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EFFECTS OF BIOCHAR FROM OIL PALM BIOMASS ON SOIL PROPERTIES AND GROWTH PERFORMANCE OF OIL PALM SEEDLINGS

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Abstract: Fertilizer is the most expensive input in oil palm cultivation. Biochar can be used to improve the nutrient use efficiency, reducing the cost of fertilizer. Application of biochar from oil palm biomass onto oil palms has been scarcely studied. This paper reports the effects of empty fruit bunch (EFB) and palm kernel shell (PKS) biochar on the soil properties and growth performance of oil palm seedlings. The EFB and PKS biochar used were slightly acidic to neutral (pH 6.08 – 7.10) with the former exhibiting well-defined macropores. The seedlings ameliorated with EFB biochar demonstrated improved plant height and biomass with increasing biochar dosage. Marked improvements in uptake of phosphorus, magnesium, calcium and boron were also observed in the palm seedlings treated with EFB biochar. This was associated with the enhanced soil cation exchange capacity (CEC) upon biochar treatment. These positive effects of EFB biochar on plants and soil however were not recorded in the treatment with PKS biochar as the biochar was characterized with marginal porous structures and poor CEC properties. The study concluded that the stimulatory effects of EFB biochar on soil properties and plant growth were primarily governed by the biochar morphology and its cation exchange properties.

Keywords: Empty fruit bunch, palm kernel shell, field study, physico-chemical properties, nutrient uptake.

Introduction

Oil palms are mostly planted on highly weathered tropical soils (e.g., Ultisols, Oxisols) in Malaysia. These soils are naturally low in fertility, (Goh *et al.,* 2003) hence, fertilizers are required to ensure sufficient nutrients to maintain crop yield. Fertilizers are the costliest input in oil palm plantations, constituting 46-85% of field expenditure (Sabri, 2009; Silalertruksa *et al.,* 2012). For this reason, any form of fertilizer loss is not only significant, but it could also adversely impact the environment, causing water pollution and greenhouse gas emissions. The nutrients applied can be discharged to the environment *via* leaching, runoff, erosion and gaseous emissions. Among these, the largest fluxes are attributed to ammonia (NH_3) volatilization (0.1-42%) and nitrate (NO_3^-) leaching (1-34%) (Pardon *et al.,* 2016). It is of utmost importance for oil palm operators to optimize nutrient use to reduce wastage and environmental impacts from the nutrient loss.

Application of biochar, a carbon-rich material produced from biomass under reducing thermal decomposition, offers an environmentally friendly alternative to increase nutrient bioavailability. The positive effects of biochar in maintaining soil moisture, increasing soil pH and improving nutrient retention have been extensively reported (Laird *et al.,* 2010; Novak *et al.,* 2012; Shen *et al.,* 2016). Its capacity to suppress soil nitrification and denitrification has also been demonstrated (Taghizadeh-Toosi *et al.,* 2012; Clough *et al.,* 2013). The biochar pore structures and surfaces shelter microorganisms, offering them abundant sources of carbon, energy and nutrients (Warnock *et al.,* 2007; Quilliam *et al.,* 2013a).

Approximately 85.5% of agricultural residue in Malaysia originates from oil palm plantations; this includes oil palm trunk, mesocarp fibre, oil palm fronds, empty fruit bunches (EFB) and palm kernel shells (PKS) (Sumathi *et al.,* 2008; Awalludin *et al.,* 2015). Over the years, oil palm solid waste continues to increase in tandem with palm oil production. This leftover biomass has yet to be fully utilized. Conversion of oil palm biomass into biochar is a promising waste-to-wealth strategy that contributes to the sustainable production of palm oil and is environmentally friendly. The beneficial impacts of biochar from various feedstock have been widely studied, however, research on the potential of biochar derived from oil palm biomass is rather scarce (Radin *et al.,* 2018). The objectives of this paper are: (1) to determine the characteristics of biochar produced from EFB and PKS and (2) to evaluate the growth performance, soil characteristics and nutrient uptake of oil palm seedlings treated with and without biochar. The findings from this study will provide insights into the potential of biochar derived from oil palm biomass in enhancing soil properties and improving oil palm growth. The positive effects would lead to improved nutrient use efficiency and reduce fertilizer input of plantations.

Materials and Methods

Biochar Samples

Biochar from EFB and PKS were produced by the Malaysian Palm Oil Board (MPOB), Bangi, Selangor. The EFB and PKS were obtained from Ulu Kanchong Palm Oil Mill, Negeri Sembilan, Malaysia. The raw EFB was pressed-shredded to 100-150 mm and PKS was sun dried until its moisture fell below 10% prior to the carbonization process (Nahrul *et al.,* 2017). Approximately 30 kg of feedstock was fed into a closed-system brick kiln reactor, which was fixed with an air suction blower that provides air flow of 36 m^3/hr to ensure uniform circulation and distribution of hot air (Idris *et al.,* 2015). Fire was ignited manually on top of the reactor using a portable propane gas burner. The reactor was covered tightly to avoid penetration of oxygen and the carbonization temperature was maintained between 300 and 400°C. For EFB biochar, the retention time was kept between 3-4 hours and PKS biochar was pyrolyzed for 5-8 hours (Idris *et al.,* 2015). The biochar was collected the next day and used in field trials.

Characterization of Biochar

The EFB and PKS biochar were analyzed (in triplicates) for their pH, electrical conductivity (EC), moisture, ash, cation exchange capacity (CEC), exchangeable cations (K^+, Mg^{2+}, Ca^{2+}) (MS 679: Part I to V: 1980), macro and micronutrient contents (Nitrogen (N), Phosphorus (P), Potassium (K), Magnesium (Mg), Calcium (Ca), Boron (B), Zinc (Zn) and Copper (Cu)) (MS 677: Part I to VIII: 1980). The morphological characteristics were evaluated using a Scanning Electron Microscope (JOEL JSM-6390LA SEM) with an accelerating voltage of 5 kV. The samples were coated with a thin film of gold prior to examination.

Fourier Transform Infrared (Thermo Nicolet iS10 FTIR) was used for functional groups characterization. The samples were scanned in the range of 4000-600 cm^{-1} (32 scans with a resolution of 4 cm^{-1}) using an Attenuated Total Reflectance (ATR)-FTIR equipped with diamond crystal. The spectrum of each sample was ratioed against a fresh background spectrum recorded from the bare ATR diamond crystal. The spectra were then baseline corrected using asymmetric least squares strategy according to Boelens *et al.* (2004).

Application of Biochar on Oil Palm Seedlings

A total of 108 7-month-old Applied Agricultural Hybrida oil palm seedlings were supplied by Sarawak Oil Palms Berhad. The seedlings were treated with EFB and PKS biochar at 0 wt.% (T1), 1.5 wt.% (T2) and 3.0 wt.% (T3), respectively. The field study with EFB biochar and PKS biochar each constitutes 54 seedlings. The dosage was selected based on literature findings. Typically, the optimum dosage depends on soil conditions and type of plants. However, some informal observations recommend 5-20 wt.%, with literature supporting even lower application rates (Hunt *et al.,* 2010; Glaser *et al.,* 2002). The palm seedlings were transplanted into polybags containing 17.38 kg of mineral soil with and without biochar accordingly. The mineral top soil was obtained from the nursery of SOP Lambir 2 Estate, which is at 2"N 113°57'50.3"E. The soil was used as received. The properties of the soil, before any treatment with fertilizer or biochar were evaluated for its texture, pH, EC, moisture, ash, total nitrogen, total phosphorous, available phosphorous, exchangeable cations and CEC. The amount of biochar added is calculated relative to the soil dry weight, where the average moisture content was determined at approximately 14%.

$$m_{BC} = \%BsC \times m_s$$
$$m_s = m_f - (m_f \times \%\ moisture_{soil})$$

where,

m_{BC}: Amount of biochar added, kg
m_s: *Mass of soil in dry weight, kg*
m_f:*Mass of fresh soil, kg*
% *BC : Percentage of biochar (dry weight)*
% *moisture*$_{soil}$: *Percentage of soil moisture*

Biochar was mixed homogeneously with the soil before transplanting. After transplanting, the seedlings were set aside for two weeks for acclimatization. The seedlings were laid out in a randomized complete block design and the polybags were placed on bricks to avoid the roots from penetrating the bags and into the ground. Granular urea and commercially available fertilizer [rock phosphate (RP), Muriate of potash (MOP) and Kieserite] were applied in both control and biochar-treated palms. In the latter, biochar was added after fertilizer amendment. The granular urea contains 46% nitrogen (N), RP comprises 27% diphosphorous pentoxide (P_2O_5), MOP and Kieserite are mineral amendments of 60% potassium oxide (K_2O) and 27% magnesium oxide (MgO), respectively. According to the estate practice, fertilizer application was scheduled and added according to the palm age. At 7 months old, 2.61 g urea N, 4.44 g RP, 2.83 g MOP and 0.74 g of Kieserite were mixed together and applied to each seedling.

Weeding and irrigation were done manually for all seedlings throughout the study. The seedlings were left to grow for nine months. The plants were watered daily to the point when water seeped out from the drain holes located at approximately 1 cm from the bottom of the polybags. The amount of water added per plant is estimated at 2-3 L. The plant height was measured from the soil ground to the highest point of the leaf every two weeks to monitor the growth rate of the seedlings. Destructive sampling was carried out according to the schedule summarized in Suppl. A1 (Supplemental Information). Three seedlings were randomly sampled from each treatment and the biomass of leaves, stems and roots were measured. The plant biomass was analyzed for the macro and micronutrient contents (N, P, K, Mg, Ca, B, Zn and Cu) and the soil was subjected to analysis of soil texture, pH, EC, moisture, ash, total N, total P, available P, exchangeable cations (K, Mg and Ca) and CEC. As shown in Suppl. A1, the field trial of EFB and PKS biochar were carried out according to different harvesting plan. This is due to the changes in the fertilizer application schedule from an interval of two months to one month. On the bimonthly schedule, samples were harvested a month after fertilizer application and for samples ameliorated on monthly interval, sampling was conducted after a week.

During the destructive sampling, the entire plant was uprooted from the polybag and the soil attaching to the roots was carefully removed. The plant was washed with rainwater/tap water from the leaves to the roots to remove dirt and soil particles. The plant samples (leaves, stems and roots) were placed in an oven at 70°C for three days before the tissue dry weights were determined. The dry weights of respective parts were summed to represent the total plant biomass. Soil sample was mixed homogeneously and dried in an oven at 40°C for three to five days to obtain a constant weight. Both plant and soil samples were further analyzed for their nutrient content.

Soil Analyses

Preparation of Soil Samples

Soil samples were ground and sieved through a 2 mm and a 150 µm sieve. The soil fraction of < 2 mm was used for analysis of pH, conductivity, moisture and ash content, total and available P, exchangeable cations (K^+, Mg^{2+}, Ca^{2+}), CEC and soil texture. For total N analysis, finer soil particle < 150 µm was used to ensure homogeneity and efficiency of chemical reactions involved.

Determination of pH and EC

The soil pH was measured using a pH meter (TRANS BP3001) in suspension of soil to water at a ratio of 1:2.5. The sample was agitated for one hour and left overnight (MS 679: Part I: 1980). The soil conductivity was measured using a conductivity meter (Eutech). For soil moisture, 10 g of soil was dried overnight in an oven at 105°C. The oven-dried sample was then combusted in a furnace at 800°C for 1 hour for its ash content.

Determination of Available P

The available P was determined based on Bray 2 method (Bray & Kurtz, 1945). The available P was extracted using a mixture of ferrous ammonium sulphate (NH_4F) and hydrochloric acid (HCl). The extract was then analysed using the Ultraviolet-Visible (UV-Vis) spectrophotometer (Shimadzu, UV1800) at 660 nm.

Determination of Total P

The total P was determined using phosphovanadatemolydate complex method. The soil was digested using a mixture of sulphuric acid and perchloric acid (1:1). The extract was then added with vanadate molybdate to develop a yellow solution for analysis using the UV-Vis spectrophotometer (Shimadzu, UV1800) at 425 nm.

Determination of CEC

The soil CEC was evaluated based on ammonium acetate leaching procedure. The soil was leached with ammonium acetate and the filtrate was collected for determination of exchangeable K^+, Mg^{2+} and Ca^{2+}(MS 679: Part IV: 1980). The soil was washed with denatured alcohol (95%) to remove excess ammonium ions, dried and subjected to leaching with KCl (0.1 N). The filtrate was distilled and titrated against 0.02 N sulfuric acid (H_2SO_4) with indicators methyl red and methylene blue (MS 679: Part V: 1980).

Soil Texture Analysis

The sand, silt and clay fractions were determined using the pipette method involving sieving and sedimentation technique. The fractions of sand, silt and clay were then calculated in percentage (Piper, 1966).

Ten grams of soil were added to 30 mL of water, 10 mL of 20% v/v H_2O_2 and a few drops of ammonia. The sample was heated gently for 15 minutes and allowed to cool. Ten millilitres of sodium hexametaphosphate was added, stirred and left to stand overnight. The mixture was transferred into a 500 mL measuring cylinder and tap water was added to mark. The mixture was agitated and left to stand overnight. After that, it was mixed vigorously for 10 minutes and left for 4 minutes. A pipette was placed at 10 cm below the surface, where 10 mL of the solution was drawn and transferred into a petri dish. This represents the silt and clay fraction. After 6 hours and 21 minutes, 10 mL of sample was similarly drawn and this fraction is referred to as clay. The petri dishes containing silt and clay fractions were placed in an oven at 100°C overnight, left to cool and weighed. The suspension in the measuring cylinder was discarded leaving the sand fraction. The sand fraction was dried and put through a 0.2 mm sieve to separate coarse and fine sand. The percentage fraction of sand, silt and clay were calculated.

Determination of Soil N

The total N in soil was determined using the Kjeldahl digestion method. A soil sample of 0.5 g was digested in a mixture of catalyst, sodium thiosulphate pentahydrate and sulphuric–salicylic acid until the solution turned clear. The digested solution was added to sodium hydroxide (NaOH), distilled and titrated against 0.02 N H_2SO_4 (prepared from concentrated acid of 98%) with methyl red and methylene blue as the indicators (MS 679: Part II: 1980).

Plant Analyses

Determination of N, P, K, Mg, Ca, Zn and Cu

Sample of dried leaves, stems and roots were ground and put through a 1 mm sieve. The samples were subjected to N, P, K, Mg, Ca, B, Zn and Cu analyses using the dry ashing method, where 1 g of sample was first charred in a furnace at 300°C for 1 hour, followed by 500°C for 5 hours.

For P, K, Mg and Ca, HNO_3 was added to the ash sample whereas for Cu and Zn, HCl was added. The samples were left to digest on a water bath for 1 hour. The digested sample was filtered into a volumetric flask and made up to 100 mL (MS 677: Part II: 1980). The concentrations of Ca, Mg, Zn and Cu were determined using Atomic Absorption Spectrophotometer (Perkin Elmer, AAS 200) while K was determined using Flame Photometer (Sherwood, 410). For P, 1 mL of the digested sample solution was added with 5 mL of ammonium vanadate/molybdate and left for 1 hour. The absorbance of the sample was measured at 425 nm using a UV-Vis spectrophotometer (Shidmadzu, UV 1800) (MS 677: Part IV: 1980).

Determination of Plant N

The N in plant was determined using the Kjeldahl digestion method (MS 677: Part III: 1980). The plant sample of 0.1 g was digested in a catalyst mixture (1 g of selenium and 100 g sodium sulphate) and concentrated sulphuric acid until the solution turned clear. The digested solution, added with NaOH and distilled water, was then distilled into a conical flask containing boric acid and titrated against 0.02 N H_2SO_4 with screen purple indicator (a mixture of methyl red and methylene blue in ethanol).

Determination of Boron

Boron was determined using Azomethine-H method. One gram of ash sample was digested with H_2SO_4 and filtered through Whatman No 1 filter paper. One millilitre of the sample solution was further added with 0.5 mL of 0.05 M EDTA and 1 mL of ammonium acetate, followed by 1 mL of Azomethine solution. The solution was measured at 425 nm using the UV-Vis spectrophotometer (Shimadzu, UV-1800).

Biochar Analyses

The pH, EC, total organic matter, exchangeable cations and CEC of biochar were analyzed using the same methods for soil analyses. For macro and micronutrients (N, P, K, Mg, Ca, B, Zn and Cu, the methods used for plant analyses were adopted.

Data Analysis

The data was subjected to Shapiro-Wilk test of normality and square root transformed before analysis using SPSS Statistics Software version 25. Effects of biochar treatments on plant growth, soil properties and nutrient contents were evaluated using Analysis of Variance (ANOVA). Fisher's Least Significant Difference (LSD) test was applied to identify the treatment differences at $p < 0.05$. The ANOVA and LSD statistical analysis were done using SAS Statistical Software version 9.0.

Results and Discussion

Biochar Characterisation

Physico-chemical Properties of EFB and PKS Biochar

Table 1 summarizes the physico-chemical properties of EFB and PKS biochar, comparing with the biochar reported in the literatures. The pH of EFB and PKS biochar was neutral/

Table 1: Physico-chemical properties of EFB and PKS biochar based on dry weight

Parameters	EFB Biochar	PKS Biochar	Literature Values
pH	7.10±0.15	6.08±0.06	9.50[a] 7.0[b] 8.15-11.04[c] 8-12[d]
Moisture (%)	9.21±0.71	3.91±0.04	0.98-3.74[e] 4.20-5.55[f] 1.13-2.40[f]
Conductivity (µS/cm) Ash (wt.%)	467±18.72 6.64 ± 1.10	557±15.87 11.30 ± 0.14	200-10000[d] 5.76-8.66[e]
Total Organic Matter (wt.%)	93.36±1.10	88.70±0.14	70.1[b] 24.1-46.4[c]
Exchangeable Mg (cmol(+)/kg)	4.32±0.63	0.41±0.07	2.32[a] 12.0[b] 4.9-8.2[c]
Exchangeable Ca (cmol(+)/kg)	3.74±0.75	2.28±0.07	17.6[a] 44.3[b] 37.38-61.48[c]
Exchangeable K (cmol(+)/kg)	4.94±1.29	0.85±0.29	5.04[a] 39.4[b] 1.96-2.77[c]
Exchangeable Na (cmol(+)/kg)	0.35±0.00	0.29±0.05	32.6[b] 0.71-5.15[c]
CEC (cmol(+)/kg)	12.16±2.10	2.53±0.21	10.2[a] 7-17[d]
N (wt.%)	0.61±0.04	0.62±0.02	0.9[b] 1.4-2.3[c]
P (wt.%)	0.089±0.005	0.033±0.00	0.315-0.707[d]
K (wt.%)	0.27±0.05	0.19±0.05	0.98-12.42[d]
Mg (wt.%)	0.24±0.01	0.11±0.02	0.23-0.78[d]
Ca (wt.%)	0.26±0.02	0.54±0.00	1.25-2.08[d]
B (ppm)	13.00±0.00	10.67±0.00	N/A
Zn (ppm)	30.02±2.63	17.90±5.40	N/A
Cu (ppm)	19.23±1.35	15.23±0.12	N/A

[a]Hailegnaw *et al.* (2019) – Coniferous wood chip pyrolysed at 700°C
[b]Mensah and Frimpong (2018) – Corncob biochar pyrolysed at 350°C
[c]Dume *et al.* (2015) – Coffee husk and corncob biochar pyrolysed at 350°C and 500°C
[d]Hadi and Norazalina (2021) – EFB and PKS biochar pyrolysed at 350°C, 500°C and 750°C
[e]Mohd *et al.* (2019) – EFB biochar pyrolyzed at 400°C, 600°C and 800°C
[f]Nurhayati *et al.* (2015) – Mesocarp fiber, PKS and EFB biochar pyrolyzed at 300 - 500°C

slightly acidic attaining a pH of 7.10 and 6.08, respectively. Comparatively, the EFB biochar was characterized with higher cation exchange capacities and nutrient contents than PKS biochar.

The pH of a biochar is essentially governed by the pyrolysis temperature as the temperature determines the reaction involved and the end products properties. It is commonly reported that biochar produced at less than 400°C is acidic in nature, distinguishable with profound C=O and O-H groups (Chan & Xu, 2009; Novak *et al.,* 2009; Hagner *et al.,* 2016; Zhang *et al.,* 2017); as the temperature increases to 400-700°C, these functional groups would be destroyed, yielding high-ash biochar rich in alkaline species such as $KHCO_3$ and $CaCO_3$ (Ippolito *et al.,* 2016; Domingues *et al.,* 2017). Novak *et al.* (2009) produced Pecan shell and switchgrass biochar of pH 5.9 and 5.4 using a temperature of 350°C and 250°C, respectively. At comparable temperatures of 300 and 375°C, Hagner *et al.* (2016) derived acidic biochar of pH 5.1 and 5.2 from the biomass of birch (*Betula spp.*). The acidic biochar is inherited with relatively fewer ion exchange sites hence they are found to exhibit lower nutrient retention capacity (Glaser *et al.,* 2002).

In this study, the EFB biochar exhibits relatively higher CEC and nutrient content than the PKS biochar. The differences are likely attributable to the feedstock used as well as the pyrolysis temperature and residence time. For instance, biochar of woody materials characteristically demonstrates lower exchangeable cation properties, however, when the pyrolysis temperature is increased, a product with enhanced CEC can be produced (Zhang *et al.,* 2015; Masís-Meléndez *et al.,* 2020). A considerable variation is observed in EFB and PKS biochar in comparison to biochar reported elsewhere; this is not unexpected, as the difference is attributed to the wide-ranging lignocellulosic compositions of biomass, their pyrolysis conditions and the methods of analyses. With specific reference to CEC, Munera-Echeverri *et al.* (2018) suggests that the method for determination of CEC in biochar can be poorly reproducible, offering an explanation to greatly vary measurements reported between studies. This variation is likewise observed in the macro and micronutrient contents reported in this study against the literature values, including those with comparable feedstock (Hadi & Norazalina, 2021). In this study, the macro and micronutrients were determined using an atomic absorption spectrometer and in Hadi and Norazalina (2021) employed inductively coupled plasma spectrometry.

The exchangeable cations in biochar, specifically Ca and Mg, were found to contribute to improved crop yield in maize planted in acidic soil. Biochar enriched with exchangeable Ca encouraged displacement of Al^{3+}, raising the soil pH. But this positive effect was seen to ebb over time, implying the needs for re-application (Cornelissen *et al.,* 2018). Major *et al.* (2010) similarly found improved maize yield correlated with increased availability of Ca and Mg in soil amended with biochar. As shown in Table 1, EFB biochar demonstrates markedly higher exchangeable Ca and Mg signifying possibly a better potential for EFB biochar.

FTIR Spectra of EFB and PKS Biochar

Figure 1 illustrates the spectra profile of EFB biochar and PKS biochar. In terms of functional groups, the FTIR spectra of biochar demonstrate a broad absorption band in the region of 3640-3200 cm^{-1} with weak aliphatic stretching bands identified between 2900 and 2800 cm^{-1}. The signal at higher frequency is designated to hydroxyl groups (alcoholic, phenolic and hydrogen-bonded OH groups) present in hydrous minerals and absorbed water (Singh *et al.,* 2016; Promraksa & Rakmak, 2020). The weak aliphatic bands are likely the characteristics of more resilient lignin, where its presence is supported by the strong aliphatic-CH_2 and aromatic-C signals between 1590 and 1400 cm^{-1}. Janu *et al.* (2021) ascertained that lignin is more difficult to decompose than ketones and aldehydes that are represented by the absorptions in 1700-1600 cm^{-1}. The typical temperature for lignin decomposition ranges between 190 – 900°C (Yang *et al.,* 2007). The vibrations at lower frequency, between 1300-1000 and 873 cm^{-1}, are attributed to the C-O and C-H stretching of alcohol/ester and aromatic groups, respectively (de Figueredo *et al.,* 2017). The weak absorption bands at 1159 and 1031 cm^{-1} are possibly signals of residue cellulose although this component, together with hemicellulose, are expected to decompose under a temperature of 220-400°C (Yang *et al.,* 2007). The presence of cellulose in biochar concurs with the findings of Glaser *et al.* (2002) and Novak *et al.* (2009) that biochar pyrolysed at lower temperatures of 300-400°C was said to possess more organic properties due to the undecomposed cellulose structures. Overall, biochar derived from EFB and PKS demonstrate major absorptions at 3300, 2980, 1570, 1390, 1240, 1060 and 880 cm^{-1}, corresponding to the functional group properties reported in oil palm based biochar elsewhere (Abdulrazzaq *et al.,* 2014; Mohd *et al.,* 2019).

Surface Morphology of EFB and PKS Biochar

Figure 2 shows the surface morphology of EFB and PKS biochar. Noticeably, EFB biochar demonstrates better defined pore structures compared to PKS biochar. This indicates larger surface area of EFB biochar which would lead to more effective nutrients adsorption, reducing nutrients loss (Glaser *et al.,* 2002). The surface morphology, like other chemical properties, is determined by the feedstock, pyrolysis temperature and residence time. Liang *et al.* (2016) reveals that some feedstock tends to retain more fibrous structure and is richer in macropores depending on their lignocellulosic compositions. When the charring temperature increases, more pores are expected to form due to the loss of volatile matter. In this study, PKS biochar reveals lower CEC (2.53 cmol(+)/kg) with ill-defined pores supporting the finding of low adsorption capacity in PKS biochar and its limited surface area by Mahmood *et al.* (2015).

Soil Characterisation

Soil Properties Prior to Treatment

The soil used for this study belongs to Bekenu series, which is equivalent to red-yellow Podzol according to the USDA soil classification system. The soil is brownish yellow to yellow in color. Suppl. A2 compares the physio-chemical characteristics of the pre-treated mineral soil used for field trials against the optimal properties recommended for agricultural soil. The soil (classified as loamy sand) is acidic with low CEC, exchangeable cations and nutrient content. The low pH indicates the presence of H^+ that can affect the accessibility of nutrients and mineralization of organic matter. Prasetyo and Suriadikarta (2006) likewise reported that the red-yellow Podzol is a marginal soil

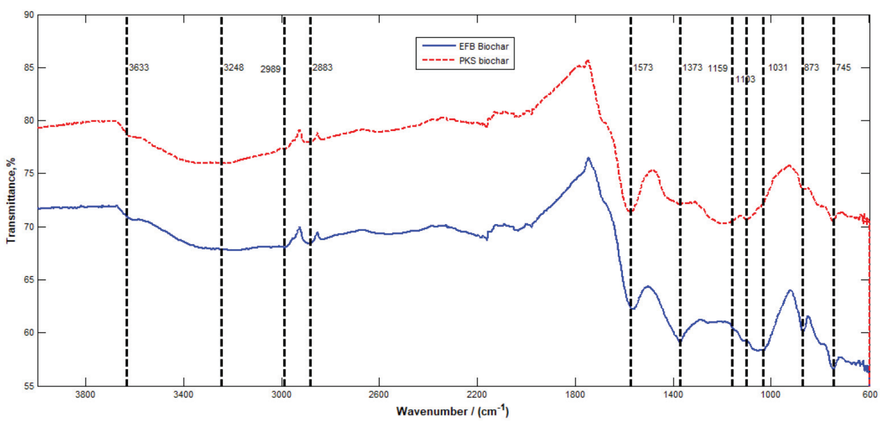
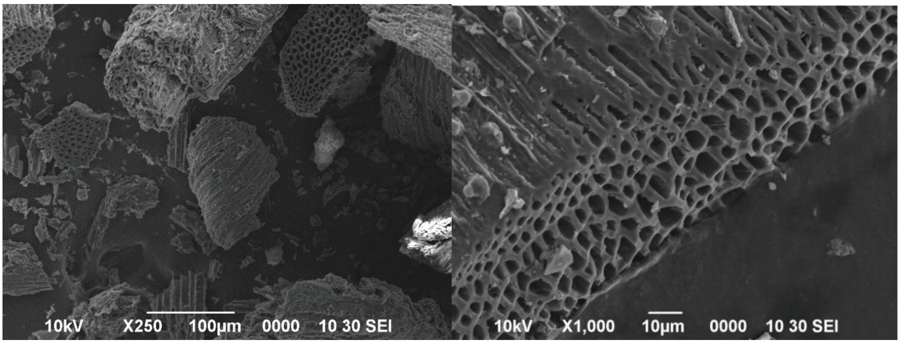
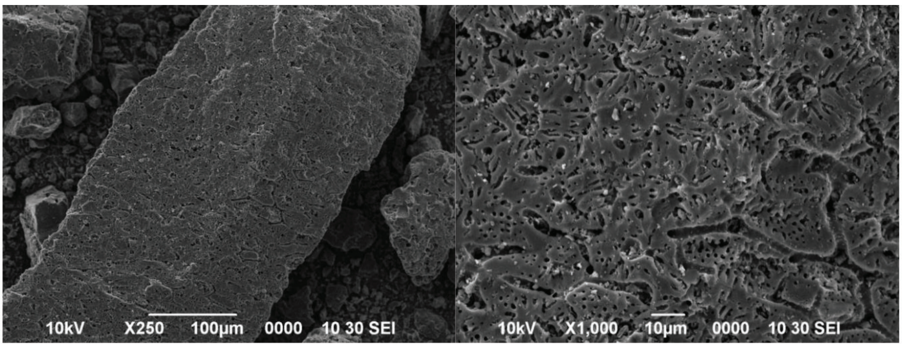


Figure 1: FTIR spectra of EFB and PKS biochar



(a) EFB biochar



(b) PKS biochar

Figure 2: Scanning Electron Micrograph (SEM) images of EFB and PKS biochar

susceptible to compaction, identified with various limitations, including low pH, clay content, aggregate stability and nutrient content. The soil used for the field trial of PKS biochar was lower in nutrient contents and exchangeable cations. Both soils, in their untreated state, were considered unfavorable for plant growth when the recommended soil properties for agricultural purposes were benchmarked.

Soil pH

The pH of treated and untreated soil with EFB and PKS biochar is summarized in Suppl. A3. The soil treated with fertilizer and biochar shows pH ranging between 4.14 and 5.46, where no significant difference is deduced between the treated and untreated soil without biochar (4.33-5.33) (EFB biochar: p=0.9910, PKS biochar: p=0.3183). The biochar used in this study was characteristically acidic/near neutral hence, the liming effect is not expected to be significant after treatment.

Soil EC

Suppl. A4 summarizes the soil EC treated with and without biochar. Statistically, there is no significant difference in EC of control (45 – 210 µS/cm) and treated soil (51 - 303 µS/cm) (p=0.5704 for EFB biochar and p=0.1825 for PKS biochar). As documented in the literature, the EC of biochar may vary considerably, ranging from as low as 40 µS/cm (Rajkovich *et al.,* 2012) to 54,200 µS/cm (Smider & Singh, 2014), depending on the feedstock used. The average EC of EFB and PKS biochar was 467 and 557 µS/cm, respectively; this is considered low as Lehmann (2007) revealed that biochar produced at a temperature less than 400°C is commonly characterised with low pH, EC as well as surface area.

Soil Moisture and Ash Content

The moisture and ash content of soil treated with EFB biochar was found to improve by 15-25% and 80-156%, respectively, depending on the biochar dosage. This observation corroborates findings that EFB biochar improves water retention (Nair *et al.,* 2017), however, this positive effect is not evidenced in soil treated with PKS biochar. This is possibly because the PKS biochar has a marginal porous structure and it is hard and coarse in particle size, giving no advantage to water retention capacity (Blaco-Canqui, 2017).

Soil CEC

Table 2 summarizes the CEC of soil treated with and without biochar. As shown, the CEC of soil treated with EFB biochar is consistently higher than the control throughout the study. This is likely associated with the porous structure of EFB biochar and its elevated CEC attribute (12.16 cmol(+)/kg), which contribute directly to improved soil surface area, density of charge and porosity. The treated soil shows a marked improvement (by a factor of 2-3) in its cation exchange properties, with Ca^{2+} being the most abundant exchangeable cation (results not shown). This positive effect of biochar on soil cation exchange properties has not been recorded in soil treated with PKS biochar, likely due to the inherently low CEC (2.53 cmol(+)/kg) and poor porosity of the biochar.

Soil C/N Ratio

Suppl. A5 summarizes the C/N molar ratio of untreated and treated soil with EFB and PKS biochar. The C/N ratio molar ratio is calculated by dividing the element %. wt with its atomic weight ($\frac{C}{N} = \frac{\frac{Weight\ percent\ C}{Atomic\ weight\ C}}{\frac{Weight\ percent\ N}{Atomic\ weight\ N}}$); it is used as an indicator for the soil productivity. The C/N ratio of treated soil ranges between 2.98-9.59 for EFB biochar and 3.80-10.79 for PKS biochar. Compared with the control (3.34-9.33), the C/N ratio of treated soil is consistently higher although no significant difference is established, indicating increasing carbon content upon biochar amendment. The notable improvement in C/N ratio of soil treated with 3 wt.% wood chips and wheat straw pallet biochar (≥ 22.6), reported by Latini *et al.* (2019), is not concurred in the present study. An effective soil amendment is expected to demonstrate a C/N ratio of between 15 and 35. If a ratio beyond this range is attained, this suggests occurrence of N immobilization whilst a lower ratio implies high input of nitrogen rich compounds, usually attributed to fertilizer application (Tangmankongwarakoon, 2019). The nitrogen enriched soil is susceptible to NH_3 volatilization, where the process can be encouraged under alkaline conditions (Liu *et al.,* 2017). The C/N ratio of biochar amended soil fluctuated over the experiment period, where a lower C/N value was attained towards the end. This is possibly due to the accumulation of N as

Table 2: The CEC of untreated and treated soil with EFB and PKS biochar

Soil CEC of EFB Biochar Treatments (cmol(+)/kg)				Soil CEC of PKS Biochar Treatments (cmol(+)/kg)			
Palm Age (month)	**T1 (0 wt.%)**	**T2 (1.5 wt.%)**	**T3 (3.0 wt.%)**	**Palm Age (month)**	**T1 (0 wt.%)**	**T2 (1.5 wt.%)**	**T3 (3.0 wt. %)**
8	1.81±0.05[b]	2.05±0.23[b]	2.76±0.23[a]	8	2.32±0.98[a]	3.01±0.28[a]	2.88±0.30[a]
10	1.71±0.18[c]	2.11±0.23[b]	2.72±0.17[a]	9	4.38±1.50[a]	5.52±2.22[a]	4.36±1.38[a]
11	2.48±0.74[b]	3.17±0.79[a]	3.30±0.58[a]	11	4.17±1.14[a]	4.17±1.52[a]	3.36±0.48[a]
13	1.95±0.13[b]	2.08±0.21[b]	2.75±0.22[a]	12	2.79±0.78[a]	3.23±0.44[a]	2.49±0.31[a]
14	1.83±0.02[b]	2.08±0.04[b]	2.89±0.24[a]	13	2.44±0.54[a]	2.93±0.24[a]	3.15±0.78[a]
15	1.69±0.41[a]	1.91±0.13[a]	2.23±0.98[a]	14	2.69±0.57[a]	2.86±0.10[a]	2.87±0.38[a]

The values represent the mean (± standard deviation) of data obtained in the experiment (n=3). The means in the same row followed by the same letters are not significantly different at $p > 0.05$ based on t-Test (LSD) a result of periodic fertilizer applications and it is also an indication of the loss of biochar over time.

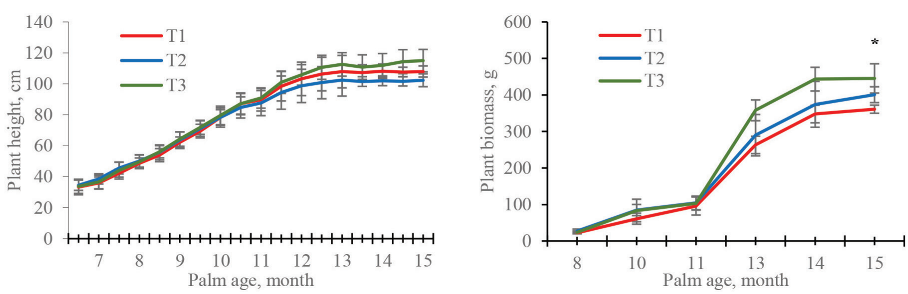
Soil Available P

The available P of soil treated with EFB and PKS are illustrated in Suppl. A6. In EFB biochar treatment, the available P is markedly higher (12.8-102.9 mg/kg) than the original soil, before addition of fertilizer and biochar (4.22 mg/kg). The level of soil-available P, after treatment, falls within the optimal range for agricultural purposes (20-40 mg/kg) (Dume *et al.*, 2015). The available P represents 4-32% of the total (106.7-305.4 mg/kg) where a significant correlation is determined between both fractions. The available P of treated soil is higher than the control, with a significant difference deduced in month 13. In the subsequent month, the available P in T1 (the control) exceeds that in the amended soil as it begins to reduce. The reducing P availability maybe an indication for re-application of biochar as the positive effects we observe on pH, EC, CEC and C/N were also seen to fade at the latter stage of the experiment. The dynamic of P content in soil is controlled by various factors including the nutrient input, changes in crop requirements and environmental factors. For available P, it is profoundly governed by the soil pH. At pH of 6-7.5, the element is the most readily available, however, as the pH reduces below 5.5 or increases above 7.5, the element will be tightly bound to iron, aluminum and calcium. In this study, the soil pH after treatment is largely less than 5.0, suggesting possible occurrence of P fixation as only 4-32% of the total P is available. In the study with PKS biochar, no significant difference is identified in the available P throughout the experiment period.

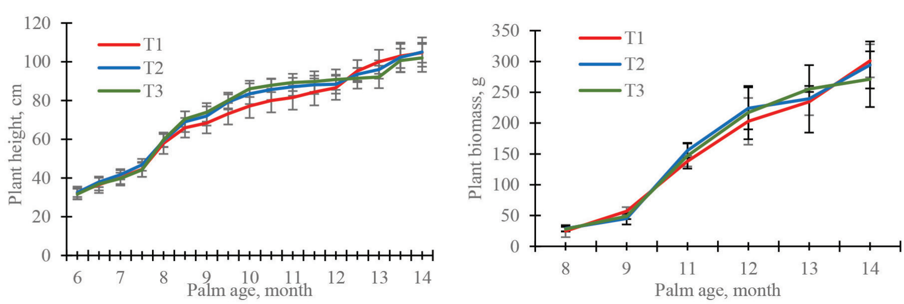
Plant Growth

Plant Height and Biomass

Figure 3 shows the average height and biomass of oil palm seedlings treated with EFB and PKS biochar. As observed, the seedlings grown in soil amended with 3 wt.% EFB biochar showed improved plant height and biomass,



(a) EFB biochar treatment



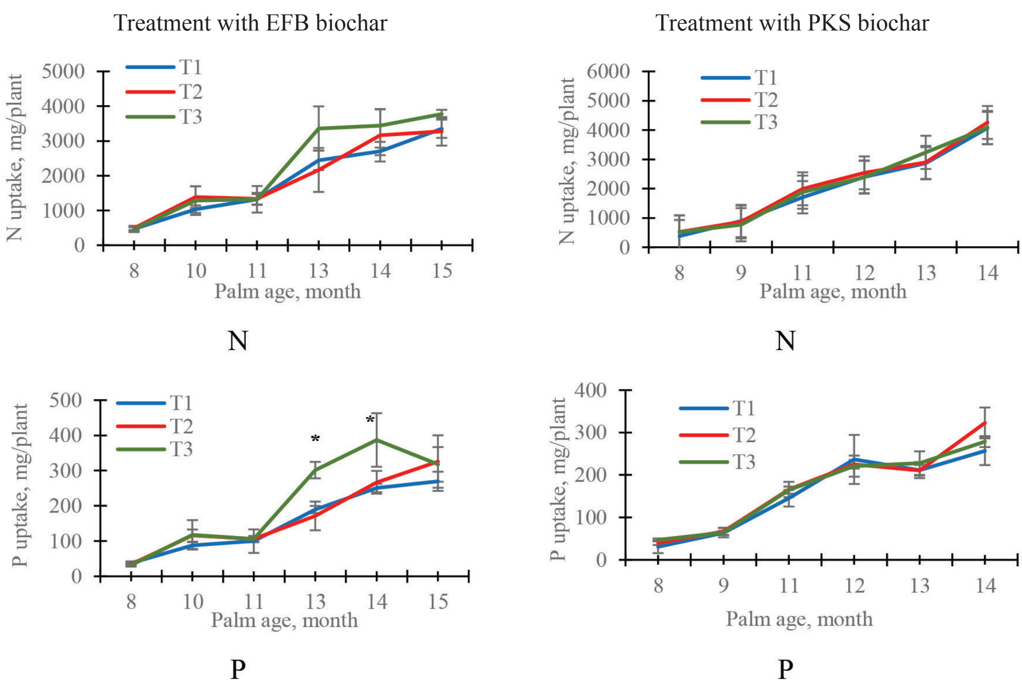
(b) PKS biochar treatment

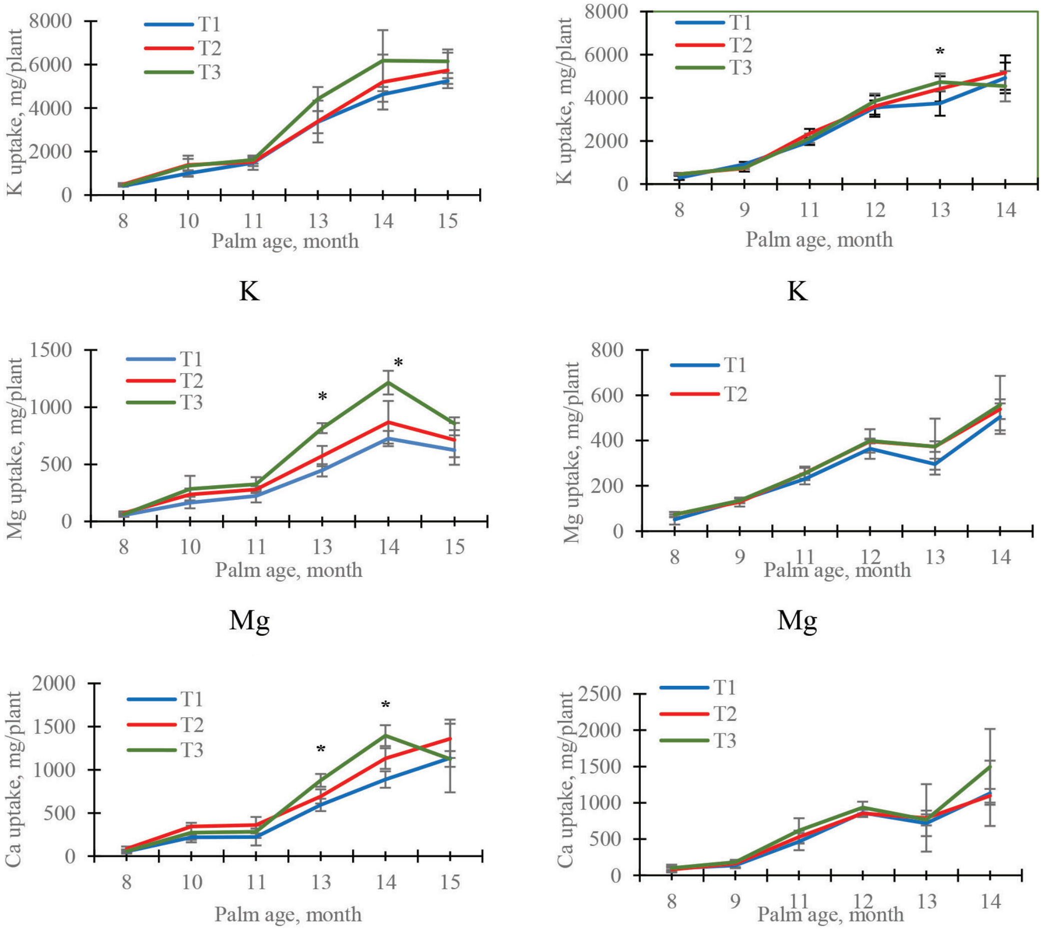
Figure 3: Plant height and biomass of seedlings against palm age for (a) EFB biochar treatment and (b) PKS biochar treatment. The symbol * denotes significant difference at $p < 0.05$

in comparison to those planted in untreated soil (0 wt.% EFB biochar) and 1.5 wt.% EFB biochar (Figure 3(a)). At 8-14 months, no significant difference in biomass was observed for various treatments. As the seedlings grew to 15 months, apparent improvements were attained (p=0.0205) corresponding to the application rate. The positive effects of biochar in combination with mineral fertilizer on plant growth were similarly reported by Carter *et al.* (2013). These improvements recorded in EFB treatment, however, were not seen in PKS biochar throughout the study. Despite being neutral and slightly acidic in pH, seedlings and soil treated with EFB biochar consistently outperformed those treated with PKS biochar.

Plant Macronutrients

Figure 4 shows the total macronutrient contents (N, P, K, Mg and Ca) in seedlings with EFB and PKS biochar treatments. The total nutrient content is the sum of nutrients found in leaves, stems and roots, expressed in mg/plant. The macronutrients found in EFB treated seedlings were consistently higher than the control, with significant differences deduced in P, Ca and Mg in months 13 and 14, between T3 and T1/T2. Typically, oil palm requires considerable number of macronutrients, including N, P, K and Mg (Woittiez *et al.,* 2017). These nutrients are particularly important for oil palm at the initial stage of growth, as they contribute to biomass accumulation (Rosenani *et al.,* 2016; Hasmah *et al.,* 2019). Elevated uptake of the aforementioned elements was evidenced in seedlings treated with 3.0 wt.% biochar, though the effect was observed to fade in month 15, indicating the need for re-application. The stimulatory effect was not recorded in PKS biochar treatment throughout the study.





*denotes significant different at P < 0.05

Figure 4: Total phosphorous (P), potassium (K), magnesium (Mg) and calcium (Ca) in seedlings of EFB and PKS biochar treatments

Plant Micronutrients

Micronutrients, including boron (B), Zinc (Zn) and Copper (Cu), are essential for the growth of oil palm, acting as catalyst to facilitate enzyme reactions. Cu and Zn are particularly critical for oil palm planted in peat soil whilst B deficiency is a common problem in oil palm plantations. In this study, the EFB biochar treatments show insignificant effects on the uptake of Zn (p=0.2873) and Cu (p=0.1357), nonetheless, a marked increase in B (p=0.0360) was recorded in seedlings of T3 (Suppl. A7). The improved B uptake confirms the plant requirements for the element and the boosted B in seedlings treated with biochar corroborates the beneficial effects of biochar. Similar observation of diminished B uptake was identified when the seedlings grew to 15 months old.

Oil palm seedlings grown in EFB biochar at 3 wt.% were observed to grow better. This however was not observed in the treatment with PKS biochar. The growth performance is likely associated with the biochar properties in which PKS biochar exhibits marginal porous structure with relatively lower CEC. Mahmood *et al.* (2015) compared the surface area of various oil palm biomasses, corroborating PKS biochar with lower surface area (23.7 m^2/g) than other forms of oil palm biomass including palm frond (857.3 m^2/g) and empty fruit bunch (95.8 m^2/g). As evidenced, soil treated with EFB biochar demonstrated improved CEC. This, in turn, is expected to contribute to improved nutrient uptake as a higher CEC indicates a greater capacity to retain cations. Seedlings treated with 3 wt.% EFB biochar show higher macronutrient content, indicating better nutrient use efficiency. This observation is likewise evidenced in micronutrient contents of the seedlings. The improvement in nutrient uptake is not evidenced in seedlings treated with PKS biochar. Radin *et al.* (2018) treated oil palm seedlings with EFB biochar at 0-1.5 wt.%; the study similarly showed positive nutrient retention and significant improvements in seedling growth in soil containing admixture of 1.5 wt.% EFB with compost and fertilizer.

Conclusion

Oil palm seedlings treated with EFB biochar demonstrated increased plant height and biomass by 7% and 23%, respectively. The macro and micronutrient contents were higher in treated seedlings suggesting improved nutrient uptake. In soil, the CEC and exchangeable cation properties were evidently enhanced upon biochar treatment. These stimulatory effects were associated with the well-defined macropores of EFB biochar and its enhanced CEC attribute. The positive effects recorded in EFB biochar, however, were not observed in treatment with PKS biochar. As a matter of fact, PKS biochar was larger in particle size and inherited lower CEC. Morphologically, its pore structures were poorly defined, hence, offered no advantage to soil and plants. The findings of this study reveal that EFB biochar can be potentially used to improve the growth performance of oil palm and its soil properties.

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