



Water holding capacity of soil amended with bamboo and sugarcane trash biochar

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ABSTRACT

The aim of this study was to investigate the suitability of locally available bamboo (*Arundinaria alpina*) and sugarcane trash (*Saccharum officinarum* Linn) biomass feedstock in East Africa to produce biochar for improving soil water holding capacity. A randomized complete block design with split-split plot arrangement was used with biomass feedstock as the main plot factor, pyrolysis temperature (350°C, 450°C, and 550°C) as sub plot factor, and biochar application rate (2, 5, and 7 wt %) as the sub-sub plot factor while controlling for drainage time with four replications. The results showed that water holding capacity of sandy loam soil could be increased by up to 124 % when biochar produced at 550°C was applied at 5-7 wt %. Therefore, application of biochar, from locally sourced biomass, has the potential to promote food production and reduce the high toll of undernourishment in East Africa by better retention of irrigation and rain water.

Keywords: Application rate, biochar, biomass feedstock, sandy loam soil, pyrolysis temperature, water holding capacity

RÉSUMÉ

Le but de cette étude était d'étudier la pertinence de la biomasse de bambou (*Arundinaria alpina*) et de déchets de canne à sucre (*Saccharum officinarum* Linn) disponibles localement en Afrique de l'Est pour produire du biochar pour améliorer la capacité de rétention d'eau du sol. Une conception de blocs complets aléatoires avec un arrangement de parcelles fractionnées a été utilisée avec la matière première de biomasse comme facteur principal du tracé, la température de pyrolyse (350°C, 450°C et 550°C) comme facteur de sous-parcelle et le taux d'application de biochar (2, 5 et 7% en poids)) comme facteur de sous-sous-parcelle tout en contrôlant le temps de drainage avec quatre répétitions. Les résultats ont montré que la capacité de rétention d'eau du sol limoneux sableux pouvait être augmentée jusqu'à 124% lorsque le biochar produit à 550 C était appliqué à 5-7% en poids. Par conséquent, l'application de biochar, à partir de biomasse d'origine locale, a le potentiel de promouvoir la production alimentaire et de réduire le bilan élevé de la sous-alimentation en Afrique de l'Est grâce à une meilleure rétention de l'eau d'irrigation et de pluie.

Mots clés: Taux d'application, biochar, matière première de la biomasse, sol limoneux sableux, température de pyrolyse, capacité de rétention d'eau

INTRODUCTION

East African countries are the most food insecure in the world with 33.9% proportion of undernourishment in 2016 (FAO *et al.*, 2017) and climate change is expected to further aggravate declining harvests. About 80% of East Africa's population contributes 40% to Gross Domestic Product and obtains their livelihoods from rain fed agriculture which is prone to drought. Therefore, sustainable water management in agriculture requires approaches that can enhance soil water holding capacity. Biochar application as a soil amendment has shown sustainable improvement in physical and hydraulic properties of soil (Kammann *et al.*, 2011; Lei and Zhang, 2013). Biochar is a solid product of pyrolysis process in which biomass feedstock is heated under no or low oxygen supply (Bruun, 2011). Experimental studies have shown that in many cases soil amended with biochar has higher water holding capacity. In their small-scale short-term pilot field study, Karhu *et al.* (2011) reported that biochar increased water holding capacity of silt loam soil by 11% as compared to un-amended control soil sample. Similarly, Laird *et al.* (2010) reported an increase in soil water retention of up to 15% after hard wood biochar addition at gravity drained equilibrium. However, Brantley *et al.* (2015) shows that much as poultry litter biochar improved soil water holding capacity, wood chip biochar did not, hence not all soil amendment with biochar can improve soil water holding capacity.

Biochar properties depend on biomass feedstock used (crop residues, by-products of the wood processing industry, animal waste, and forestry residues) and the pyrolysis conditions under which it is prepared (Lei and Zhang, 2013). But it is evident that there is limited information on the effect of biomass feedstock, pyrolysis conditions and application rate on soil water holding capacity (Brantley *et al.*, 2015). Many studies report increase in water holding capacity with corresponding increase in biochar application rate (Basso

et al., 2013; Mangrich *et al.*, 2015; Liu *et al.*, 2016). However, it is economically not practical to optimize biochar properties and biochar application rates to soil especially in areas with limited biomass feedstock (Novak *et al.*, 2009; Filiberto and Gaunt, 2013). Crop residue biomass from sugarcane and bamboo harvests presents an important resource in East Africa, which can otherwise be utilized for biochar production. For example, in 2016, East African countries produced approximately 21 million tonnes of sugarcane on a total area coverage of 362 thousand hectares with an average yield of 51.7 tons/ha (FAO, 2017). This is smaller and less efficient production if compared to the leading producer, Brazil which produced 768.7 million tonnes on 10.23 million ha with a yield of 75.2 tones/ha in the same year. Therefore, East Africa is projected to increase its sugarcane production to 27.2 million tonnes given improved agronomic practices and even more with increase in area allocated for sugarcane farming (FAO, 2017).

Sugarcane produces trash (consisting mainly of leaves) which constitutes 10-20% of the harvested cane yield (Yadav *et al.*, 1994) and can be used for biochar production. In addition to agricultural residues, bamboo with its fast-growing rate of three feet per day, ability to withstand erratic weather, its regenerative nature without need for replanting and high residues from diverse applications can generate significant amount of biomass suitable for biochar production (Julia, 2018). Bamboo forest coverage in Kenya, Tanzania, and Uganda is estimated to be 150,000 ha, 127,000 ha, and 61,662 ha respectively (Chihongo, 2000; Kasozi, 2008; KEFRI, 2008). The mean annual productivity of a bamboo plantation is estimated to be 47.8 tons/ha/yr dry material (Tewari *et al.*, 2015) with a potential to attain a peak absorption of 5.5 t C/ha in the 5th year (Yiping *et al.*, 2010). It is therefore important to look for ways to diversify utilization of the bamboo residues in a beneficial way.

Based on the above, the objective of this study

was to investigate the suitability of two abundant biomass feedstock: bamboo (*Arundinaria alpina*) and sugarcane (*Saccharum officinarum* Linn) in East Africa to produce biochar for improving soil water holding capacity. The effect of feedstock, pyrolysis temperature and biochar application rate on water holding capacity of biochar-soil mixtures was investigated.

METHODOLOGY

Study area. All experiments carried out in this study were conducted under controlled conditions at the University of Edinburgh, UK Biochar Research Centre (UKBRC) laboratories, School of Geosciences, King's Buildings, West Mains Road, Edinburgh, United Kingdom.

Study design. A randomized complete block design with split-split plot arrangement was used with biomass feedstock (bamboo and sugarcane trash) as the main plot factor, pyrolysis temperature (350°C, 450°C, and 550°C) as sub plot factor, and biochar application rate (2, 5, and 7 wt%) as the sub-sub plot factor while controlling for drainage time with four replications. The temperature range selected includes recommendations of previous studies for complete carbonization (Hernández-Mena *et al.*, 2014). Lower biochar application rates were chosen to accommodate recommendations

of previous studies (Puehringer, 2016; Hien *et al.*, 2017).

Biomass feedstock collection. Biomass from two agricultural wastes which are bamboo branches and sugarcane trash were randomly sourced within East Africa as feedstock to produce biochar. Bamboo branches were collected from a farm located in Iganga district in Eastern Uganda whereas dry sugarcane leaves known as trash were obtained from Bungoma farm in western Kenya at 00 34'00"N 34°34'00"E. Biomass feedstock was dried, packed in sealed double bags and then delivered under an import license to the UKBRC laboratories at the University of Edinburgh for experimental tests under controlled conditions.

Biochar production. Biochar production from the two feedstocks was done in accordance to Crombie *et al.* (2013) as described below. Biomass feedstock was cut into small pieces of approximately 10 cm length in order to maximize biochar production, oven dried overnight at 80°C to remove any absorbed moisture prior to pyrolysis. The dried biomass feedstock was then pyrolyzed separately by slow pyrolysis using highly controllable laboratory fixed bed pyrolysis unit. The pyrolysis setup is illustrated in the schematic diagram in Figure 1.

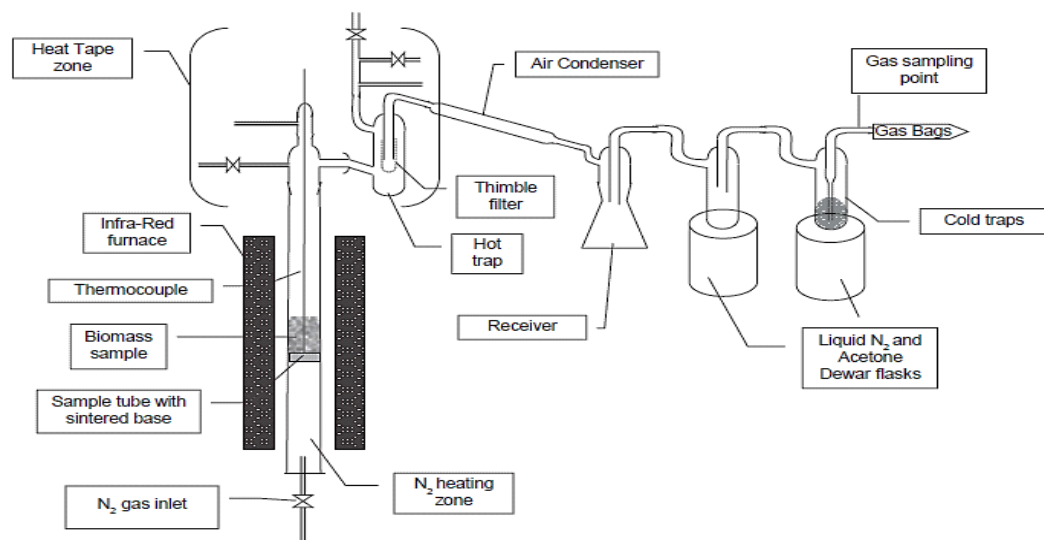


Figure 1. Schematic laboratory furnace condenser system at UKBRC, The University of Edinburgh (Crombie *et al.*, 2013)

The dried biomass was weighed, placed in a pre-weighed fixed bed glass reactor tube (50 mm ID) which was then inserted inside a tube furnace, with attached condenser system. The pressure sensors were zeroed and the system was purged with Nitrogen (N₂, 99.5%) gas at 0.2 l/min for five minutes before the start of heating. The material was then heated up to the desired peak pyrolysis temperature (350°C, 450°C and 550°C) at a heating rate of 20°C/min and then kept at the peak temperature for 30 minutes in order to allow complete conversion of the biomass to biochar. The furnace was then left to cool for about two hours until the temperature dropped to 100°C. The weight of the glass reactor containing biochar was determined. The biochar was then removed from the glass reactor and stored in a sealed glass jar. All mass measurements were done using Sartorius Excellence E2000D balance, with a scale accuracy of 0.01g.

Soil-biochar mixture preparation. The soil used in this study was a typical coarse textured sandy loam soil (8-14% clay), collected from Rothamsted Research's Woburn Experimental farm, 70 ha in mid Bedfordshire (Poulton, 2006) under the material transfer agreement ref. 12117. The soil sample was chosen because it has a high proportion of sand (50-70%) which is responsible for low water holding capacity. Prior to analysis, the soil that passed through the 2 mm sieve mesh was oven dried at 80°C overnight, and then cooled to room temperature in a desiccator containing silica gel. Each biochar sample was lightly crushed using a mortar and pestle, and then sieved using a 2 mm sieve mesh. The biochar that passed through the 2 mm sieve mesh was mixed thoroughly to obtain a uniform sample that would mix evenly with soil. Having attained a uniform mixture, each batch of biochar sample was placed in a clearly labelled flat bottomed aluminium dish, oven dried at 80°C overnight to remove any absorbed moisture, and then cooled to room

temperature in a desiccator containing silica gel. Each dry biochar sample was thoroughly mixed with dried soil in order to make different soil-biochar mixtures containing biochar proportions (2, 5, and 7 wt%).

Water holding capacity determination. Water holding capacity (WHC) of soil biochar mixtures can be determined by various methods and the estimates are greatly influenced by method used (Silva *et al.*, 2014). It can be determined by gravimetric method (g water/g soil-biochar mixture), volumetric method (ml water/ml soil-biochar mixture), physiological method as proposed by Briggs and Shantz (1912), or soil water content retained at 1500 kPa estimated in Richards chamber (Klein *et al.*, 2006). Other methods as described by Zermeño-González *et al.* (2012) include neutron scattering, tensiometers, time domain reflectometry, and porous blocks. In this study, gravimetric method was used because of its simplicity (Kursar *et al.*, 2005), accuracy, low cost and direct measurement in application suitable for the peasant farmers in East Africa.

Weights of filter papers (Whatman cat no 1001 125 mm) and funnels were recorded and carefully matched in pairs to be used for each soil-biochar sample. Funnel tips were tightly closed with blue tack to prevent water from seeping through during the soaking time. A sample of 5g soil-biochar mix was weighed and carefully placed onto the corresponding pair of funnel and filter paper. A small amount of de-ionized water was added in order to saturate the whole sample. A glass rod was then used to gently stir so that all the particles were efficiently soaked. Care was taken to avoid losing any particle by washing off any remaining particles with de-ionized water back into the mixture. All samples were then covered with aluminum foil to minimize any water loss through evaporation. Each funnel containing the soil-biochar sample was placed

on the corresponding labeled test tube, left to soak until all particles were saturated (based on preliminary tests) after 60 minutes. Then the blue tack was carefully removed to allow water to freely drain through the funnel into the test tube.

A blank (only the filter paper) was also prepared and treated exactly in the same way as the rest of the samples to serve as the control. All soil-biochar samples were placed in a refrigerator to allow free drainage for 30, 60, 120, and 180 minutes time intervals. At the end of each draining time, the aluminum foil was removed and the total weight (g) of the funnel, filter paper, and wet sample were recorded. At this stage, a soft tissue was used to remove any water drops which passed through the filter paper but did not make it all the way out of the neck of the funnel. WHC was calculated using the formulae below as in (Yu *et al.*, 2013).

$$\text{WHC} = \frac{\text{Weight of retained water in soil biochar sample (g)}}{\text{Weight of soil biochar sample (g)}}$$

The weight of retained water in the soil-biochar sample was computed as shown below

$$Y = (W_t - W_b) - W_c$$

- Where,
- Y = Weight of retained water in soil-biochar sample
- W_b = Total weight of funnel, filter paper, and dry soil-biochar mixture
- W_c = Total weight of retained water by blank
- W_t = Total weight of funnel, filter paper, and wet

soil-biochar mixture after drainage time, t
 Drainage time, t = 30 minutes, 60 minutes, 120 minutes, and 180 minutes

Data analysis. The collected data were entered into MS Excel spreadsheet and water holding capacity computed. It was then followed by data organization in a separate spreadsheet for analysis. GenStat Discovery Edition 4 statistical software was used to perform linear mixed model analysis. The model gives the relationship between water holding capacity and effects of biomass feedstock, pyrolysis temperature, biochar ratio, and drainage time. A linear mixed model was chosen because water holding capacity was measured at different drainage times, hence yielding a longitudinal data which gives rationale for consideration of drainage time covariate on water holding capacity. Fixed effects entered in the model comprised of biomass feedstock, pyrolysis temperature, biochar ratio and all interactions whereas drainage time was entered as a random effect.

RESULTS AND DISCUSSION

Biochar yield at various peak pyrolysis temperatures. The percentage mass yield (on dry weight) of biochar for both bamboo and sugarcane trash feedstock decreased with increase in pyrolysis temperature as shown in Table 1. The biochar yield results confirm the well-known trend that biochar yield decreases with increase in pyrolysis temperature

Table 1. Biochar yield for sugarcane trash and bamboo at various pyrolysis temperatures

Biomass feedstock	Pyrolysis temperature (°C)	Biochar yield (wt %)
Sugarcane trash	350	37.72
	450	34.17
	550	32.97
Bamboo	350	45.29
	450	34.73
	550	29.21

(Guizani *et al.*, 2017). Bamboo yielded higher amounts of biochar than sugarcane trash at temperatures less than 450°C, but lower yield as the temperature increased to 550°C. Biochar yield is directly proportional to lignin content of biomass feedstock (Dorez *et al.*, 2014). The higher biochar yield of bamboo than sugarcane trash could be as a result of higher lignin content of bamboo (24.84-32.65%) than sugarcane trash (22.7-23.1%) as reported earlier by Wahab *et al.* (2013) and Gómez *et al.* (2014).

Water holding capacity (g/g) of soil-biochar mixtures at various pyrolysis temperatures.

Water holding capacity of the un-amended sandy loam soil used as the control treatment was 0.33 g/g. Water holding capacity results for mixtures of soil with biochar produced at 350°C, 450 °C and 550 °C pyrolysis temperatures are shown in Table 2.

The amount of water retained in the soil-biochar samples decreased with increase in drainage time. However, the rate of decrease of water retained was lower between 120 minutes and 180 minutes which imply that times shorter than 180 minutes were not sufficient for water to drain properly. Generally, all biochar from both biomass feedstocks improved the water holding capacity of soil after amendment as evidenced by higher values of water holding capacity of soil samples with biochar compared to the soil without biochar of 0.33 g/g. However, the raw data could not help in identification of significant factors responsible for the increase in water holding capacity.

Upon running the linear mixed model in GenStat Discovery Edition 4, residual plots did not reveal any deviation from homoscedasticity or normality. The estimated variance components in the random model were generally small in magnitude (< 0.005) and positive with exception of main plots. This implies that variation increases with increase in unit sizes from

replications to sub plots, but not between whole plots. However, random variation among units is negligible in magnitude. Therefore, fitting a linear mixed model for the data was suitable. Table 3 below shows statistical output with probabilities of significance for fixed effects which were obtained by sequentially adding terms to fixed model.

Results in Table 3 show that only biochar application rate and its interaction with pyrolysis temperature registered significant effect on water holding capacity of soil-biochar mixtures ($p < 0.05$). Detailed effect of each term on water holding capacity of soil biochar mixtures is as explained in the subsequent sections below.

Effect of feedstock on water holding capacity of soil biochar mixtures.

Soil-biochar mixtures prepared from bamboo feedstock had generally higher water holding capacity compared to sugarcane trash feedstock. However, the difference was not statistically significant ($p = 0.215$). Gray *et al.* (2014) reported that water holding capacity of biochar is influenced by its porosity which implies that water holding capacity of biochar made from sugarcane trash is approximately equal to that made from bamboo. This could explain the insignificant difference of feedstock effect on water holding capacity of soil biochar mixtures. Findings of Yang *et al.* (2018) show that porosity of bamboo derived biochar responsible for such water holding capacity is 76%. Therefore, the differences in water holding capacity of sandy loam soil amended with biochar from bamboo and sugarcane trash are not statistically significant.

Effect of biochar application rate on water holding capacity of soil biochar mixtures.

Increase in biochar application rate in the soil-biochar mixture significantly increased water holding capacity ($p < 0.001$) with lowest and highest biochar application rates at 2 and 7 wt %, respectively as shown in Figure 2.

Table 2. Water holding capacity (g/g) of soil-biochar mixtures at various pyrolysis temperatures

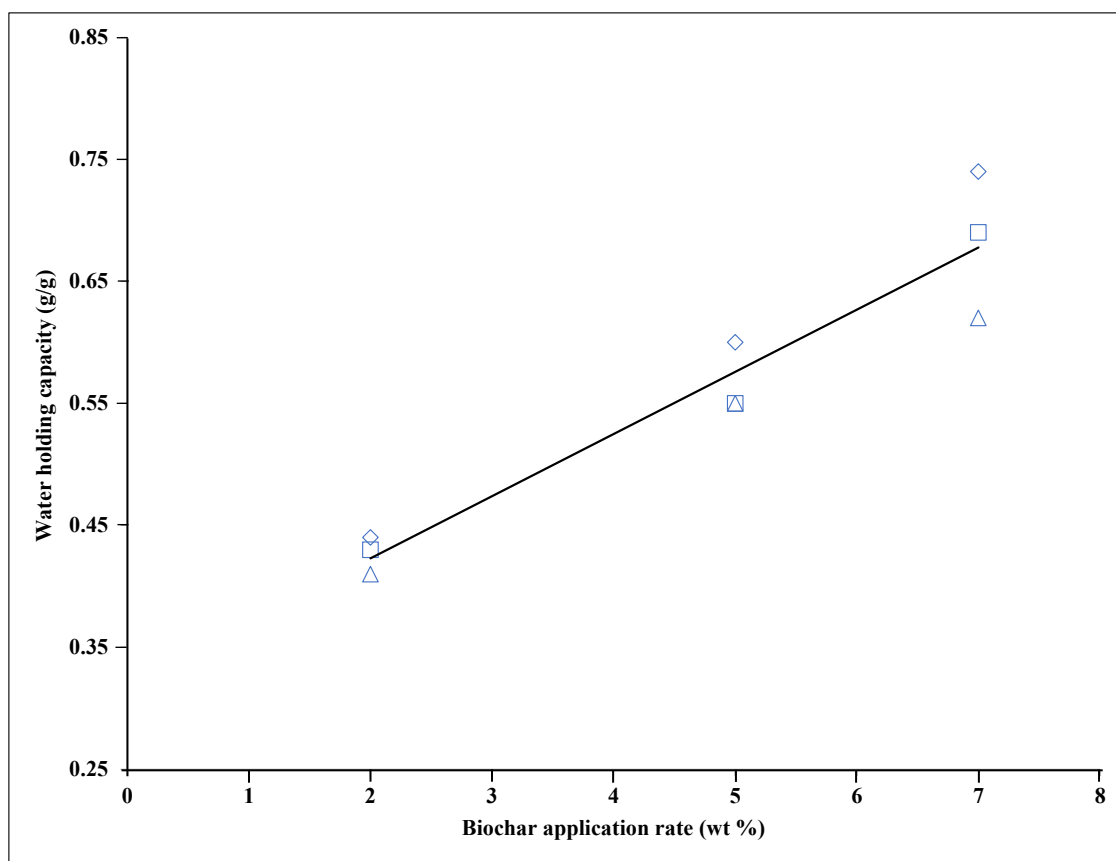
Biochar feedstock	Biochar application rate (wt %)	Pyrolysis Temperature ($^{\circ}$ C)												
		350 $^{\circ}$ C				450 $^{\circ}$ C				550 $^{\circ}$ C				
		Time (min)	30	60	120	180	30	60	120	180	30	60	120	180
Bamboo	2	<i>Mean</i>	0.46	0.45	0.44	0.43	0.42	0.42	0.41	0.41	0.47	0.46	0.45	0.44
		<i>std</i>	0.05	0.04	0.04	0.05	0.07	0.07	0.06	0.07	0.04	0.04	0.04	0.04
	5	<i>Mean</i>	0.60	0.60	0.57	0.55	0.57	0.56	0.55	0.55	0.65	0.64	0.61	0.60
		<i>std</i>	0.14	0.14	0.14	0.13	0.12	0.12	0.12	0.12	0.08	0.08	0.08	0.08
	7	<i>Mean</i>	0.66	0.66	0.64	0.62	0.73	0.70	0.69	0.69	0.80	0.77	0.75	0.74
		<i>std</i>	0.04	0.03	0.03	0.03	0.15	0.16	0.17	0.17	0.05	0.07	0.07	0.07
Sugarcane trash	2	<i>Mean</i>	0.45	0.44	0.42	0.41	0.46	0.46	0.46	0.46	0.40	0.41	0.40	0.39
		<i>std</i>	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.04	0.03	0.03	0.03
	5	<i>Mean</i>	0.57	0.57	0.55	0.55	0.62	0.61	0.60	0.59	0.59	0.59	0.58	0.57
		<i>std</i>	0.06	0.06	0.05	0.05	0.03	0.03	0.04	0.04	0.03	0.03	0.02	0.02
	7	<i>Mean</i>	0.60	0.60	0.58	0.57	0.74	0.74	0.74	0.73	0.76	0.75	0.74	0.73
		<i>std</i>	0.08	0.09	0.09	0.08	0.11	0.11	0.11	0.11	0.11	0.08	0.07	0.07

Note: Mean and Standard deviation (Std) values were computed from four replicates

Table 3. Statistical output of the linear mixed model for water holding capacity

Fixed term	Wald statistic	n.d.f	F statistic	d.d.f	F pr
Feedstock	2.46	1	2.46	3	0.215
Temperature °C	4.48	2	2.24	12	0.149
Biochar application rate	184.85	2	92.42	36	<0.001
Feedstock* Temperature °C	0.33	2	0.16	12	0.85
Feedstock* Biochar application rate	0.09	2	0.05	36	0.954
Temperature °C* Biochar application rate	11.5	4	2.88	36	0.036
Feedstock* Temperature °C* Biochar application rate	0.76	4	0.19	36	0.941
Time (min)	0.78	1	0.78	215	0.379

*Interaction between independent variables



Pyrolysis temperature 350°C △ 450°C □ 550°C ◇

Figure 2. Water holding capacity versus Biochar application rate

These findings are in agreement with Abel *et al.* (2013) and Githinji (2014) who reported that water holding capacity of sandy loam soil increases with biochar application rate due to the corresponding increase in porosity with increasing biochar.

Interaction of biochar application rate and pyrolysis temperatures of biomass feedstock on water holding capacity of soil biochar mixtures. Generally, soil samples amended with biochar pyrolyzed at higher temperatures registered correspondingly higher water holding capacity. Much as the effect of pyrolysis temperature of biomass feedstock alone on water holding capacity was not statistically significant ($p=0.149$), its interaction with biochar application rate registered a significant effect on water holding capacity of sandy loam soils amended ($p=0.036$) as illustrated in Figure 2. The difference in water holding capacity of soils amended with biochar prepared at the three pyrolysis temperatures was small at lower biochar application rates (5 wt%) and increased greatly at higher biochar application rates (7 wt%). This is in agreement with Puehringer (2016) who reported that notable differences in soil water holding capacity are evidenced at higher biochar application rates. Similarly, Chan *et al.* (2008) reported that increase in pyrolysis temperature alters biochar properties which can be attributed to more pores and cracks created in the basal structural sheets of biochar, hence increasing the surface area for retaining more water (Downie *et al.*, 2009). Complete thermal decomposition of cellulose and hemicelluloses for enhanced pore structures are sufficiently developed at around 500°C (Hernández-Mena *et al.*, 2014). This further explains the significantly high water holding capacity of soils amended with biochar pyrolyzed at 550°C compared to those produced at lower temperatures with increasing application rate of biochar.

However, as practical biochar application rates are directly proportional to quantity of feedstock

required and biochar preparation cost (Filiberto and Gaunt, 2013), such high application rates can limit economic feasibility of soil amendment with biochar (Dickinson *et al.*, 2015). Therefore, based on the results of this study, spot application of biochar prepared from bamboo and sugarcane trash at 550°C and application rate of 7 wt % around the plant is recommended to increase water holding capacity of sandy loam soil. Spot application of biochar increases use efficiency by lowering biochar requirement per hectare, hence enhancing economic viability of soil amendment with biochar.

CONCLUSION

In this study, biochar made from bamboo and sugarcane trash can considerably (by up to 124%) improve water holding capacity of sandy loam soil. This can lead to improved water availability for plant roots uptake, and hence increase in crop yields or drought resistance. The findings of this study show that application of biochar produced from locally sourced biomass to sandy loam soils in East Africa has the potential to promote food production and reduce the high level of undernourishment within the region by better retention of irrigation and rain water.

The study recommends further research on field trials of spot application of biochar made from bamboo and sugarcane trash at peak pyrolysis temperature of 550°C and amended with sandy loam soil at 7 wt% biochar application rate to assess its economic viability. The authors also recommend further studies to consider effect of matching particle size distribution to soil on water holding capacity, and biochar porosity measurement as affected by feedstock choice and processing.

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STATEMENT OF NO CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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