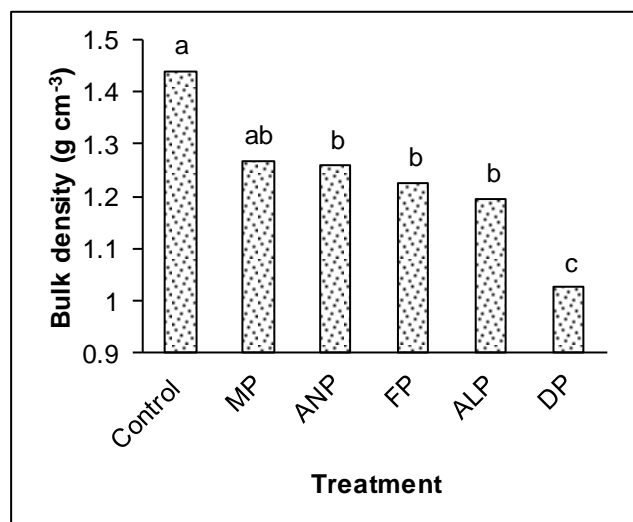


Figure 2: Bulk density, soil porosity, soil moisture and organic matter in different POME sludge treatments (Means with the same letter are not significantly different at $p < 0.05$)

Root length density

Root length density measurement of DP ($334.16 \text{ cm cm}^{-3}$) and control (75.53 cm cm^{-3}), showed significant difference compared to ALP ($271.70 \text{ cm cm}^{-3}$), FP ($258.24 \text{ cm cm}^{-3}$), ANP ($203.02 \text{ cm cm}^{-3}$) and MP ($143.69 \text{ cm cm}^{-3}$) (Figure 3). Based on this study, similar results were reported that the increases in root length density through nitrogen uptake efficiency strictly related to nitrogen uptake characteristics of the root system and the availability of nitrogen, carbohydrate and nitrate in the rhizosphere (Henry and Raper, 1991; Scholberg *et al.*, 2002; Zotarelli *et al.*,

2008) Moreover, the root length density growth was increased during maize growth due to continuous deposition of organic matter, fertilization, cultivation (Marschner, 2011), demand of mineral nutrient (Peng *et al.*, 2012) and closely related to soil moisture absorption (Kashiwagi *et al.*, 2006). Consequently, the greater addition of mineral nutrients and high yields were related with greater total root length at maturity (Ning *et al.*, 2015). In addition, the major reason for differences in root growth in each POME sludge treatments may be associated to the the nitrogen mineralization rate (Bilalis *et al.*, 2010). This study had proven that adequate amount of nutrients present in the different POME sludge treatments might increase the maize growth performance and root length density (RLD). Peng *et al.*, (2012) reported that about 50% loss of maize root length occurred during root washing. The actual root length in the soil should be much higher than those shows in Figure 3.

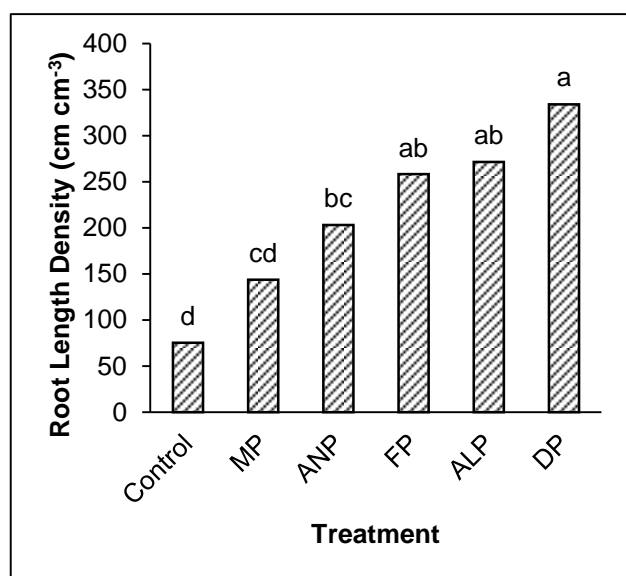


Figure 3: Effect of treatments on root length density (Means with the same letter are not significantly different at $p < 0.05$)

Shear strength parameter

Figure 4 shows the results of shear strength from the different POME sludge treatments. The analyzed data indicates that there was significant different of shear strength ($p < 0.05$) compared to all the treatments. The shear strength in the DP treatment (500.72 kN m^{-2}), ALP (464.14 kN m^{-2}), FP (462.83 kN m^{-2}), ANP (454.39 kN m^{-2}) and MP (449.67 kN m^{-2}). The control treatment (422.95 kN m^{-2}) showed the lowest result of shear strength. Shear strength results were correlated to the moisture content and organic

matter factor. Hence, was highly affected by the clay material in the soil (Bláhová *et al.*, 2013). The water content in the soil also correlated with organic matter in the soil profile. Organic matter increased the water holding capacity (WHC) at the optimum level (Bot and Benites, 2005). Organic matter also improved the quality of water infiltration and retention capacity of the soil and contributed to the availability of nutrients for plant uptake.

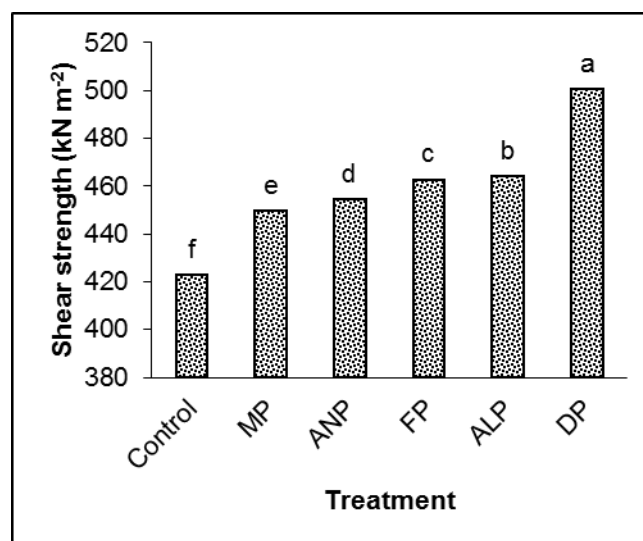


Figure 4: Effect of shear strength in the different POME sludge treatments (Means with the same letter are not significantly different at $p < 0.05$)

Roots shear strength

Data in Figure 5 indicated the results of six different treatments on the effect of roots reinforcement towards the shear strength. The maize treated with DP treatment was significantly different on shear strength analysis and root length density (RLD) (Figure 3 and Figure 4). The high densities of plant roots in this treatment enhanced better anchorage and provided better aggregates stability to the Entisols. Generally, the graph showed that the shear strength was obtained after the application of normal stress at 100 kN m^{-2} , 200 kN m^{-2} and 300 kN m^{-2} in all samples. The peak strength or shear strength was plotted for different POME sludge that was used in the soil as treatment. Relatively, the DP treatment was low cohesion, c , while the angle of internal friction, ϕ , increased and the shear stress at failure was obtained from the shear strength equation. The maximum shear strength in DP treatment was 500.72 kN m^{-2} , ϕ was 30° and the root density was observed at 334.16 g m^{-3} (Table 1). The treatment with high root density in ALP with 271.7 g m^{-3} showed the decrease of cohesion value to 135 and ϕ value was slightly increased. The maize treated with DP treatment indicated high shear strength compared to all the treatments (Figure 5). The result had shown that



Table 1: Soil and POME sludge treatment indicated root density and shear strength parameter of Entisols.

Treatment	Root density (cm cm ⁻³)	Cohesion (c)	Angle of Internal Friction (ϕ)	Shear strength(kN m ⁻²) (τ)
Control	75.53	140	25 ⁰	422.95
MP	143.69	135	26 ⁰	449.67
ANP	203.02	130	27 ⁰	454.39
FP	258.24	120	28 ⁰	462.83
ALP	271.7	100	29 ⁰	464.14
DP	334.16	80	30 ⁰	500.72

the presence of high root density might increase the shear strength of Entisols. Ali and Osman (2008) reported that roots system and roots density increased the shear strength of the soil. The cohesion value in control treatment was slightly lower than the other treatments. While the cohesion value (c) was low, the ϕ value tends to increase.

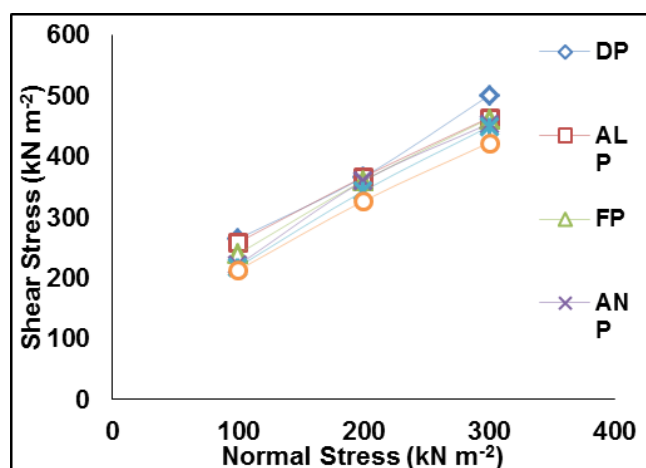


Figure 5: Relationship of shear stress and normal stress for POME sludge treatment (control, MP, ANP, FP, ALP and DP)

The relationship of shear strength and moisture content

The analyses of linear correlation showed that there was a positive correlation between shear strength (kN m⁻²) and moisture content (%) from each of the treatments (Figure 6). The application of POME sludge was able to reduce the bulk density and improve fertility status of Entisols. In addition, increase of water content also correlated to the volume of pore distribution in the soil. The POME sludge treatment significantly increased water holding capacity of the soil. Bláhová *et al.*, (2013) reported that shear strength of soils is highly affected by moisture conditions. Soil texture also contributes to the increase of

water content especially if the soil contains high clay materials. In this experiment, Entisols contained 13% of clay. Increased clay contents in the soil can improve the plasticity (Bingjian, *et al.*, 2013). Nevertheless, relationships derived from this study also indicated similar results that higher the shear strength, the greater the influence of moisture content on the values of the angle of internal friction and cohesion (Zydrón and Dqbrowska, 2012).

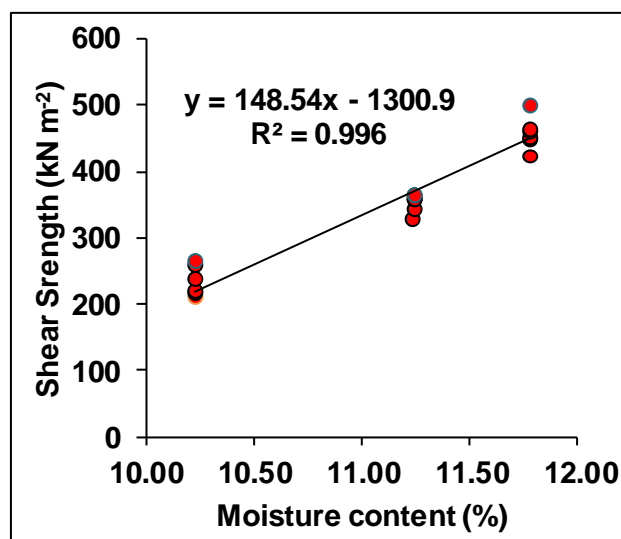


Figure 6: Correlation between shear strength (kN m⁻²) and moisture content (%)

The relationship of shear strength and root length density

Figure 7 shows the significant effect or positive correlations between shear strength (kN m⁻²) and root length density (cm cm⁻³). The highly significant correlation was identified in all the treatments ($R^2 = 0.9615$). Effects of the treatments with high organic matter; FP, ALP and DP sludge was able to improve the soil physical properties and

increased soil water holding capacity which highly benefited for roots plant uptake (Isa *et al.*, 2017). In addition, roots absorbed water and enabled the plant to maintain its turgidity. Furthermore, soils with high organic matter content and cation exchange capacity (CEC) cause mineral elements in soil to be transferred or absorbed by the roots, especially potassium (K) (Jones and Jacobsen, 2005).

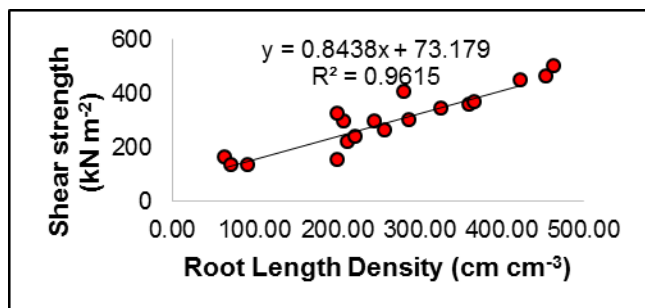


Figure 7: Correlation between shear strength (kN m^{-2}) and root length density (cm cm^{-3}).

Conclusion

The maize production treated with POME sludge from the dumping pond (DP) was the best soil amendment in this studies which was capable to increase the soil shear strength with low cohesion and high angle of internal friction contributed by the root densities and roots elongation. It was obviously shown that the appropriate and suitable organic amendment might increase roots reinforcement and shear strength of the Entisols. Furthermore, POME sludge amendment significantly affects the bulk density, soil compaction, increased porosity and organic matter content of the soil.

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