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Effect of Activated Biochar on Soil Physical Properties and Heat Capacity in a Humid Tropical Ultisol

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Abstract
Management of Soil physical properties is key in managing sustainable soil productivity. This study was carried in the high tunnel hoop house located at the Teaching and Research Farm of the Rivers State University Port Harcourt, to determine the effect of activated biochar on some soil physical properties and heat capacity.
The Biochar materials included: wood shaving (WS), corn cob (CC), hard wood (WD), palm kernel shell (PK), cattle bone (BN). These were produced separately by pyrolysis and used to amend the topsoil used.
Results showed that biochar improved some soil physical properties. Bulk density was reduced from 1.42gcm^{-3} in the control to 1.28 gcm^{-3} by CC biochar., and total Saturated hydraulic conductivity was increased by 108% by BN biochar, while total porosity was increased from 47 to 52% by the CC biochar. CC and BN also significantly increased (p=0.05) moisture retention capacity when compared to the control. Aggregate size distribution and soil heat capacity were not significantly affected by the biochar amendment. However, the volumetric heat capacity of all treatments were significantly higher when wet (between 7.27 x 10^{-1} cal cm^{-3} ^{0}C^{-1} to 8.13 x 10^{-1} cal cm^{-3} ^{0}C^{-1}) than when the soils were dry(between 2.33 x 10^{-1} cal cm^{-3} ^{0}C^{-1} to 3.18 x 10^{-1} cal cm^{-3} ^{0}C^{-1}). Results suggest that for soils with low saturated hydraulic conductivity or waterlogged conditions, the BN biochar can be effectively used to increase saturated water flow. WD and WS biochar amended soils with 50% total porosity, had moisture retention capacity was significantly lower than the control. This suggests that their pore sizes were more of macropores which conduct moisture, than micropores which retain moisture.
Key words: biochar; soil physical properties; heat capacity.

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I. INTRODUCTION

Over the years, research abound on the use of plant and animal residues to improve on soil fertility status and productivity. However, high temperatures consistent with the tropics makes organic matter decomposition rates high (Fierrer *et. al.*, 2005, Fang *et. al.*, 2005, Broad Bent, 2015, Lien and Wang 2013). This lends to the use of biochars as a soil ammendments due to its ability to retain nutrients for longer periods (Busscher *et. al.*, 2011, Adekiya *et. al.*,2020). Studies have shown that soil amendment with biochar improved soil physical properties(Lien and Wang 2013, Kimet and Lehmann 2010, Liang *et. al.*, 2006, Joseph *et. al.*, 2010, Chang et al 2007 and 2008), chemical properties (Lehmann *et. al.*, 2009, Adekiya, *et. al.*, 2019, Lehmann and Rondon 2006 and Ajayi *et. al.*, 2016) and therefore crop yield.

However, some soil physical properties do not appear to change readily with the amount of biochar used. In general, biochar appears to have greater benefits on coarse-textured soils than on fine-textured soils (Omondi et al., 2016); like in properties like bulk density, water retention, saturated hydraulic conductivity. It is the other way round with properties like soil aggregation where clay particles provide a cementing effect.

There are also varying reports on the effect of biochar on some soil moisture related properties. Saturated hydraulic conductivity values were reported to decrease approximately linearly as the rate of biochar application increased. Another study observed increased saturated hydraulic conductivity as a result of adding charcoal to native soils over an extended period of time (Ayodele *et. al.*, 2008 and Oguntunde, *et. al.*, 2009). Other studies have reported no significant change in saturated hydraulic conductivity t due to interaction of biochar application and a variety of soils (Hardie, *et. al.*, 2014).

It appears that for clay soils, biochar may enhance (increase) saturated hydraulic conductivity by increasing the number and/or connectivity of macropores, while sandy soils may have decreased saturated hydraulic conductivity due to the absorptive capacity of the biochar. Changes in saturated hydraulic conductivity are linked to changes in soil porosity, aggregation, and water holding capacity. Many studies have observed decreases in bulk density and increases in porosity as a result of biochar application (Chan, *et. al.*, 2008, Chen, *et. al.*, 2011, Githinji, 2014, Mukherjee and Lal, 2014).

Soil thermal properties include thermal conductivity, volumetric heat capacity, and thermal diffusivity. These properties directly influence the energy balance and the storage and transfer of heat through the soil. (Zhang *et. al.*, 2013). The few published studies on biochars have found that its application may affect soil temperature. Corncob biochar addition has been reported to reduce soil thermal conductivity by 3.5% under 4.5 Mg ha-1 of biochar (Zhao *et. al.*, 2016). Soil moisture and bulk density influences soil heat dissipation (Ochsnor *et. al.*, 2001). The beneficial effects of biochar on soil thermal properties can have large implications for the storage and transfer of heat through the soil and mitigation of climatic fluctuations.

These findings in the temperate notwithstanding, research on biochar effects on soil physical, moisture and temperature related properties in the humid tropical environment, with highly weathered soil. The aim of this study is to assess the effects of biochar from various materials on the physical and thermal properties of an ultisol in the humid tropics.

II. Material and Method

Study Site

The study was conducted in the High Tunnel Hoop House located at the Teaching and Research Farm Rivers State University, Port Harcourt. The study location lies in the humid tropical zone of the southern Nigeria. It lies between latitude 4.5°N and longitude 7.0°E on an elevation of 18m above sea level. The mean annual rainfall in Port Harcourt ranges from about 3,000mm to 4,500mm, annual temperature ranges from 22°C to 29°C while relative humidity varies between 75% and 95%. Port Harcourt soils are of coastal plan sands which range from loamy sand to sandy loam in the surface soil horizon, with pH values of between 4.0 and 5.8 in water (Ayohagha and Onuegbu. 2002).

Experimental Material

Top soil was obtained from uncultivated fallow soil in Port Harcourt Nigeria. The biochar materials used were wood shaving (WS), corn cob (CC) hard wood (WD), palm kernel shell (PKS) and cattle bone (AB). Hard wood (WD) and wood shaving (WS) were collected from a Timber Mill in Port Harcourt City of Rivers State Nigeria. Palm kernel shells were collected from Vika Farm in Uyo, Akwa Ibom State Nigeria. Cattle bone (AB) and corn cob (CC), were collected from the Rivers State University Teaching and Research farm abattoir and maize units, respectively.

Production of Biochar

The Plant and Animal materials (Corn cobs, palm kernels shell, wood shaving, wood and animal bone) was subjected to heating through a process known as pyrolysis using a cut drum (local drum) method. The char was removed by sprinkling water to put off the fire and left to cool for (3) three days. After which the char were bagged and kept for use. The various biochars were activated by mixing each biochar with dried poultry manure and fish pond effluent in the ration 1:1:4. The mixtures were left covered to cure for a period of 21 days. The bags were kept weed free by hand picking and kept at field capacity moisture content for another 4 weeks. The treatments consisted of six (6) levels of biochar which include; wood (WD), wood shaving (WS), com Cob (CC), palm kernel shell (PKS), cattle bone (BN) and a control (Co). These were replicated three times

Data Collection

A cylindrical metal cores with a dimension of 5cm internal diameter x 5cm height was used to collect undisturbed soil samples from the various treatments. they were used to determine bulk density, total porosity, water holding capacity, saturated hydraulic conductivity of the soil. Bulk density was determined using the procedure described by Blake and Hartage (1986), using the undisturbed samples to be collected with a cylindrical cores measuring 5cm in height and 4.6cm in diameter. The bulk density was given as a ratio of mass of oven-dried soil to column. The bulk density will be derived from the equation below:

$$\ell b = Ms/Vb \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where:

ℓb = Bulk density (gcm^3)

Ms = Mass of oven dried soil (g)

Vb = Bulk volume of the soil (cm^3)

Total porosity was calculated from the bulk density by assuming average particle density as $2.65kgm^3$ using the equation

$$P = (1 - \ell b/\ell s) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where;

P = Total porosity

ℓb = Bulk density (Kgm3)

ℓs = particle size density (kgm^2)

The water holding capacity was determined by converting the saturation gravimetric moisture content to the volumetric moisture content using the following equations.

θm = Mw/Ms ………………………..(3)

θv = (θm x ℓb) / ℓw…………………(4)

Where;

Θm = Gravimetric moisture content

Mw = Mass of water (g)

Ms = Mass of solid particles (g)

θv = Volumetric moisture content (cm^3cm^{-3})

ℓb = Bulk density (gcm^3)

ℓw = Particle density (gcm^3)

Saturated hydraulic conductivity was determined using the constant head permeameter method as described by Klute and Dickson (1986). It was derived from an empirical relationship between the flux of water through saturated columns of soil and the hydraulic head loss expressed as follows:

$q = Q^1 /At \ \alpha \ \Delta H/L$…………………………………… (5)

$Q^1 /At = Ks \ \Delta H/L$……………………………………. (6)

$Ks = Q^1 /AT \times L/\Delta H = Q^1L / \Delta HAT$ ……………… (7)

Where,

q = flux density of water (cm sec^{-1})

Q^1 = equilibrium volume of water passing through the soil column (cm^3)

L = length of soil column (cm)

A = cross sectional area through which the flow takes place (cm^3)

ΔH = Change of hydraulic head

T = time (sec.)

h = pressure head (cm)

Ks = saturated hydraulic conductivity (cm sec^{-1})

The dry aggregates distribution was determine using with a nest of sieves by the procedure of Kenper and Chepil as described by Nweke and Nnabude (2014), and mean weight diameter was calculated with the formula below.

MWD $=\sum_{i=1}^{n} XiWi$……………………………………………(8)

Where;

MWD = Mean weight diameter (mm)

Xi = Mean diameter size range of aggregates separated by a sieve (mm)

W_1 = Weight of aggregates in that size range, as a function of the total dry weight of the sample analyzed (g)

The volumetric heat capacity was estimated by the sum of the product of the heat capacity of the various components of the soil and the their volume fraction in the soil as shown below.

Csoil = fmcm + foco + fwcw + faca ………………………. (9)

Where C = volumetric heat capacity ($Cal^oC^{-1}cm^{-3}$), c = heat capacity, m = mineral matter, o = organic matter, w = water, a = air and F = volume fraction of each component.

Bulk samples were also collected from the treatments; air dried,crushed to pass through a 2mm sieve and used for routine soil analysis. Particle size distribution was determined by Bouyoucos hydrometer method as described by Gee and Bauder (2002). The percentage of sand, silt and clay were used to assign the sample to a textural class based on the soil textural triangle. The top soil was analyzed for pH, total nitrogen, organic carbon, organic matter and carbon:nitrogen ratio. The pH was determined in a soil water ratio of 1: 2.5 using pH meter with a glass electrode. Organic carbon was determined by Walkey and Black method and total nitrogen by micro-Kjedahl method, available phosphorus by bray-1 extraction method, and exchangeable bases by the ammonium acetate extraction method (Boem, *et. al*., 2011).

III. Results and Discussion

Properties of the Soil Used in the Experiment

The result of some physical and chemical properties of the top soil used for the experiment is as shown on Table 4.1. The soil is loamy sand with an acidic pH of 4.97. It is low in total nitrogen (0.004%) and a percentage organic matter content (2.02%). The soil was generally low in exchangeable base; which is typical of ultisols.

Table 1: Properties of the top soil used in the experiment

Soil Properties	Value
% Sand	85.8
% Silt	10.4
% clay	3.8
Textural class	Loamy sand
pH H_2O	4.97
% organic carbon	1.7
% organic matter	2.02
% total nitrogen	0.004
Available P ($cmolkg^{-1}$)	0.18
Ca^{2+} ($cmolkg^{-1}$)	0.017
Mg^{2+} ($cmolkg^{-1}$)	1.0
Na^{+} ($cmolkg^{-1}$)	6.0
K^{+} ($cmolkg^{-1}$)	4.0

Effect of Activated Biochar on Some Soil Physical Properties

Particle size distribution was significantly affected by amending the soil with biochar (Table 1). Soils amended with the various biochars showed increased %silt contents from 5.4% in the control (CO) to 8.1, 7.1, 7.1, 7.1 and 6.4% for wood (WD), palm kernel (PK), wood shaving (WS), corn cob (CC) and animal bone (BN) biochars, respectively. This resulted in the change of most of their soil texture from loamy sand to a finer texture of sandy loam.

Table 2: Effect of Biochar on Particle Size Distribution

Treatment	% clay	% silt	% sand	Texture
Cattle bone	10.1	6.4	83.5	Loamy sand
Corn cob	10.4	7.1	82.5	Loamy sand
Palm kernel shell	11.4	7.1	81.5	Sandy loam
Wood	10.4	8.1	81.5	Sandy loam
Wood shaving	11.1	7.1	81.9	Sandy loam
Control	11.7	5.4	83.2	Loamy sand

Bulk density was significantly reduced by all the biochars used (Fig.1).
The bulk density values were in the order CC < WD & WS< BN < PK < CO. The CC amended soils had the least bulk density of $1.28gcm^{-3}$ when compared to the control with $1.4gcm^{-3}$
This agrees with previous reports that biochar significantly decreases bulk density by increasing the pore volume (Mukherjee et al.,2014).

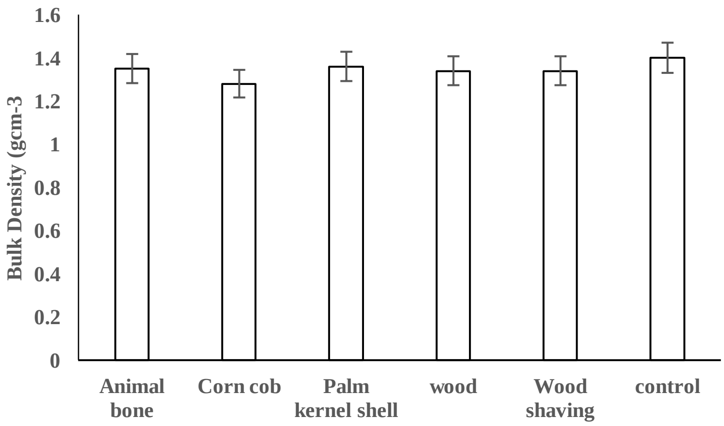

Fig 1: Effect of biochar on bulk density:

The result of the effect of biochar on total porosity showed that as the bulk density reduced the total porosity increased (Fig. 2). The CC biochar treatment gave the highest total porosity of 52%, followed by the WS and WD biochars (50%) and BN and PK biochars (49%). This is consistent with the requirements of total porosity values for an ideal soil structure (Mbonu and Opara-Nadi, 2008, Atkinson *et al.*, 2010 and Orji and Oko-Jaja 2016). This suggests that organic biochar can be use to improve on the volume of pores and therefore and enhance soil structure and reduce soil degradation.

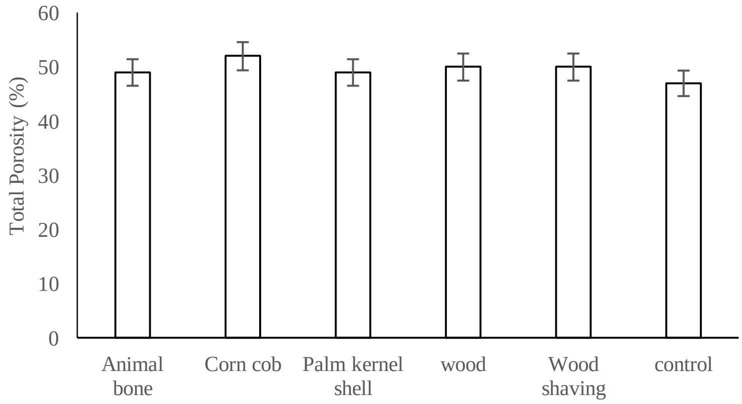

Fig. 2: effect of biochar on porosity

The results of the effects of biochars on the soil saturated hydraulic conductivity show that the BN, CC and WD positively affected saturated hydraulic conductivity, while the PK and WS negatively affected saturated hydraulic conductivity (Fig. 3). Several studies have reported that the incorporation of biochar to soil increased the saturated hydraulic conductivity (Oguntunde *et al.*, 2008). This study has however, shown that not all biochar materials will increase the saturated hydraulic conductivity of the soil. The PK and WS biochars reduced the saturated hydraulic conductivity from 7.1 cmhr^{-1} in the control to 6.0 cmhr^{-1} and 6.1 cmhr^{-1} respectively. It is also noted that the BN biochar significantly increased the soil saturated hydraulic conductivity to 14.7 cmhr^{-1}, with a 108% increase. This suggests that for soils with low Ks or waterlogged conditions, the BN biochar can be effectively used to increase saturated water flow.

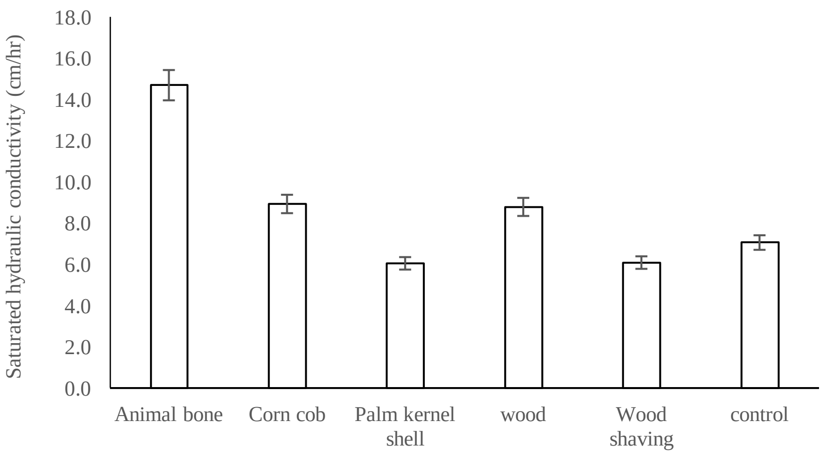

Fig. 3: Effect of biochar on saturated hydraullic conductivity

The result of water holding capacity is as affected by biochar amendment is as shown on Fig.4. The results show that BN and CC biochars positively affected water holding capacity, WD and WS negatively affected it, while PK biochar had no effect on it.

Although the WD and WS biochars had 50% total porosity, their moisture was significantly lower than the control. This suggests that their pore sizes were more of macropores which conduct moisture, than micropores which retain moisture. This is also observed with the CC biochar with the highest total porosity and highest water holding capacity. This implies that it has more of micropores. Its low saturated hydraulic conductivity also explains this observation; as saturated hydraulic conductivity is dependent more on macro porosity.

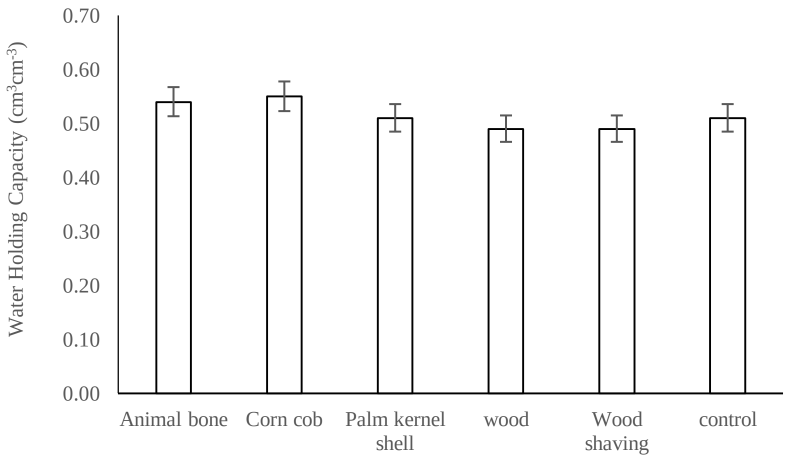

Fig 4: effect of biochar on Water Holding Capacity

Results show that the amendment with biochars generally had no significant difference on aggregate size distribution Fig. 5. However, there was an increase in the percentage of aggregates >3.5mm in diameter, soil amended with WS. This also resulted in a decrease in the smaller range of aggregates for the same treatment. The Mean weight diameter across all treatment was between 1.86 and 2.01mm Fig. 6. This indicates that most of the aggregates were in the lower range of diameter, including the control with mean weight diameter of 1.98mm. It was also observed that the BN biochar further reduced the mean weight diameter to 1.86mm when compared to the control.

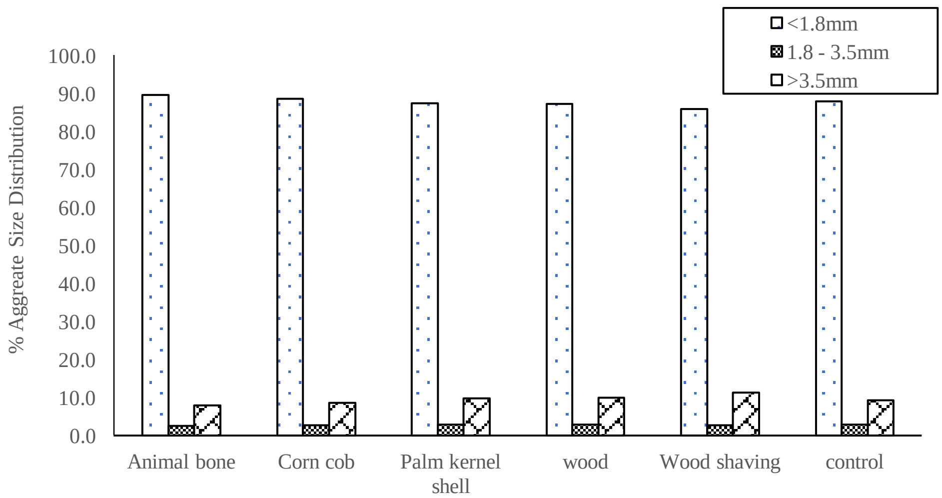

Fig.: 5: Effect of Aggregate Size Distribution

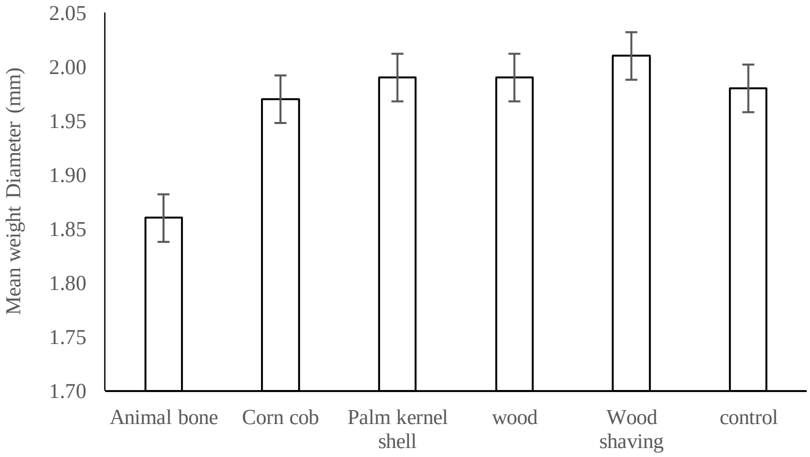

Fig 6: Effect of biochar on Aggregate mean weight diameter

Effect of Biochar on Heat Capacity of the Soil

The heat capacity was not affected by amending the soil with biochar (Fig 4.6). The results show that all amendment had no significant effect (P =0.05) on the heat capacity of the soil as compared with the heat capacity of the control. Similar study in Italy found no effect of biochar application at 30 and 60 Mg ha^{-1} on soil temperature at 7.5 cm depth (Ventura *et. al.*, 2012).

However, across all the treatments, the heat capacity was higher in wet soils than in the dry soil. The range was between 7.27 x 10^{-1} cal $cm^{-3}\,{}^{0}C^{-1}$ to 8.13 x 10^{-1} cal $cm^{-3}\,{}^{0}C^{-1}$ for the wet soils and between 2.33 x 10^{-1} cal $cm^{-3}\,{}^{0}C^{-1}$ to 3.18 x 10^{-1} cal $cm^{-3}\,{}^{0}C^{-1}$ for the dry soils. The specific heat of water being very high (1.0 x 10^{-1} cal $cm^{-3}\,{}^{0}C^{-1}$) may have contributed to this; as the heat capacity of the soil is a function of the heat capacities of the various components of the soil. Similar findings have also been reported by Ochsnor *et. al.,* 2001 and Onwuka and Mang, 2018. It was also observed that the WD biochar had the lowest highest volumetric capacity for both dry and wet soil.

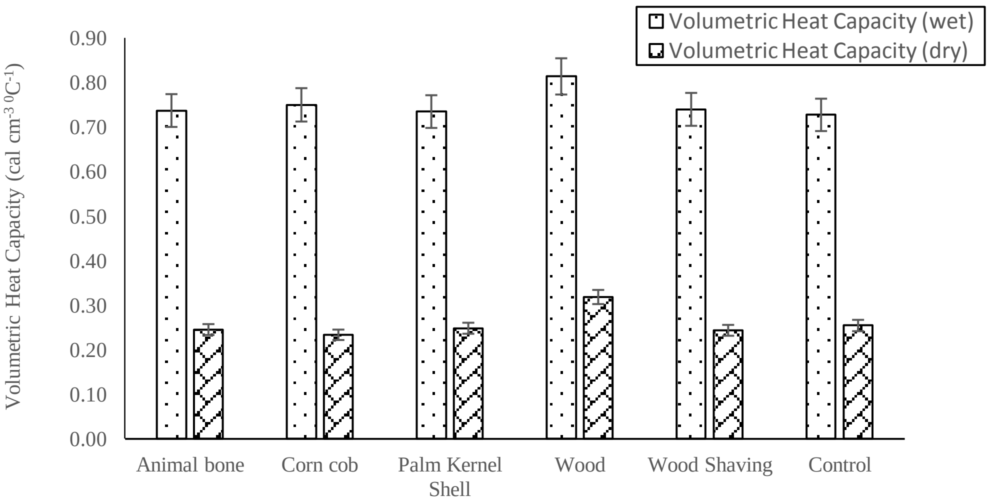

Fig 7: Effect of Biochar on Volumetric Heat Capacity

IV. Conclusion

Physical properties play a great role in the mechanical behaviour of the soil. Water air and nutrient and heat movement are determined by their effects on soil structure.

Incorporation of plant and animal residues have been used to improve these properties. However, their fast decomposition in the tropics does not make this approach sustainable. The biochar technology is therefore gaining a lot of grounds. The result of this study has shown that the different plant and animal residues, used differently to produce biochars have improved most of the physical properties assessed. Heat capacity was not affected by biochar amendment, but results collaborated previous studies that heat capacity of soils when wet or at high moisture contents significantly differs from their heat capacity when the soil is dry or at low moisture contents.

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