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Optimization of fertilizer use efficiency, soil quality and oil palm (*Elaeis guineensis* Jacq.) growth with biochar under drip irrigation conditions

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Summary: Biochar (BC) is an eco-friendly product characterized with high content of carbon and usually obtained by heating biomass without oxygen. Utilizing BC as organic material to amend the problematic soils and improve plant growth and yield has been proved previously. This study investigated the effect of vetiver grass biochar (VGB) on fertilizer use efficiency, soil quality, and oil palm growth performance. A net house experiment was conducted at the Farm Unit, UiTM Sarawak Branch, between August 2022 and March 2023. A factorial randomized complete block design (RCBD) with five treatments and four replications was devised. Treatments applied were: T0) absolute control; T1) 100% NPK fertilizer; T2) 100% vetiver grass biochar; T3) 50% vetiver grass biochar + 50% NPK fertilizer; and T4) 25% vetiver grass biochar + 75% NPK fertilizer. The BC application significantly improved the fertilizer use efficiency through reducing the rate of fertilizer applied. It also significantly enhanced most soil-measured chemical properties and soil nutrients. The growth performance of oil palm plant was significantly enhanced by BC application in terms of plant height, hump diameter, leaf number, chlorophyll content, and plant biomass. The BC application demonstrated its usefulness in managing soil and cultivating oil palm plant sustainably by reducing the rate of fertilizer applied and improve the fertilizer use efficiency. Based on the output, we suggest that treatment T3 (50% vetiver grass biochar + 50% NPK) can be used to improve the growth performance of oil palm.

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Key words: biochar, drip irrigation conditions, soil amendment, sustainable agriculture

Introduction

Modern farming and sustainable agriculture techniques have become important in order to reducing the demand for agricultural production and reducing the rate of fertilizer applied while improving the plant growth. An organic product called biochar (BC) obtained from heating biodegradable organic biomass in the absence of oxygen (Bohari et al., 2020). BC is an eco-friendly product that contains high percentage of carbon, usually produced with the absence of oxygen at temperatures below 700 °C (Bridgwater, 2003). BC has many desirable properties such as high porosity, high variable charge, and high surface area, which make it an efficient product to be used in the agricultural and environmental applications (Rafael et al., 2019). BC has high stability and resistance toward the degradation in soil due to its aromatic structure (Atkinson et al., 2010). The main role of using BC is to amend the problematic soils (Mete et al., 2015). BC is known as the most valuable soil conditioner (Torabian et al., 2021). However, various factors and elements affect the potential of BC, such as source of biomass (Atkinson et al., 2010), temperature of the pyrolysis process (Albalasmeh et al., 2023), and soil conditions (Smider & Singh, 2014). Using BC as a soil organic amendment has been suggested by many researchers in order to improve fertilizer use efficiency, enhance soil chemical properties, quicken soil nutrient cycling, and boost plant growth and yield (Jia et al. 2021; Mohawesh et al. 2021; Hossain et al. 2020; Martinsen et al. 2015; Marín-Martínez et al. 2021; Ajeng et al. 2020; Jabborova et al. 2021). The existence of BC in soil lead to enhance soil fertility through increasing N retention (Sigua et al. 2016; Jia et al. 2021) and increasing cation exchange capacity (Aziz et al. 2015; Unger et al. 2011). Premalatha et al. (2023) reported that fertilizer use efficiency was increased by 10% - 30% with the biochar addition. Jia et al. (2021) also reported that biochar could reduce nitrogen loss from soil and improve the fertilizer use efficiency. Singh et al. (2022) reported that biochar addition led to increase soil cation exchange capacity up to 45%. Bindu et al. (2017) have reported that biochar addition improved soil pH. Martinsen et al. (2015) have stated that soil pH was increased by 0.5 using cacao shell biochar, by 0,05 using oil palm shell biochar, and by 0.04 using rice husk biochar. Ghorbani & Amirahmadi (2018) reported that biochar application increased soil pH and enhance the nutrient availability in soil. They also demonstrated that biochar increased the carbon content in soil and decreased the nutrient leaching from soil. Jia et al. (2021) reported that soil nutrients levels (NPK) were enhanced by BC. Wu et al. (2023) stated that soil organic carbon was increased with the biochar addition. Liang et al. (2006) reported that the concentration of phosphorus in soil was increased with the biochar addition. Hanpattanakit et al. (2021) also reported that the concentration of potassium in soil was elevated using BC. Peng et al. (2021) reported that there was an increase in the storage root yield of sweet tomato as a result of biochar addition. Bijay-Singh & Craswell (2021) stated that biochar application improved the growth and yield of ginger plant. Adekiya et al. (2022) reported that there was an increase in the number and weight of tubers in the produced tomato as a result of biochar addition. Youssef et al. (2017) stated that biochar addition led to increase plant growth, leaf photosynthesis, and tuber yield of potato. According to Carpenter et al. (2014) there was a positive impact in the weight of carrot produced with the biochar addition. González-Pernas et al. (2022) reported that the addition of BC has significantly improved the radish fresh biomass. Ajeng et al. (2020) reported that the application of BC reduced the rate of fertilizer used, improved the nutritional status of soil, and enhanced the growth and nutrient uptake of oil palm. Aleiadeh et al. (2024) reported that the addition of BC improved the fertilizer use efficiency, increased the growth of oil palm, and enhanced soil nutrients content. According to Mete et al. (2015) The most striking effect for BC application is usually seen on the tropical soils. According to Albalasmeh et al. (2023), biochar produced from various types of feedstocks or raw material shall be tested in order to determine it's effects on soil and plant. On the other hand, using vetiver grass biochar as organic amendment to enhance soil properties and improve oil palm growth is not reported yet. Therefore, this study investigated the feasibility and potential of using vetiver grass biochar to improve soil quality and oil palm growth performance under drip irrigation conditions.

Materials and methods

Biochar production and characterization

The fresh raw material of vetiver grass was collected from smallholders in Bintulu, Sarawak, Malaysia. The raw material was thoroughly cleaned, washed, and cut. Following that, the vetiver grass raw material was sun-dried for 4-5 days and continued by further drying in an oven with a temperature of 105 in order to achieve a constant weight (Chan et al., 2021). Once it is completely dried, the vetiver grass raw material was crushed and ground into a fine powder using a heavy-duty grinder. The powdered sample of vetiver grass raw material was placed in a folded aluminum foil before being carbonized at 365 °C for 2 hours (Aziz et al. 2021; Shafie et al. 2012). A large chamber muffle furnace (Type 62700; Thermo Scientific Barnstead/Thermolyne, USA) was used to perform the carbonization process (Bohari et al., (2020). Then, the BC was allowed to pass through 1-mm sieve for the characterization purpose. The pH and EC analysis of the BC were done using an Oakton pH 700 Benchtop Meter (Barwant et al., 2018), and a CON 700 EC meter (Eutech Instruments, USA) (Bohari et al., 2020). Nutrient analysis of the BC was done according to the standard procedures of the United States Salinity Laboratory Staff (United States Salinity Laboratory Staff, 1954). The BC specific surface area was determined by methylene blue adsorption method according to Albalasmeh et al. (2023).

Net house experiment

A net house experiment was conducted at the Farm Management Unit of UiTM Cawangan Sarawak between August 2022 and March 2023. A net house of about 300 m^2 was used at the experimental site. The net house study was conducted with red yellow podzolic soil for 7 months, between August 2022 and March 2023. In general, red yellow podzolic soil has two families, which are BEKENU and MERIT (Teng, 2004). In this experiment, red yellow podzolic soil used is related to MERIT family, and characterized with low pH, low aggregate stability, and low nutrient content. The experimental design consisted of five treatments with four replicates, with eight plants per treatment. The treatments applied were: T0) absolute control; T1) 100% NPK fertilizer; T2) 100% vetiver grass biochar; T3) 50% vetiver grass biochar + 50% NPK fertilizer; and T4) 25% vetiver grass biochar + 75% NPK fertilizer added before transplanting the plant seedlings. Oil palm (*Elaeis guineensis* Jacq.) seedlings were planted inside polybags under drip irrigation conditions. The spacing between each polybag was 60 cm x 60 cm, and the gap between each replication was one meter. The net house maintenance practices were carried out and closely monitored throughout the experiment. These practices included regular weeding of polyethylene bags, pest and disease control, keeping the net house clean, and checking the irrigation-fertigation system. In order to ensure a sufficient irrigation for the plants, the plants were watered three times daily using a timer-drip irrigation system. The layout of the treatments replications and drip irrigation system is shown in ***Figure 1***. Soil samples were taken at depth of 0 – 20 cm for chemical analysis. A factorial randomized complete block design (RCBD) with five treatments and four replications was devised. The rate and amount of vetiver grass biochar and compound fertilizer used are shown in ***Table 1***.

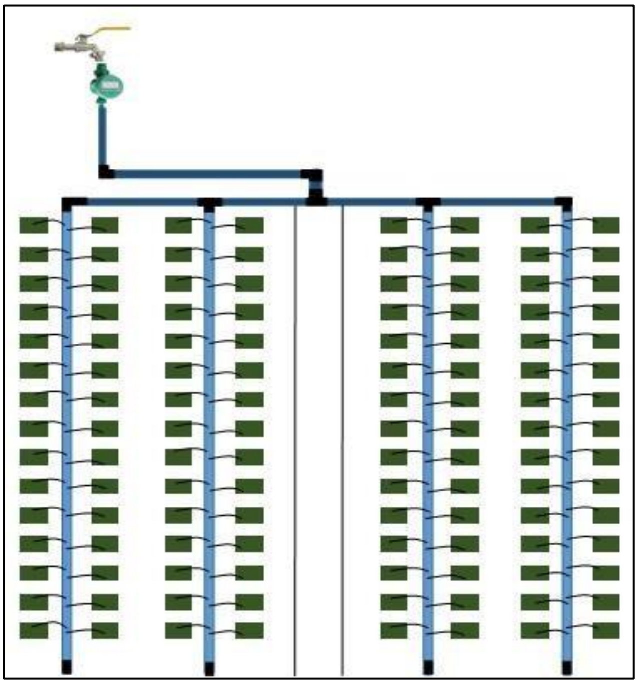

Figure 1. The layout of treatments replications with drip irrigation system used in the net house experiment.

Table 1. Composition of treatments and rate of fertilizer

Treatments	Percentage (rate)	Quantity (g/plant)
T0	Absolute control	0 g
T1	100% NPK	20 g
T2	100% VGB	140 g
T3	50% VGB + 50% NPK	70 g + 10 g
T4	25% VGB + 75% NPK	35 g + 15 g

Soil sampling and analysis

The chemical analysis of soil was done after the net house experiment done. Soil samples from each treatment were extracted and kept in plastic jars. Soil pH and EC were measured using the same method used by Albalasmeh et al. (2023). Soil pH was measured using a pH meter (1:1) (Orion Star A211, Thermo Scientific). Soil CEC was assessed using the ammonium acetate leaching method (Hussain & Malik, 1985). The Walkley-Black Method was used to measure the soil organic carbon (Wakley & Black, 1934). The Kjeldahl method was used to determine the total nitrogen in soil (AOAC, 1995). The Olsen method was used in order to determine the concentration of phosphorus in soil (Olsen, 1954). The exchangeable potassium in soil was determined by the atomic absorption (Knudsen et al., 1982).

Plant analysis

In general, this study focused on five parameters: plant height (cm), bole diameter (mm), leaf number per plant, chlorophyll content (SPAD value), and plant biomass. Plant growth parameters were observed and measured between the first and the seventh month after planting (MAT), following the same method used by Ajeng et al. (2020). Plant height was measured using metered tape. Bole diameter was measured using a digital caliper at 5 cm height from the soil surface. Leaf number per plant was counted manually and recorded. A chlorophyll meter (SPAD-502, Minolta, Japan) was utilized to measure the chlorophyll value in the plant leaf (Mohawesh et al., 2021). The destructive sampling process was done in order to determine the plant dry biomass. The destructive sampling was conducted at the 9th MAT. The weight was recorded as plant fresh weight. Then, the plant was dried using the oven for three days until reaching a constant weight (Zubir et al., 2020). After that, the weight was recorded as plant dry weight. The weight of plant biomass was recorded using an electronic digital balance (A&D GF-300 Precision Balance).

Statistical analysis

The statistical analysis for measured soil and plant parameters was carried out using the Statistical Analysis System version 9.4 software (SAS, 2013). ANOVA test was used to compare the mean value of each treatment followed by DMRT in order to determine the significant groupings among the treatments at significance level of $p< 0.05$.

Results and discussion

Biochar characteristics and soil properties

Table 2 shows the BC characteristics. The initial soil properties were; pH 4.3, CEC 3.21 cmol Kg-1, total organic carbon 1.18%, total nitrogen 0.13%, phosphorus content 0.37%, potassium content 0.08%.

Effect on soil properties

Table 3 shows the effect of different experimental treatments on soil properties including soil pH, CEC, soil organic carbon, nitrogen, phosphorus, and potassium content. Soil pH was influenced and enhanced with BC. It can be seen that pH value of soil was elevated from 4.3 to 5.80, 6.43, and 7.68 after biochar application rates of 25, 50, and 100 %, respectively. However, the highest value of soil pH was recorded in treatment T2 (100% biochar) ***(Table 3)***. The enhancement of soil pH value can be related to the high alkalinity nature of the BC (8.43) (Table 2). It also could be attributed to the addition of base cations and nutrients to soil from the derived biochar (Xiao et al., 2016). Bindu et al., (2017) reported that biochar addition increased soil pH. Martinsen et al. (2015) also reported that soil pH increased using different types of biochar. Furthermore, it may be related to the BC ability to increase base saturation and decrease the amount of exchangeable aluminum in soil (Zhang et al., 2017). Soil cation exchange capacity was significantly influenced by BC application. Soil cation exchange capacity was significantly influenced by BC application. The soil CEC highly influenced by BC and this effect can be easily noticed in treatment T2, which possess the highest value of 8.92 cmol Kg-1 (Table 3). Marín-Martínez et al. (2021) reported that soil CEC was improved by BC. Singh et al. (2022) also reported that soil CEC was increased and reached up to 45% as a result of BC addition. This increase in soil CEC may be related to some characteristic of the derived biochar such as the existence of strong functional groups and exchangeable sites, which could increase soil CEC value (Alkharabsheh et al., 2021). In addition, this increase may be related to the adsorption, desorption, and redox reaction processes of the derived biochar (Joseph et al., 2010). Soil organic carbon was highly influenced by BC application. BC significantly influenced and increased the organic carbon content in soil and the highest value was obtained in soil samples treated with treatment T2 ***(Table 3)***. Wu et al. (2023) reported that organic carbon content in soil was increased upon the biochar addition. The enhancement of soil organic carbon content with the BC treatments is due to the high carbon content of the BC used ***(Table 2)***. The NPK content of soil was enhanced with BC treatments. The highest NPK content was observed in treatment T3 while the lowest was in treatment T0 ***(Table 3)***. The improvement of soil N content with BC may be related to slow-release characteristics of the biochar such as CEC, which increase the amount of nutrients in soil (Jindo et al., 2020). The enhancement of soil P content with BC treatments could be related to the ability of BC to alters the solubility of P through changes in soil pH, which increase P content in soil (Arif et al., 2017). The increase in soil K content with BC treatments may be related to some characteristics of the BC such as large surface area, negative surface charge, and the porous structure of the biochar, which improves the nutrient retention including K (Liang et al., 2006). The application of BC increased soil nutrients levels (NPK) (Jia et al., 2021). Xiao et al. (2016) reported that soil nutrient status was improved by BC application.

Table 2. Physicochemical characteristics of biochar.

Parameter	Unit	Value
pH	–	8.43
EC (1:20)	mS cm^{-1}	5.53
N	%	1.39
P	%	0.39
K	%	2.17
C	%	62.17
H	%	4.62
SSA	$m^2 g^{-1}$	139.41

Table 3. Effect of different treatments on soil pH, CEC, organic carbon, N, P and K

Treatment	pH	CEC (cmol kg^{-1})	OC (%)	N (%)	P (%)	K (%)
T0	4.30^{e}	3.19^{e}	1.13^{d}	0.10^{e}	0.31^{e}	0.07^{e}
T1	4.50^{d}	4.46^{d}	0.47^{e}	0.52^{c}	0.88^{c}	0.42^{c}
T2	7.68^{a}	8.92^{a}	3.94^{a}	0.39^{d}	0.59^{d}	0.31^{d}
T3	6.43^{b}	6.50^{b}	2.60^{b}	0.89^{a}	1.35^{a}	1.76^{a}
T4	5.80	5.77	2.11	0.64	1.19	1.29

Note: Different letters in the same column indicate significant ranking orders by DMRT at $p<0.05$.
T0 = Absolute control, T1= 100% NPK, T2= 100% VGB, T3= 50% VGB + 50% NPK, and T4= 25% VGB + 75% NPK

Table 4. Effect of different treatments on plant growth parameters over 7 months

Treatment	Plant height (cm)	Bole diameter (mm)	Leaf number	Chlorophyll content (SPAD value)
T0	44.96^{e}	26.89^{d}	7.33^{e}	36.51^{e}
T1	64.36^{c}	40.21^{bc}	15.47^{c}	47.82^{c}
T2	50.49^{d}	33.88^{c}	12.64^{d}	41.39^{d}
T3	74.27	46.39	19.72	54.49
T4	67.72	43.40	17.26	50.34

Note: Different letters in the same column indicate significant ranking orders by DMRT at $p<0.05$.
T0 = Absolute control, T1= 100% NPK, T2= 100% VGB, T3= 50% VGB + 50% NPK, and T4= 25% VGB + 75% NPK

Effect on plant growth performance

Table 4 shows the effect of different treatments on plant growth parameters over 7 months. The highest value of plant height, bole diameter leaf number, and chlorophyll content was noticed in plants treated with treatment T3, whereas the lowest was in treatment T0 ***(Table 4)***. Rodríguez et al., (2009) reported that sugarcane plant's height and bole diameter were improved by BC. The increase of plant height and bole diameter in plants treated with treatments T3 and T4 may be due to some characteristics of the BC such as porosity and CEC, which increase the retention of nutrients and make it more available for plant uptake especially when the BC is applied with fertilizer, hence improving plant height and bole diameter (Adileksana et al., 2020). (Sokchea & Preston, 2011; Bijay-Singh & Craswell, 2021) reported that there was enhancement of the plant's leaf number as a result of the BC application. Akhtar (2015) also reported that higher chlorophyll content of plant was recorded after the BC application. Albalasmeh et al. (2023) reported that chlorophyll content in both barley and wheat significantly increased with the BC application. The improvement of plant's leaf chlorophyll content with biochar treatments is due to the ability of BC to enhance the availability of nutrient in soil and make them more available and accusable by plant especially nitrogen which mainly affect the value of chlorophyll content (Albalasmeh et al., 2023).

Effect on plant biomass

Figure 2 shows the effects of different treatments on plant's fresh and dry biomass. Plant's fresh and dry biomass were highly influenced by BC. The highest mean value of fresh and dry biomass was obtained from plants treated with treatment T3, whereas the lowest was in T0. The enhancement of plant's biomass with BC was previously reported (Jabborova et al., 2021; González et al., 2022). The enhancement of plant biomass is highly dependent on soil's properties, soil fertility and nutritional status, which are mainly enhanced by BC (Albalasmeh et al., 2023).

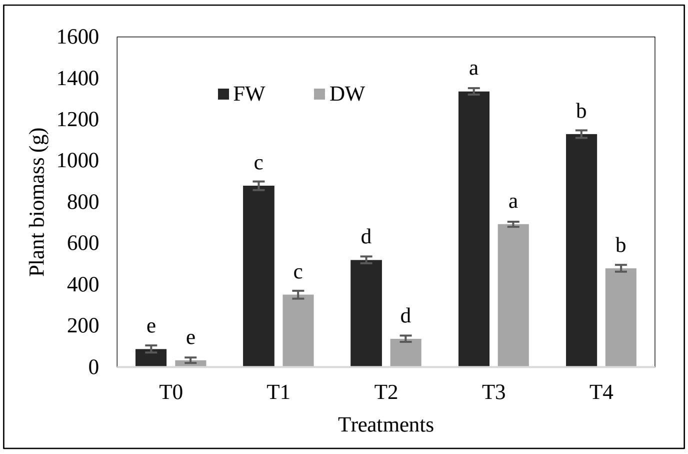

Figure 2. Effect of different treatments on plant biomass.

Note: Different letters represent significant difference using Duncan's Multiple Range Test. T0= Absolute control, T1= 100% NPK fertilizer, T2= 100% vetiver grass biochar, T3= 50% vetiver grass biochar + 50% NPK fertilizer, and T4= 25% vetiver grass biochar + 75% NPK fertilizer.

Conclusions

Based on the results, the application of VGB had positive effects on soil and plant. The application of VGB improved soil chemical properties, soil nutrients (NPK) level, and oil palm growth. soil chemical properties. The VGB application increased soil pH, CEC, organic carbon, and soil nutrients N, P, and K. The composition (50% VGB + 50% NPK fertilizer) is suggested to improve growth performance of oil palm planted in acidic soil.

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