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MODELLING THE EFFECT OF WOOD AND MAIZE COB-DERIVED BIOCHAR APPLICATION ON SOIL DYNAMICS AND MAIZE GROWTH FOR SUSTAINABLE AGRICULTURE

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Abstract: Intensive agriculture has degraded global agricultural land and resulted in a food crisis. The application of biochar in agricultural soil has been proven effective at improving soil quality and increasing crop yield. This study aims to develop a simulation and investigate the effect of wood-derived biochar (WBC) and maize cob-derived biochar (MBC) at different application rates on soil pH, soil cation exchange capacity (CEC), soil organic carbon (SOC) and the productivity of the maize cropping system. The prediction regarding the effect of biochar on soil pH was the most accurate of all the parameters studied. The simulation was good at predicting the change of properties in calcareous clay soil for both WBC and MBC, as well as WBC in acidic, sandy soil. The results demonstrated that amendments to both WBC and MBC successfully improved the soil pH, SOC and CEC. The effect was more significant when higher biochar application rates were applied. The biochar amendment enhanced the properties of acidic sandy soil more significantly as compared to calcareous clay soil. Overall, WBC and MBC are potential green fertilisers capable of enhancing soil quality for the sustainable development in agriculture.

Keywords: Biochar amendment, soil properties, crop yield, biomass utilization, sustainable agriculture.

Abbreviation or Nomenclature:

BC_0	Biochar application rate	$dtBC_{biom}$	Daily flux of biochar carbon to microbial soil organic matter pool
$C{:}N_{soil}$	Carbon to nitrogen ratio of soil	T_f	Temperature modifier
dtBC	Daily amount of biochar carbon decomposes	$dtBC_{CO2}$	Daily loss of biochar carbon to the atmosphere
$dtBC_{hum}$	Daily flux of biochar carbon to humic soil organic matter	O_{ob}	Observed value
$dX_{hum}BC$	Decomposition rate for humic soil organic matter pool	$dX_{biom}BC$	Decomposition rate for microbial soil organic matter pool
ef_{biomBC}	New amount of decomposed carbon retained in the microbial soil organic matter pool	ef_{biom}	Amount of decomposed carbon retained in the microbial soil organic matter pool
ef_{formBC}	New amount of decomposed carbon retained in the system	ef_{form}	Amount of decomposed carbon retained in the system
f_{labile}	Fraction labile carbon in biochar	n_f	Nitrogen modifier

f_{loss}	Biochar lost during application	n_{clay}	Non-carbonate clay
$fr_{fombiom}$	Amount of carbon flow from the fresh organic matter pool to microbial soil organic matter pool	S_{si}	Simulated value
$fr_{fomhumBC}$	Amount of carbon flow from the fresh organic matter pool to humic soil organic matter pool	ef_{formBC}	New amount of decomposed carbon retained in the system
MAPE	Mean absolute percentage error	$Soil_{BC}$	Labile and recalcitrant biochar remaining in the soil
MRT1	Labile pool mean residence time	SOC	Soil organic carbon
MRT2	Recalcitrant pool mean residence time	$Soil_{BCl}$	Labile biochar remaining in the soil
$Soil_{cec}$	Soil cation exchange capacity	$Mass_{fr}$	Mass fraction of biochar in soil
$Soil_{cecBC}$	Soil cation exchange capacity after biochar application	$fr_{biomhum}$	Amount of carbon flow from the microbial soil organic matter pool to humic soil organic matter pool
$Soil_{phBC}$	Soil pH before biochar application	$dX_{form}BC$	New dynamic decomposition rate for Agricultural Production Systems Simulator fresh organic matter pool
w_f	Surface water modifier	$fr_{fombiomBC}$	New amount of carbon flow from the fresh organic matter pool to microbial soil organic matter pool
dtNBC	Net rate of nitrogen mineralisation or immobilization during biochar decomposition	$dtNBC_{released}$	Daily mineralized nitrogen during biochar decomposition
$dtNBC_{need}$	Daily amount of nitrogen needed for biochar decomposition	K_{des}	Absorption capacity
K_{ads}	Desorption capacity	NH_{4ads}	Adsorbed ammonium from the soil solution
NH_{4des}	Desorbed ammonium from the soil solution		

Introduction

Soil quality is defined as the soil's capacity to support plant growth, mitigate the permeation of precipitation to secure watersheds and restrain pollutants such as industrial and agricultural waste (Bünemann *et al.,* 2018). Soil is vital for humans because of the sources of food derived from it. However, soil has degraded in recent years due to human activities (Zhu *et al.,* 2019). The problem with soil quality is mainly due to the physical, chemical and biological constraints which inhibit the growth of plants generally and crop especially in agriculture. Nutrient deficiencies in a crop are commonly due to lack of nitrogen, phosphorus and potassium in the soil. These nutrient deficiencies could be caused by leaching, volatilisation, denitrification and surface run-off of nutrients which result in deterioration of soil and environmental pollution.

The demand for food production from agriculture has been rising due to the rapid increase in the world's population. Between 2005 and 2050, an expansion of 70% to the food production capacity is expected to secure the demand for food (Kopittke *et al.,* 2019). The deterioration of soil quality is a threat to the agriculture industry worldwide. The soil degradation due to excessive agricultural pollution has caused a loss of soil fertility and a drop in food production capacity. To alleviate these concerns, solutions that boost soil fertility are sought after.

Biochar is a pyrogenic carbon product derived from carbon-rich content waste materials via pyrolysis, gasification and hydrothermal carbonisation of biomass mainly from plants and agriculture residue (Huang & Gu, 2019; Kavitha *et al.,* 2018).

Generally, the physical and chemical properties of biochar are highly dependent on the type of feedstock and pyrolysis (thermal decomposition) conditions. A study of the available literature shows that biochar could be used for soil amendment to improve its physicochemical properties. Biochar amendment has been found to affect soil dynamics such as porosity, bulk density, pH- levels, nutrient content, availability and holding capacity as well as its cation exchange capacity (CEC) (Huang *et al.,* 2019). The effect of biochar on plant growth performance was found to vary depending on the type of biochar (Shetty & Prakash, 2020) and type of soil (pH and texture) (Elias *et al.,* 2020). Biochar has also been used as a carbon sequestration material to mitigate climate change and immobilise heavy metals in contaminated soil (Jain *et al.,* 2020). The quality of the topsoil was found to be significantly influenced by the properties of biochar (feedstock and synthesis conditions) and the biochar application ratio.

Most of the past studies conducted on soil amendment using biochar focused on alleviating the soil fertility as well as production of crop through laboratory experiment or field trials. The studies on prediction of biochar's effects on soil by modelling and simulations have been limited. The Agricultural Production Systems Simulator (APSIM) has been used recently by researchers as the platform for modelling and simulation of agricultural systems. However, studies on the effect of biochar application on soil dynamics and crop yields using APSIM are scarce (Dokoohaki *et al.,* 2019; Aller *et al.,* 2018; Archontoulis *et al.,* 2016). Dokoohaki *et al*. (2019) investigated the effect of biochar on soil hydrological properties by using APSIM. Aller *et al*. (2018) simulated the effect of hardwood and corn stover-derived biochar on nitrate leaching, SOC and corn yield under various management conditions.

Meanwhile, Archontoulis *et al*. (2016) predicted the effect of biochar on corn yields, corn stover, bulk density, pH, SOC and soil moisture content by developing biochar model using APSIM. APSIM is capable of modelling and understanding complex soil interaction systems (Aller *et al.,* 2018). Hence, to understand the complex interaction between biochar and soil, the APSIM simulation tool is an appropriate means of investigating the effects of biochar on soil properties and crop yields. The use of APSIM coupled with biochar modelling would be able to simulate, predict and evaluate the effects of biochar on soil amendments. Biochar is commonly produced from lignocellulosic biomass which comprises of agricultural and forest waste.

In this study, wood maize cob waste was selected as the precursors since wood is the most abundant forest waste and wood waste-derived biochar is commonly used in experimental case studies whereas maize is the largest crop produced in the world. The Kaoma soil (acidic soil) possesses low CEC, pH, SOC and fertility whereas Lusaka soil (alkaline soil) possesses moderate CEC and fertility, high pH levels and SOC (Cornelissen *et al.,* 2013). Thus, it is important to improve the fertility and properties of both Lusaka and Kaoma soil types to enhance crop yields. The experimental study on the effect of softwood and maize cob-derived biochar on Lusaka and Kaoma soil types has been conducted by Cornelissen *et al.* (2013). However, to-date, modelling and simulation studies have not reported on the effects of softwood and maize cob-derived biochar on crop yields, SOC, CEC and pH levels for both Lusaka and Kaoma soil types.

Therefore, this study aims to simulate the effect of wood and maize cob-derived biochar at different biochar application rates on the properties of calcareous clay soil (Lusaka soil) and acidic sandy soil (Kaoma soil) as well as maize yield using the APSIM modelling program.

Materials and Methods

APSIM version 7.10 was used in this study to simulate the application of wood and maize cob-derived biochar on the Lusaka calcareous clay soil and Kaoma acidic sandy soil by evaluating the effects of biochar on the soil dynamics. The development of the biochar simulation was performed in stages and covered the assumption of the APSIM model on biochar simulation and determination of biochar mathematical model as well as deviation and validation tests on the data.

In this study, the simulation model was developed based on the model used by Cornelissen *et al.* (2013) for biochar effects on maize yields and the biochar model by Archontoulis *et al.* (2016), along with the corn crop model, soil model and soil N and C cycling model. The biochar model consisted of three parameters:

(i) biochar type and management,
(ii) biochar and soil interactions and
(iii) biochar model parameters that were assumed constant.

The second and third parameter categories were limited and required specific data for the simulation model. Hence, these parameters were assumed based on the study of Archontoulis *et al.* (2016) while $C:N_{biom}$ and $C:N_{soil}$ were default values in APSIM as shown in Table 1. The meteorology dataset from the year 1990 until 2020 for the model were obtained from Prediction of Worldwide Energy Resources, POWER data access viewer version v1.1.1.

Meanwhile, the soil models were assumed to be Africa deep clay soil with medium fertility and Africa deep sandy soil with low fertility, selected from the built-in soil models. The assumption and selection of the data was based on the site data obtained by Cornelissen *et al.* (2013) for Lusaka and Kaoma climates and soils, respectively.

The details of the soil information and biochar soil model are listed in Table 2. The biochar parameters were influenced by the type of feedstocks used. The parameters such as lost during application and residence time were assumed based on the study of Archontoulis *et al.* (2016). The values for f_{loss}, f_{labile}, MRT1 and MRT2 were 0.02, 0.13, 1 year and 500 years, respectively. The values of f_{loss} and f_{labile} were assumed based on biomass-based biochar, consistent with the biochar used in the literature to conduct simulation studies. The MRT1 of 1 year and MRT2 of 500 years were reported to have no significant effect if applied for short-term biochar treatment, thus these values were acceptable (Archontoulis *et al.,* 2016; Cornelissen *et al.,* 2013).

The biochar parameters as shown in Table 3 were assumed based on the study of Cornelissen *et al.* (2013) which used wood-derived biochar and maize cob-derived biochar.

The model field management was selected based on the field design of Cornelissen *et al.* (2013) as shown in Table 4. The management practices such as tillage, biochar tillage, fertilising, sowing and harvesting were programmed in the simulation operation schedule. The cultivar used in the simulation was based on the study of Aller *et al*. (2018) which had improved the cultivar and was suitable for biochar application on maize crop.

Table 1: Biochar and APSIM model parameters

Biochar and Soil Interaction Parameters	**Value**
P_{fom} (m^2/kg^2 C)	0
P_{hum} (m^2/kg^2 C)	0
P_{biom} (m^2/kg^2 C)	0
P_e (m^2/kg^2 C)	0
P_f (m^2/kg^2 C)	0
P_{e2} (m^2/kg^2 C)	0
P_{f2} (m^2/kg^2 C)	0
K_{ads} (mg/L)	0.006
K_{des} (mg/L)	0.006
Q_{LL}	0
K_{dul}	-0.15
K_{ads} (g/g)	-0.15
BD^a	0.8
CN_{biom}	8
$C:N_{soil}$	12
Biochar Model Constant Parameters	**Value**
Cnrfbc	0.693
Optbc (g/g)	25
Efbc (g/g)	0.4
Frbcbiom (g/g)	0.05

Notes:

P_{fom}	Positive priming coefficient for fresh organic matter	BD^a	Fraction reduction in bulk density due to tillage
P_{hum}	Positive priming coefficient for humic soil organic matter	CN_{biom}	Carbon to nitrogen ratio of the microbial soil organic matter pool
P_{biom}	Positive priming coefficient for microbial soil organic matter pool	$C:N_{soil}$	Soil carbon to nitrogen ratio
P_e	Negative priming coefficient 1 for fresh organic matter	K_{dul}	Slope parameter in water retention drain upper limit quality modifier
P_f	Negative priming coefficient 2 for fresh organic matter	Optbc	Carbon to nitrogen ratio at or below biochar mineralizes nitrogen
P_{e2}	Negative priming coefficient 1 for microbial soil organic matter pool	Efbc	Biochar carbon retention efficiency
P_{f2}	Negative priming coefficient 2 for microbial soil organic matter pool	Frbcbiom	Fraction of biochar to microbial soil organic matter pool
K_{ads}	Adsorption capacity	K_{des}	Desorption capacity
Q_{LL}	Quality modifier on water retention lower limit		

Table 2: Biochar soil model and soil information (Cornelissen *et al.,* 2013)

Soil Information	**Lusaka Soil**	**Kaoma Soil**
Site coordinate	Latitude: -15.22712 Longitude: 28.22269	Latitude: -14.49571 Longitude: 24.52970
Soil type	Clay loam (Haplic Luvisols, medium fertility and clay illuviation)	Aerolian sand (Ferrallic Arenosols, infertile and coarse white sand)
Soil model	Clay_Deep_MF_200mm (No869-Generic)	Sand_Deep_LF_111mm (No914-Generic)
Soil order	Alfisol	Entisol
Sand	0.30	0.88
Clay	0.27	0.04
U_{pH}	9.5	9.5
L_{pH}	3.5	3.5
P_{pH}	10	10
pH	7.9	5.6

Notes:

U_{pH}	Soil pH upper level
L_{pH}	Soil pH lower level
P_{pH}	Constant adjusting buffering capacity

Table 3: Biochar variable parameters (Cornelissen *et al.,* 2013)

Parameters	**Softwood (WBC)**	**Maize Cob (MBC)**
BC_{lv} (Mg/ha)	50	40
BC_{ecec} (cmolc/kg)	86	39.9
CN_{BC}	83	87
f_{carbon} (g/g)	0.64	0.74

Notes:

BC_{lv}	Biochar liming value
BC_{ecec}	Biochar effective cation exchange capacity
CN_{BC}	Biochar carbon to nitrogen ratio
f_{carbon}	Carbon fraction in biochar

Table 4: Model field parameters (Cornelissen *et al.,* 2013)

Sowing Parameters	**Action**
Crop	Maize
Sowing density (plants/m^2)	4
Sowing depth (mm)	50
Cultivar	B_105_biochar
Crop growth class	Plant
Row spacing	900
Biochar tillage depth (mm)	150

Development of Simulation Model

All the assumptions used to develop the simulation model in this study were based on the studies of Aller *et al*. (2018) and Archontoulis *et al*. (2016). The mathematical model of biochar by Archontoulis *et al*. (2016) could be described into components such as biochar application, SOC, C/N ratio, pH and CEC of the soil.

Biochar Application on Soil

The decomposition of biochar was obtained using Equation 1. The temperature and water surface function were assumed based on the built-in function in APSIM as these parameters were affected by soil water in soil module and climate from meteorology data (Archontoulis *et al.,* 2016). Meanwhile, the nitrogen modifier was developed using Equation 2.

$$dtBC = BC_0 \, x \, (1 - f_{loss}) \, x \, f_{carbon} \, x \left[\frac{f_{labile} \, x \, ln(2)}{365 \, x \, MRT_1} + \frac{(1 - f_{labile} \, x \, ln(2)}{365 \, x \, MRT_2} \right] x \min\left(w_f \, x \, T_f \, x n_f\right) \qquad (1)$$

$$n_f = min\left(1, e^{\frac{-cnrfbc \, x \left(\left(\frac{Soil_{BCI}}{N_{avail}}\right) - Optbc\right)}{Optbc}}\right) \qquad (2)$$

Similarly, the amount of decomposed biochar was derived from the flux of biochar for CO_2, BIOM and HUM as stated in Equation 3.

$$dtBC = dtBC_{co2} + dtBC_{biom} + dtBC_{hum} \qquad (3)$$

Equations 4, 5 and 6 represented the daily flux of $dtBC_{CO2}$, $dtBC_{BIOM}$ and $dtBC_{HUM}$, respectively.

$$dtBC_{co2} = dtBC \, x(1 - efbc) \qquad (4)$$

$$dtBC_{biom} = dtBC \, x \, efbc \, x \, (frbcbiom) \qquad (5)$$

$$dtBC_{biom} = dtBC \, x \, efbc \, x \, (1 - frbcbiom) \qquad (6)$$

Soil Organic Carbon (SOC)

The priming effect of biochar was assumed to be affected by FOM, BIOM and FUM. Archontoulis *et al*. (2016) stated that the model for SOC was based on three pools: FOM, BIOM and FUM. These pools were affected by the positive priming and negative priming effects. The positive priming effects for FOM, BIOM and HUM were expressed in Equations 7, 8 and 9, respectively.

On the other hand, the negative priming effect for FOM was expressed in Equations 10, 11 and 12, whereas Equations 13 and 14 were applied for BIOM and HUM, respectively.

$$dX_{form}BC = X \; x \; \left(1 + P_{form} \; x \; \frac{Soil_{BC}}{1000}\right) \tag{7}$$

$$dX_{biom}BC = X \; x \; \left(1 + P_{biom} \; x \; \frac{Soil_{BC}}{1000}\right) \tag{8}$$

$$dX_{hum}BC = X \; x \; \left(1 + P_{hum} \; x \; \frac{Soil_{BC}}{1000}\right) \tag{9}$$

$$ef_{formBC} = ef_{form} x \left(1 + P_e x \frac{Soil_{BC}}{1000}\right) \tag{10}$$

$$fr_{fombiomBC} = fr_{fombiom} x \left(1 + P_f x \frac{Soil_{BC}}{1000}\right) \tag{11}$$

$$fr_{fomhumBC} = dX_{fom}BC - ef_{formBC} - fr_{fombiomBC} \tag{12}$$

$$ef_{biomBC} = ef_{biom} x \left(1 + P_{e2} x \frac{Soil_{BC}}{1000}\right) \tag{13}$$

$$fr_{biomhum} = fr_{biomhum} x \left(1 + P_{f2} x \frac{Soil_{BC}}{1000}\right) \tag{14}$$

Biochar Effect on C/N Ratio

Nitrogen was mineralised or immobilised upon the decomposition of biochar, depending on the C/N ratio. The net of the N mineralised and immobilised was the difference of N released.

Soil pH and Cation Exchange Capacity (CEC)

The soil CEC after the application of biochar was calculated by Equation 15. Soil CEC in the equation was a function of soil order, SOC and the percentage of non-carbonated clay as shown in Equation 16.

Meanwhile, the mass fraction was a function of biochar application into the soil as shown in Equation 17. The soil pH was affected by the soil CEC after biochar application as shown in Equation 18.

$$Soil_{cecBC} = Soil_{cec} \times (1 - Mass_{fr}) + BC_{ecec} \times Mass_{fr} \tag{15}$$

$$Soilcec = f(n_{clay}, SOC, soil\ order) \tag{16}$$

$$Mass_{fr} = \frac{Soil_{BC}}{f_{carbon} \; x \; BD_0 \; x d_{layer} \; x \; 1000} \tag{17}$$

$$Soil_{pHBC} = Soil_{pH} + \frac{Mass_{fr} x BC_{lv}}{Soil_{cecBC}} x \frac{(U_{pH} - Soil_{pH}) x (Soil_{pH} - L_{pH}) x P_{pH}}{(U_{pH} - L_{pH})} \tag{18}$$

Deviation Test for Biochar Model

The simulation was run on two types of soil with each type tested without the application of biochar and with biochar applications at different rates for two types of biochar feedstock. In this manner, a total of ten simulations were run (2x(1+2x2) =10) as shown in Table 5.

The simulation studies of Cornelissen *et al.* (2013) were conducted for two years based on field experiments. Table 6 shows the amount of biochar applied on the simulated soils. The field application was lower than the simulation due to the biochar application being based on a planting basin, whereas in the simulation the application was assumed based on whole field (broadcasting) (Cornelissen *et al.,* 2013).

Table 5: Conditions used in simulation runs

Conditions	Kaoma Soil	Lusaka Soil
Without biochar	Maize yield, pH, CEC and SOC	Maize yield, pH, CEC and SOC
High application rate of MBC	Maize yield, pH, CEC and SOC	Maize yield, pH, CEC and SOC
Low application rate of MBC	Maize yield, pH, CEC and SOC	Maize yield, pH, CEC and SOC
High application rate of WBC	Maize yield, pH, CEC and SOC	Maize yield, pH, CEC and SOC
Low application rate of WBC	Maize yield, pH, CEC and SOC	Maize yield, pH, CEC and SOC

Table 6: Biochar application rates

Treatment	Control (kg/ha)	Low (kg/ha)	High (kg/ha)
Field	0	800	4000
Simulation	0	6000	30000

The modelling efficiency on a scale of 0 to 1 was used as an indicator for the goodness of fit. The models performance and deviation between the actual measured and simulated results were evaluated by using a mean absolute percentage error (MAPE) equation and calculation method, as represented by Equation 19. The MAPE was a scale-independent approach, expressed as a percentage error, which was selected as the tool to analyse the relative error of the model (Aller *et al.,* 2018; Chen *et al.,* 2017).

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{|O_{ob}-S_{si}|}{|O_{ob}|} \quad (19)$$

Results and Discussion

Deviation Test

Maize Yield

Table 7 and Table 8 compares the maize grain yield obtained from the simulation model and field experiments by Cornelissen *et al*. (2013) using WBC and MBC, respectively on clay soil. Table 7 shows that the simulation model predicted a gradually decreasing trend of maize yield on WBC application on Lusaka clay soil, with a deviation of 11.21% from the experimental data.

A small decrease of 0.71 kilogrammes/hectare (kg/ha) was observed when the application rate of WBC was increased by a factor of six from low treatment to high treatment. Hence, a further increase in the application rate did not show a significant decrease in the maize yield. The simulated low treatment and high treatment biochar were within the standard error of 10%, which was 7.93% and 6.36%, respectively.

This indicated that the simulation model accurately predicted the WBC application on the soil. However, the control (system without biochar) showed a deviation of 19.33%. The model underestimated (>10% deviation) the control. The results of the biochar treatment were consistent with the results obtained from the field experiments, which showed a decrease of 25% when WBC was applied for both low and high treatments.

Cornelissen *et al*. (2013) targeted that a significant increase was doubling the yield over 100% while a modest increase was at 50% to 100% and vice-versa. Thus, it was concluded that the biochar treatment on the Lusaka farm was not significant because the changes were lower than the modest. The reason of underestimate the control at 19.33% deviation might be due to the biochar model simulated the control model as a very low biochar application. Thus, the deviation was modest based on the definition by Cornelissen *et al*. (2013).

Similar results were observed by Archontoulis *et al*. (2016) in which corn grain yield showed a small increment at a high biochar application rate, from 20 Mg/ha to 100 Mg/ha. This indicated the sensitivity of the biochar model in predicting the corn grain yield. Archontoulis *et al*. (2016) stated that the simulated effect of biochar on the corn grain yields was reduced due to the crop system of the model, which identified the yield as a final output that was interconnected with several variables of the soil and plant.

Hence, the model was less sensitive in predicting the grain yields. The small decline in the maize yields simulated in WBC treatment was consistent with the literature, which revealed that the type of biochar applied to the soil affected the soil properties and plant growth. Some studies showed that the application of wood-derived biochar on soil negatively affected the soil quality and plant growth. Aller *et al*. (2018) obtained a small decrease in the corn yield after undergoing wood biochar treatment. The largest decline was only 2.6% at the highest biochar application of 90 Mg/ha. The study stated that the decline in yield was due to N stress.

Moreover, Zhang *et al*. (2012) found that the high C/N ratio of wood biochar would contribute to the decline in maize yield. The biochar model predicted that the N availability would decrease after biochar treatment because labile (volatile) carbon in the biochar was being decomposed and therefore induced N immobilisation, which put the maize crop under N deficiency and resulted in a decline in yield (Ameloot *et al.,* 2015; Aller *et al.,* 2018). Besides, the application of WBC with a high pH level of 8.3 negatively impacted the alkaline Lusaka clay soil.

Liu and Zhang (2012) stated that the biochar in soil induced the oxidation of SOC. The oxidation activities produced an acidic functional group on the surface of biochar, thus neutralising the pH of alkaline soil. This resulted in a reduction in soil pH, which decreased the soil fertility and collectively reduced the yield.

Table 8 illustrates that the model estimated a decrease in maize yield with an increase of MBC treatment on Lusaka clay soil, coherent with the field experimental results. The initial yield without biochar application was 7340.33 kg/ha. At low treatment, the yield slightly decreased to 7340 kg/ha with a deviation of 18.44%. The simulation model predicted that further increase in MBC treatment decreased the yield to 7338.99 kg/ha with a 10.50% deviation.

The model was able to predict the results at high treatment accurately but deviated from the measured data at the control and low treatment. The simulated yield obtained for MBC was like WBC in which the application of biochar at a higher rate reduced the yield. The model underestimated the control because it was assumed as a very low biochar treatment. At both low and high treatments, the model predicted a small decline in yield corresponding to control. This was possibly due to the mechanism of the biochar model.

Archontoulis *et al*. (2016) stated that the biochar model integrated biochar, soil, crop, climate and management by a feedback system. The effect of individual biochar was offset by this mechanism, which diminished the individual biochar effect on yield. Archontoulis *et al*. (2016) also reported a small increase in yield when the biochar treatment was increased, which indicated that the model simulated small changes even though a large amount of biochar was applied.

The decreasing trend was due to the C/N ratio of MBC was high, an increase in the MBC application rate induced N stress on the maize crop, thus impeding the growth of maize crop (Aller *et al.,* 2018). Besides, the biochar feedstock could be another reason.

A study conducted by Egamberdieva *et al*. (2019) found that no significant effect was observed on chickpea growth after MBC treatment. The simulated results of MBC were similar to WBC, but slightly differed in the trend. Aller *et al*. (2018) stated that the effect of biochar on simulated yield was not exactly a biochar effect because it was mixed up with the tillage effect in the management module.

Free *et al*. (2010) reported that poorer sowing management slowed down the growth

Table 7: Simulated biochar model versus field experiments (Cornelissen *et al.,* 2013) of maize grain yield using WBC on Lusaka clay soil

WBC	Maize Yield (Case Study)	Maize Yield (Simulated)	MAPE (%)
None	9100	7340.33	19.33
Low	6800	7339.76	7.93
High	6900	7339.05	6.36

Table 8: Simulated biochar model versus field experiments (Cornelissen *et al.,* 2013) of maize grain yield using MBC on Lusaka clay soil

MBC	Maize Yield (Case Study)	Maize Yield (Simulated)	MAPE (%)
None	9100	7340.33	19.33
Low	9000	7340.00	18.44
High	8200	7338.99	10.50

of maize. It was also reported that the type of biochar feedstock and biochar application rate had not significantly affected the growth of maize.

Table 9 and Table 10 compare the maize grain yield obtained from the simulation model and field experiments by Cornelissen *et al*. (2013) using WBC and MBC, respectively on Kaoma sandy soil. Table 9 shows that the application of WBC on the sandy soil improved the maize yield.

The models predicted a small increase in yield in WBC treatment at 1941.39 kg/ha and 1941.33 kg/ha on low and high application rates, respectively. The addition of biochar did not show a significant increase in the yield. The model underestimated control and low treatment biochar while overestimated high treatment. Based on the average deviation of 15.75%, the model moderately simulated the field experiments at high biochar application, but the deviation increased at low biochar application levels.

The results were consistent with the Lusaka clay soil in which the model was more capable of predicting at a high application rate. This indicated that the biochar model had low sensitivity and predicting power on crop yield for both Lusaka and Kaoma soils.

The increase in yield was consistent with the field experiments at a low biochar application rate. Based on the measured data, the increase in yields was not significant at a low biochar application rate, but the yields tripled at high treatment. This indicated that the effect of high biochar application was strong on Kaoma clay soil due to the acidic and sandy properties of the soil. However, the increase in simulated yield was insignificant on high biochar application. Zhang *et al*. (2012) stated that wood-derived biochar was high in the C/N ratio and its application on soil would limit the maize production.

High applications of wood biochar with high C/N ratio resulted in N immobilisation and less N available in the soil. Moreover, the yield of maize grain was integrated with biochar-soil variables with a feedback system (Archontoulis *et al.,* 2016). The increase in yield due to soil pH and CEC improvement was counter-balanced by C/N ratio variables at the high treatment of biochar, which resulted in an underestimated yield.

Table 10 illustrates that the yield decreased from 1940.91 kg/ha to 1925.37 kg/ha and 1924.51 kg/ha on low and high biochar application rates, respectively. The measured experimental data showed that the yield quadrupled at a high biochar application rate. However, the simulation results showed a significant decrease after low treatment and gradually decreased for high treatment instead of an increase in the yield.

The biochar model was unable to simulate accurately at high biochar treatment levels, which underestimated the high treatment of biochar. The type of soil and biochar coupled with the low sensitivity of the biochar yield model were the possible reasons for the deviation of data.

The WBC used in the simulation studies had a high C/N ratio and low CEC. N mineralisation in the soil was reduced by high C/N ratio of biochar, which led to N deficiency in the soil. This resulted in less N intake by the plants and impeded the growth (Bista *et al.,* 2019; Kizito *et al.,* 2019). Hailegraw *et al*. (2019) stated that the biochar with high CEC increased the CEC of soil and the effect was based on the biochar properties. The low CEC of MBC did not significantly increase the CEC of sandy soil, which resulted in low exchangeable nutrients in the soil for maize intake.

Archontoulis *et al*. (2016) stated that the growth of crops in the biochar model was affected by the soil water content. The increased soil water content might promote the leaching effect on the soil system and limited the maize yield. The cumulative negative effect of biochar-soil interaction induced a negative result in the simulation.

pH, CEC and SOC

Table 11 compares the MAPE of soil pH levels, CEC and SOC between simulation and field experimental data for Lusaka clay soil and Kaoma sandy soil. The simulation results showed that the pH had a deviation of 8.01% and 7.43%, respectively for 5% WBC and MBC application rate on clay soil. The deviation obtained for WBC was higher than MBC due to the different properties of the biochar.

Table 9: Simulated biochar model versus field experiments (Cornelissen *et al.,* 2013) of maize grain yield using WBC on Kaoma sandy soil

WBC	Maize Yield (Case Study)	Maize Yield (Simulated)	MAPE (%)
None	1600	1940.00	21.31
Low	1700	1941.39	14.20
High	2200	1941.33	11.76

Table 10: Simulated biochar model versus field experiments (Cornelissen *et al.,* 2013) of maize grain yield using MBC on Kaoma sandy soil

MBC	Maize Yield (Case Study)	Maize Yield (Simulated)	MAPE (%)
None	1600	1940.91	21.31
Low	1700	1925.37	13.26
High	3000	1924.51	35.85

Table 11: Comparison of MAPE of soil pH, CEC and SOC between simulation and field experimental data

Condition		MAPE (%)		
Soil	**Biochar**	**pH**	**CEC**	**SOC**
Lusaka	WBC	8.01	14.12	5.32
	MBC	7.43	7.45	7.64
Kaoma	WBC	3.44	18.23	13.79
	MBC	3.82	14.06	15.74

The pH of WBC at 8.3 was higher than MBC at 8.0. The model estimated that the addition of high pH biochar would increase the soil pH more than the low pH biochar. This was mainly because in the biochar model, the pH was a function that was influenced directly by the initial soil pH, biochar liming value and CEC, as represented in Equation 18. The effect of biochar application was determined based on the pH rather than an integrated process that involved several processes and variables such as crop yield. Thus, the model was more sensitive and capable to predict the soil pH value.

However, this caused a larger deviation for WBC than MBC from the measured data. Based on the experimental data, the addition of WBC did not increase the pH of alkaline soil, which contradicted with the model prediction that the WBC application increased the soil pH to 8.4.

Meanwhile, low liming value and pH of MBC did not increase the soil pH as much as WBC, which resulted in a lower deviation. The simulated results were consistent with the experimental results reported by Zhu *et al*. (2015) which showed that only the addition of high pH biochar had significantly increased the soil pH.

The application of WBC and MBC on sandy soil in the other hand showed MAPE of 3.44% and 3.82%, respectively. The small deviation indicated that the model accurately simulated the effect of biochar on soil pH. Butnan *et al*. (2015) showed an improvement of pH in Ultisols (acidic and sandy) soil after biochar application. The model on the effect of pH was most valid, in which the deviation on soil pH was the smallest, consistent with the findings reported by Archontoulis *et al*. (2016).

For CEC, the addition of WBC on clay soil showed a larger deviation than MBC at 14.12% and 7.45%, respectively. The experimental data showed that the WBC increased the soil CEC more than MBC at 22.8 cmolc/kg and 19.4 cmolc/kg, respectively due to the high CEC of WBC. The simulated CEC for WBC and MBC was 18.4 cmolc/kg and 18.2 cmolc/kg, respectively.

The CEC model was influenced by the type of soil and biochar. The biochar with a low CEC value was fresh biochar whereas biochar with a high CEC value was aging biochar. The higher CEC in WBC soil had a lower effect on soil due to the biochar CEC model integrated the effect of aging without specifically identifying the aging mechanism (Archontoulis *et al.,* 2016).

Similarly, the deviation was lower for the MBC application on acidic soil as compared to WBC, which was 14.06% and 18.23%, respectively. Martinsen *et al*. (2015) reported that the soil CEC increased from 5.62 cmolc/kg to 8.12 cmolc/kg and 7.93 cmolc/kg for cacao shell (197 cmolc/kg) and rice husk (20 cmolc/kg) biochar, respectively. Thus, the increase was higher for high CEC biochar as compared to low CEC biochar as observed in the simulation results.

The simulation results for SOC showed that the WBC and MBC application on clay soil had a deviation of 5.32% and 7.64%, respectively. The results indicated that the biochar model was good in predicting SOC in alkaline clay soil. Zhang *et al*. (2018) reported that the SOC in higher biochar treatment was significantly higher than in the soil without biochar application. The simulation results were consistent with the literature, in which the SOC was increased after 5% biochar treatment for both WBC and MBC.

The data showed that the SOC was higher after the MBC application as compared to the WBC application due to the MBC had a higher C/N ratio and organic carbon. The SOC was found to be affected by the priming effect. Hernandez-Soriano *et al*. (2016) reported that the application of biochar increased the amount of carbon in the labile pool due to fast mineralisation. Meanwhile, the SOC in Kaoma soil showed a deviation of 13.79% and 15.74% from the measured data for WBC and MBC application, respectively. According to Archontuolis *et al*. (2016), the model had a low capability to simulate a variable that had complex interaction in soil, which showed a high value of deviation in SOC. Overall, the simulation model was good in predicting the soil pH, but became less accurate at predicting more complex variables such as CEC and SOC.

Model Performance

Effect of Biochar on Maize Yield

Figure 1 illustrates the effect of WBC and MBC treatments on maize grain yield for clay soil and sandy soil crop systems. The application of WBC and MBC reduced the maize yield in alkaline clay soil. The effect of MBC on the maize yield was more significant as compared with WBC. Overall, the change of maize yield from control was not significant which was -0.0182%, -0.0181%, -0.0174% and -0.0078% for high MBC, low MBC, high WBC and low WBC, respectively.

These results indicated that the treatment of both MBC and WBC at either a low or high rate only slightly affected the maize yield in alkaline clay soil. Similar results were observed in the study conducted by Novak *et al*. (2019) which reported that the maize yield from the different treatments of biochar (woodchip, poultry litter and switchgrass at 100% and 50% application rates) did not produce a significant difference from control.

Furthermore, the corn yield was decreased in five out of six treatments. Zhang *et al*. (2012) reported that the biochar amendment increased the crop yield by 7.3% and 15.8%, respectively for 20 tonne/ha and 40 tonne/ha of biochar added on the alkaline soil. However, it was reported that the increase in yield was not proportional to the increase in the biochar application rate. The yield would decrease if the C/N ratio of biochar was high, in which the reduction in yield was observed for biochar with a C/N ratio of 15 as compared with the C/N ratio of 13.

Hence, the high C/N ratio of wood biochar would contribute to the decline in maize production. The application of biochar with a high C/N ratio caused N immobilisation and less N available in the soil.

This resulted in the deficiency of N in crops (Ahmed & Schoenau, 2015). The reduction in the simulated yield was due to the biochar added counter-balanced the soil N. The counterbalance of soil properties resulted in a small decline rather than an expected significant increase in the yield. Besides, further increase in the pH of the alkaline soil after application of biochar might cause negative impact on plant growth.

This was due to the alkalinity effect of biochar which increased the soil pH, causing the precipitate of the macronutrient and micronutrient in alkaline soil and became inaccessible for plant growth (Salem *et al.,* 2019). On the other hand, the acidic sandy soil showed a positive effect with the application of wood biochar. An increase of 0.0731% and

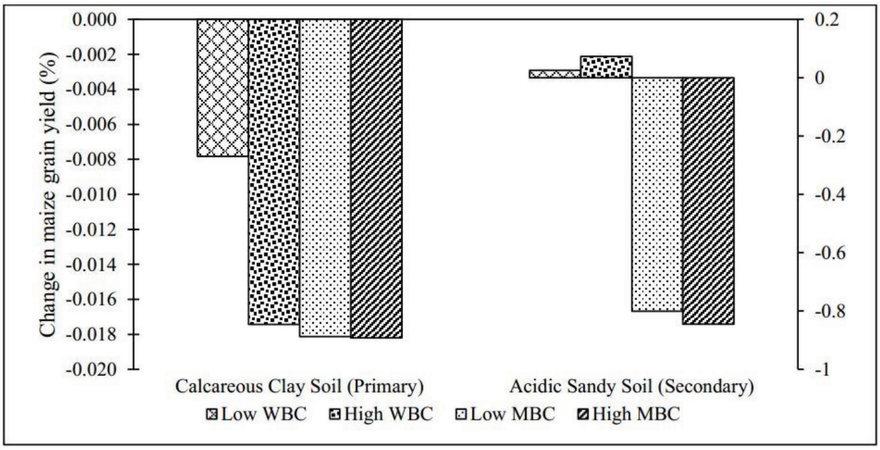

Figure 1: Comparison of change in maize grain yield between biochar and control treatments for Lusaka soil and Kaoma soil crop systems under different application rates of WBC and MBC

0.0257% was observed for high WBC and low WBC treatment, respectively.

The yield was increased by 0.0474% when the WBC application was increased by five times. The simulation model predicted that the addition of WBC would not significantly affect the maize yield. Adekiya *et al*. (2020) reported that the yield of the crop was increased with biochar treatment from 0 to 30 ton/ha in acidic sandy soil. The study claimed that the increase in biochar treatment increased the porosity and moisture content while reducing the bulk density. The improved soil properties increased the nutrient absorption of crops due to the strengthened root penetration which increased the crop yield.

However, there was no significant increase for short season crops due to the inert nature of biochar (Adekiya *et al.,* 2019). According to Carter *et al*. (2013), the biochar effect on longer cycles was more significant than the short cycle. Hence, the effect of WBC on acidic sandy soil increased to a minimal degree due to the short cropping management applied in the simulation studies. In this study, a significant decline of -0.8449% and -0.8006% in the maize yield was observed in high and low MBC treatment on acidic sandy soil, respectively. The decrease of yield in the MBC amendment on acidic sandy soil was due to the high pH and C/N ratio of MBC.

The high pH of MBC increased the pH of acidic sandy soil after being applied in the soil, which significantly increased the soil pH. However, a huge increment of pH in the soil after excessive application on low pH soil would decrease the N uptake of plants from the soil due to the decrease of NO_3^- and NH_4^+ in the soil because of volatilisation, hence it reduced the crop growth and yield. Meanwhile, the optimum pH of WBC has increased the pH at optimum increment without excessively changing the soil properties that would negatively affect the crop growth.

Moreover, the high C/N ratio of MBC would increase the N immobilisation, thus it decreased the crop yield as N became unavailable for crop growth due to the competition between soil microorganism and plant.

The biochar effect on crop yield was linked to N uptake of plants by Tisserant and Cherubini (2019) which found that high application rate of biochar on low pH (<5) and CEC (<5 cmol/kg) soil could reduce the N uptake of plants. Thus, the simulation model predicted that the maize yield was declined under MBC application in acidic sandy soil with pH of 5.6 and CEC of 4.3.

In conclusion, the effect of biochar on soil properties and crop yield was influenced by the type of biochar used in the soil amendment and the type of soil.

Effect of Biochar on Soil pH

Figure 2 presents the effect of WBC and MBC treatments on soil pH for clay soil and sandy soil crop systems. For alkaline clay soil, the soil pH was increased by 17.77% and 19.77% at low and high WBC application rates, respectively.

When compared with the control sample, the soil pH was increased by 4.25% and 18.75%, respectively for low and high treatments. The results depicted that low pH biochar and low biochar treatment did not significantly increase the pH of calcareous clay soil.

According to Zhu *et al*. (2015), the addition of biochar with high pH of 8.36 and 8.16 on Loess and Purple soils showed an insignificant change in soil pH. Moreover, for black soil with high pH of 8.35, only high pH biochar caused significant changes in the soil pH.

The simulated results were consistent with the literature data, in which the model predicted that the application of WBC with a high pH value significantly increased the pH of alkaline clay soil as compared to MBC. The application of WBC on acidic sandy soil increased the soil pH by 29.06% at low treatment levels and doubled to 57.75% at high treatment levels.

Meanwhile, the pH was increased by 17.54% at low MBC application rate and 64.10% at high MBC application rate. This showed that the MBC application rate had a significant effect

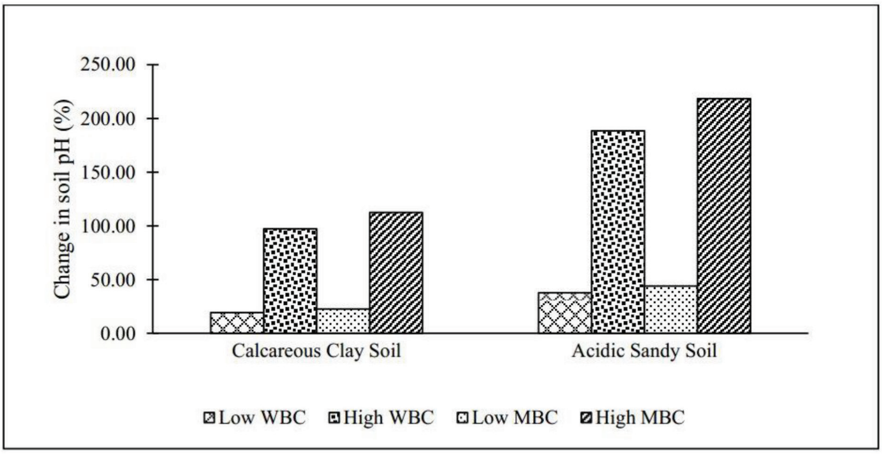

Figure 2: Comparison of change in soil pH between biochar and control treatments for Lusaka soil and Kaoma soil crop systems under different application rates of WBC and MBC

on enhancing the acidic sandy soil. The findings were supported by Juriga and Simansky (2019) which claimed that the application of biochar improved the soil pH.

The study also stated that the high soil pH was observed by increasing the application rate of biochar. The application of WBC and MBC increased the pH of Lusaka soil and Kaoma soil possibly attributed to the high inherent pH of the biochar, base cation content, calcium carbonate content as well as calcium carbonate equivalent (Shetty & Prakash, 2020).

Effect of Biochar on Soil CEC

The effect of biochar on soil CEC is shown in Figure 3. At low biochar application rates on alkaline clay soil, both WBC and MBC had an insignificant impact on soil CEC, which increased by 1.85% and 0.82%, respectively. At the high application rates, the soil CEC increased by 9.27%, four times higher than the low treatment.

A similar trend was observed for MBC application which increased the soil CEC by 4.13%. At low treatment, the soil CEC was

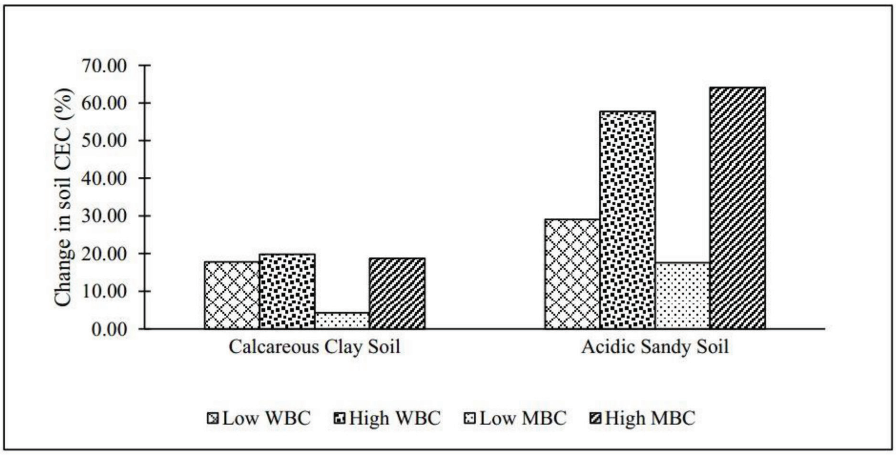

Figure 3: Comparison of change in soil CEC between biochar and control treatments for Lusaka soil and Kaoma soil crop systems under different application rates of WBC and MBC

increased by 4.64% and 2.15% for WBC and MBC, respectively.

The soil CEC was increased by five times at a high application rate, at 23.33% and 10.73% for WBC and MBC, respectively. Kizito *et al*. (2019) reported that the CEC of wood biochar treatment (58 cmol/g) was higher than corn biochar (41 cmol/g), which resulted in a high increment for wood-derived biochar.

Adekiya *et al*. (2019) also reported that the soil CEC was increased at a higher biochar application rate. The biochar properties such as liming ability (alkalinity), base cation concentration and proton consumption capacity were the main reasons for the different effects demonstrated on soil CEC when treated with different rates of biochar (Chintala *et al.,* 2014).

On the other hand, the type of soil also affected the CEC differently under biochar treatment. According to Zhu *et al*. (2015), the increase in CEC was only significant in low CEC soil such as Red soil and Chaotu soil, but not for high CEC soil. Similarly, in this study the improvement of the CEC as predicted for Kaoma sandy soil was more significant than Lusaka clay soil after the biochar amendment due to the low initial CEC of Kaoma sandy soil.

The biochar enhanced the soil CEC due to the surface of the biochar particles which contained strong carboxylic and phenolic functional groups with negative charge (Alkharabsheh *et al.,* 2021).

Effect of Biochar on SOC

Figure 4 presents the effect of WBC and MBC treatments on SOC for clay soil and sandy soil crop systems. The SOC was the most sensitive variable in the biochar model due to the complexity involved which contributed to the low accuracy to predict this variable. The SOC was predicted to increase by 19.33% and 22.44% after applying low WBC and low MBC in calcareous clay soil, respectively.

At a high biochar application rate, the SOC was increased by five times to 97.13% and 112.34% for WBC and MBC treatment, respectively. The SOC increased by 37.37%, 188.35%, 44.01% and 218.45% for low WBC, high WBC, low MBC and high MBC, respectively in sandy soil.

The increase in SOC was proportional to the application rate of biochar. The simulation results were consistent with the field experimental data obtained by Cornelissen *et al*. (2013). The amount of SOC was found to change in a uniform order during the growth of crops, which was consistent with the findings of Yang *et al*. (2020).

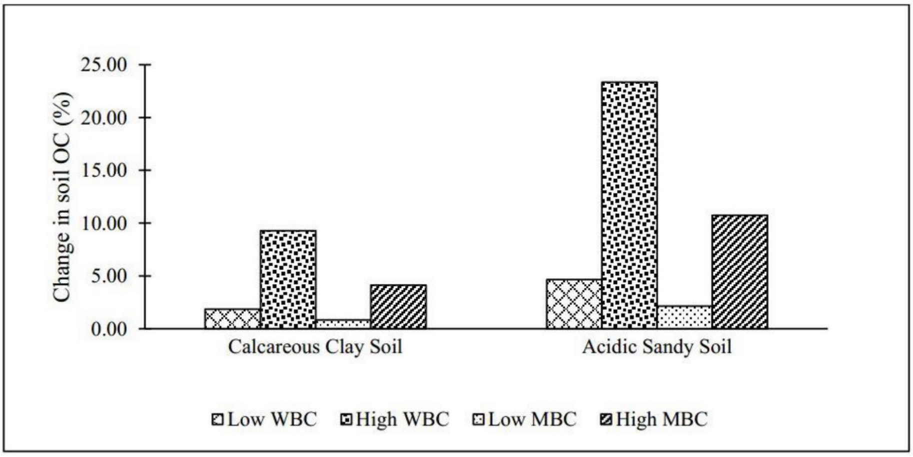

Figure 4: Comparison of change in SOC between biochar and control treatments for Lusaka soil and Kaoma soil crop systems under different application rates of WBC and MBC

Meanwhile, Zhang *et al*. (2018) reported that the soil treated by biochar had higher SOC than the control treatment, which was influenced by the amount of biochar added. This was possibly due to the amount of SOC mineralisation had been decreased with increased biochar application. The simulation model developed in this study also predicted that the SOC increased proportionally with application rate, in which the SOC increased by five times when the biochar amount was increased by five times from low treatment to high treatment. Overall, the content of the SOC had been improved for both Lusaka soil and Kaoma soil due to the high organic carbon content of the MBC and WBC.

Conclusion

In this study, a simulation model has been developed by using APSIM to investigate the effects of WBC and MBC at different application rates on soil pH, CEC, SOC and maize yield. The results obtained for calcareous clay soil showed that as the biochar treatment was increased from 6 ton/ha to 30 ton/ha, the soil pH increased from 14.5% to 17.77% for WBC and from 4.24% to 19.77% for MBC.

The soil CEC increased from 1.85% to 9.27% for WBC and from 0.82% to 4.13% for MBC. The SOC increased tremendously from 19.33% to 97.13% for WBC and from 22.44% to 112.34% for MBC. The results obtained for acidic sandy soil showed that the soil pH increased from 29.06% to 57.75% for WBC and from 17.54% to 64.10% for MBC.

The soil CEC increased from 4.64% to 23.33% for WBC and from 2.15 to 10.73% for MBC. The SOC also increased tremendously from 37.37% to 188.35% for WBC and from 44.01% to 218.45% for MBC.

However, a small decrease in maize yield was obtained for clay soil from -0.0174% to -0.0078% for WBC and from -0.0182% to -0.0181% for MBC. The maize yield for sandy soil increased from 0.0257% to 0.0731% for WBC but decreased from -0.8006% to -0.8449% for MBC. The simulation model developed was considered modest in simulating the effects of WBC and MBC on soil dynamics and maize yield. The prediction of the biochar effect on soil pH was the most accurate among all the variables studied. The simulation model was good at predicting the change of properties in calcareous clay soil for both WBC and MBC as well as WBC in acidic sandy soil.

The results demonstrated that both WBC and MBC amendment successfully improved the soil pH, SOC and soil CEC as compared to control. The effect was more significant when a higher application rate of WBC was applied. The biochar amendment enhanced the properties of acidic sandy soil more significantly as compared to calcareous clay soil. Based on the simulation studies, Kaoma soil was more suitable for biochar utilization as compared to Lusaka soil.

The MBC and WBC had enhanced the soil dynamics of Lusaka soil and Kaoma soil, however the biochar application effect on maize yield was insignificant. This was due to the insufficient N content present in MBC and WBC to support maize growth. Overall, WBC and MBC are potential green fertilisers for enhancement of soil quality towards sustainable agriculture.

To improve the simulation model developed in this study, a cascade system is recommended to be implemented in future studies to minimize the effect of the feedback system of each variable that neutralizes the effect of biochar. The study on the effect of wood and maize cob-derived biochar on the growth of other crop systems and water retention properties in various soil types and/or conditions are also recommended to be studied.

In addition, the effect of various biochar types on soil dynamics and crop yield could also be investigated as the properties of biochar are influenced by the feedstock type, pyrolysis condition and biochar synthesis method.

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Appendix

Biochar Model

Biochar on C/N ratio

$$dtNBC = dtNBC_{released} - dtNBC_{need}$$

$$dtNBC_{need} = \frac{dtBC_{biom}}{CN_{biom}} + \frac{dtBC_{hum}}{CN_{hum}}$$

$$dtNBC_{released} = \frac{dtBC}{CN_{BC}}$$

Biochar on NH_4 Absorption and Desorption

$$NH_{4ads} = K_{ads} \frac{K_{ads}\ x\ \left(\frac{Soil_{cecBC}}{Soil_{cec}}\right)}{1 + K_{ads}\ x\ \left(\frac{Soil_{cecBC}}{Soil_{cec}}\right)}$$

$$NH_{4des} = K_{des} \frac{K_{des}\ x\ \left(\frac{Soil_{cecBC}}{Soil_{cec}}\right)}{1 + K_{des}\ x\ \left(\frac{Soil_{cecBC}}{Soil_{cec}}\right)}$$