



## RESEARCH ARTICLE

# The water retention properties of biochar derived from broiler poultry litter as applied to the Botswana soil

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## ABSTRACT

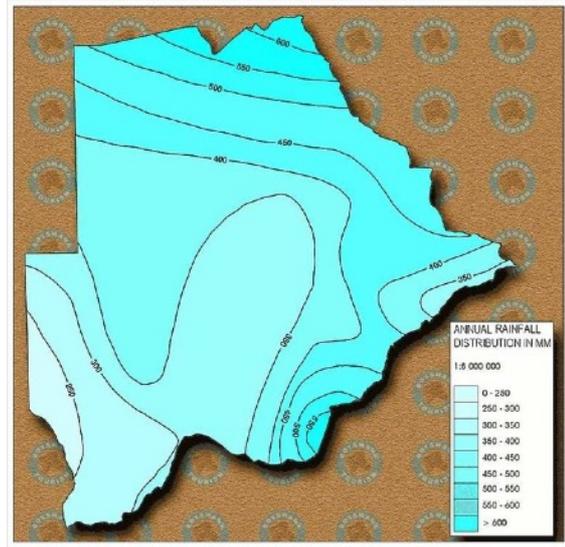
Crop farming in Botswana is very modest and of high risk compared to its neighboring countries because of significant dependency on reduced and unreliable rainfall and as a result of soils with poor water holding capacity and low cation exchange capacity. For this reason, only about two thirds of the available arable land are planted and of the planted land only about half is harvested, which translates into only one third of productive arable land. This study examines how addition of poultry litter (PL) biochar affects water retention properties of Botswana's sandy soils. While many variables should be studied to fully comprehend this aspect, this paper exploits in detail, effects of biochar addition in reducing rate of water loss by evaporation. This work provides convincing evidence that addition of PL-derived biochar (as little as 10%) can significantly reduce water loss by evaporation, thus increasing water soil retention. It is demonstrated that water retention properties increase with increasing rate of biochar application. Two types PL-derived biochar were studied: (i) one with sunflower husks bedding and another (ii) with woodchips bedding. Though both biochars showed similar response to the test, the biochar with sunflower husks was slightly superior. Biochar also indicated significant hygroscopicity, when dried and left exposed to the atmosphere, as moisture content increased with increasing humidity. Based on initial indicators, further study should be done at laboratory and field scale to determine optimum conditions of biochar application in the quest to improve food security for Botswana, as well as improve employment and environmental goals of the country. A comprehensive further study should critically examine Field Capacity, Permanent Wilting Point, and Plant Available Water. As an ultimate goal, enhancing soil moisture retention properties of Botswana's sandy soil enables to increase success rate in the traditional farming sector and, consequently, offers potential to accomplish "No Poverty" and "Zero Hunger" sustainable development goals.

**Keywords:** Poultry Litter, Pyrolysis, Water Retention, Biochar, SDG's

## 1. Introduction

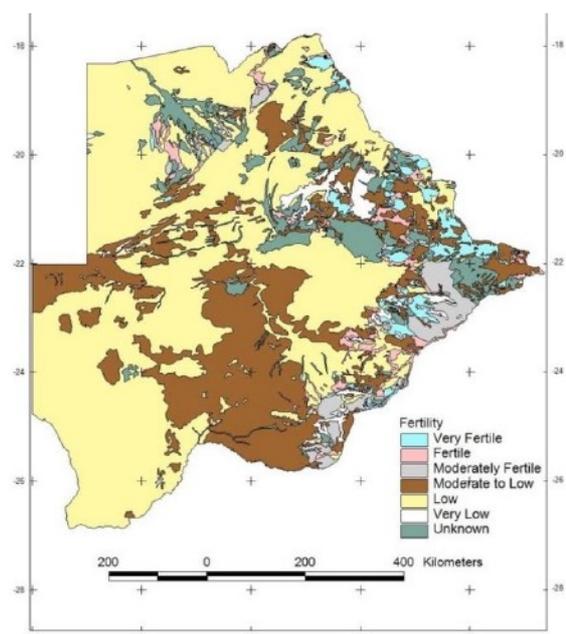
The productivity of crop production in Botswana has historically been very low compared to its neighboring countries. One of the main reasons for this is its huge dependency on relatively low and unreliable rainfall as seen in Figure 1. This, together with the fact that the soil quality is typically relatively poor, has made crop farming in Botswana a high risk. (Hitchcock, 1986; Seanama Conservation Consultancy, 2012; Utlwang and Gothatamang, 2015; Kashe *et al.*, 2017). Large parts of Botswana's arable soil is of low to moderate fertility (Figure 2). The sandy soils in these areas are low in nutrients and organic matter, and have poor water holding capacity and low cation exchange capacity (Kashe *et al.*, 2017). Rain-fed (dryland) agriculture constitutes almost all of the grain produced in Botswana. This, combined with the low moisture retention properties of most soils in Botswana, has led to a history of reoccurring crop failures. Figure 3 shows that on average over the past decade only about two thirds of the available arable land is actually planted and of the planted land only about half is harvested (Government of Botswana, 2017). This means that on average, only a third of the arable land is productive. Of the available arable land, only 26.7% falls in the commercial sector (Utlwang and Gothatamang, 2015) while the majority of arable land falls in the traditional sector where subsistence farming on 5 hectares farms (on average) is practiced by 70% of rural households to derive their livelihood (Hitchcock, 1986; Seanama Conservation Consultancy, 2012; Kashe *et al.*, 2017). Regular failure to produce crops (Kashe *et al.*, 2017) is resulting in a reduction in the tradition farming sector while commercial farming is on the increase (Utlwang and Gothatamang, 2015). This is resulting in higher unemployment, more dependency on government grants and all of the other negative consequences in the rural villages. Poultry farming in the commercial sector produces a huge amount of poultry litter (PL) and this is commonly disposed of in Southern Africa (and many other parts of the world) by means of land application with detrimental effects on the environment. While it is not permitted to dispose of this agricultural waste in this manner, farmers do not currently have any other feasible alternative and hence the practice continues. A commercial plant is currently being built by Pyro Carbon Energy (PCE) to prove the concept of converting PL into valuable products such as biofuel, electricity and biochar by means of pyrolysis. While this technology is optimized for energy (e.g. biofuel and electricity), the biochar is essentially considered a valuable byproduct in this process with high market potential (Han *et al.*, 2018; Kocsis *et al.*, 2018a). PL-derived biochar has been receiving increasing attention as a composting and soil

enhancer. It has the potential to increase humification, enhance microbial activity, immobilize heavy metals and organic pollutants (preventing them from being absorbed by plants), reduce  $\text{NH}_4$ , increase the soil pH, retain moisture, reduce salinity stress, enhance plant growth and improve respiration rate (Kocsis *et al.*, 2018b; Guo *et al.*, 2020).

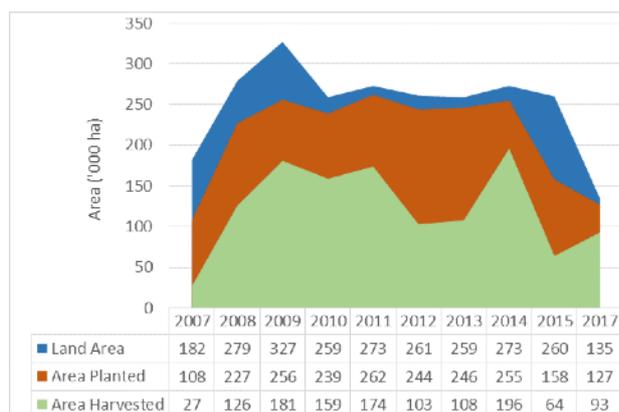


**Figure 1. Mean annual rainfall (mm) in Botswana (Source: (Kashe *et al.*, 2017)**

Botswana with its global index score of 59.8 is currently ranked 120 out of 162 in terms of its sustainable development goals (Sachs *et al.*, 2020). By increasing the soil moisture retention properties of Botswana's sandy soil, it is possible to increase success in the traditional farming sector and consequently there is potential to address at least the "1. No Poverty", "2. Zero Hunger", and "12. Responsible Consumption" Sustainable Development Goals (SDG's).



**Figure 2. National fertility soil map of Botswana (Source: (Kashe *et al.*, 2017)**



**Figure 3. Land area: available, planted and harvested (Source: Government of Botswana, 2017)**

This study specifically focusses on PL-derived biochar's ability to increase the moisture retention of Botswana's soil.

## 2. Material and Methods

To investigate the water retention properties of biochar typical Botswana sandy soil from the Palapye region was collected from within the boundaries of the Botswana International University of Science and Technology (BIUST) campus.

PL-derived biochar was obtained from PCE's laboratory scale pyrolysis reactor which is a batch reactor located in the BIUST pyrolysis laboratory.

Samples were prepared by conducting pyrolysis at a moderate temperature of 500°C (Mašek, and Buss, 2020) using two broiler PLs having different beddings: (a) PL with wood chips bedding and (b) PL with sunflower husks bedding. The pyrolysis temperature for producing biochar can range from as low as 300 °C to as high as 1000 °C (Mollinedo *et al.*, 2015; Ni *et al.*, 2020) and the resulting variation of water retaining properties of the biochar could vary significantly in this range. While others have used lower (Ni *et al.*, 2020) and higher (Abel *et al.*, 2013; Razzaghi *et al.* 2020) pyrolysis temperatures, the temperature used in the current application was to optimize for the energy products (i.e. biofuel and gas) yields, with biochar being the byproduct. The effects of pyrolysis temperature are therefore not within the scope of this study. The moderate pyrolysis temperature used in this study would leave a fraction of volatile matter in the biochar and the effect thereof on plants in the Botswana setting is under investigation and will be reported on in the future.

Twelve 100 mL samples were produced from the materials listed in Table 1 by mixing them in ratios given in Table 2. The biochar samples produced in the pyrolysis reactor and the sand were taken for moisture test in a thermogravimetric analyzer (TGA) by weighing 1g of the sample into an empty crucible and heating it to

**Table 1. Material densities**

Description	Density [kg m <sup>-3</sup> ]
Biochar derived from woodchip bedding PL	294
Biochar derived from sunflower bedding PL	268
Botswana Sand	1527

107 °C immediately after the pyrolysis runs to ensure that no accumulation of moisture took place due to hygroscopic effects.

### 2.1. Water retention test

All samples (except F, K, and L) were soaked in 32.4 g water (the amount of water required to fully saturate the sandy soil). The samples were dried in the sun while recording time of exposure to direct sun (hours). Sub-

**Table 2. Sample preparation**

	Sample ID	Biochar Content (dry basis)		
		Vol [%]	Mass [g]	Mass [%]
PL Bedding Type	A, F	0	0.0	0.0
	B, C, D, E, K	10, 20, 50, 100	2.9, 5.9, 14.7, 29.4	2.1, 4.6, 16.1, 100.
Woodchip	B	10	2.9	2.1
	C	20	5.9	4.6
	D	50	14.7	16.1
	E, K	100	29.4	100.
Sunflower Husk	G	10	2.7	1.9
	H	20	5.4	4.2
	I	50	13.4	14.9
	J, L	100	26.8	100

samples (1.0 g from each sample) were taken and analyzed in a TGA to determine the moisture content after the day's exposure to the heat of direct sun.

### 2.2. Hygroscopic Properties of Biochar

Sample K and L, made up of dry biochar (0% moisture) were used to measure the hygroscopic characteristics of the biochar. The dry biochar samples were taken from

**Table 3. Land application rates [t ha<sup>-1</sup>]**

% Biochar [kg kg <sup>-1</sup> ]	Soil depth [cm]		
	5	10	20
1.0	8	15	30
2.1	16	31	63
4.6	34	68	135
16.1	107	214	428

the pyrolysis reactor and immediately exposed to the atmosphere. Sub-samples of these samples were also immediately analyzed by in a TGA to confirm zero moisture after pyrolysis.

### 2.3. Field Capacity

Often referred to as water holding capacity or water retention capacity, field capacity (FC) is the amount of water or moisture remaining in the microspores of soil after excess water drainage (Rai *et al.*, 2017). At this point, the soil is considered to be at field capacity, and plant absorption of water and nutrients is at optimum (de Oliveira *et al.*, 2015).

### 2.4. Permanent Wilting Point

Permanent Wilting Point (PWP) refers to the moisture content below which plants roots are unable to absorb water. Without addition of water, many plants will die at this point. At wilting point, a plant will need about 15 bars of tension to absorb water from the soil, which is too high for most plants (Rai *et al.*, 2017).

### 2.5. Plant Available Water

Plant Available Water (PAW) is mathematically derived from FC and WP and represent the actual amount of water available for a plant to utilize. By definition, it is the amount of water stored at Field Capacity less the amount remaining in the soil at PWP (Rai *et al.*, 2017).

$$\theta_{AWC} = \theta_{FC} - \theta_{PWP}$$

Where:  $\theta_{AWC}$ ,  $\theta_{FC}$ , and  $\theta_{PWP}$  are PAW, FC, and PWP moisture contents respectively, all expressed in % v/v.

### 2.6. Total Porosity

As discussed in 2.3, pores play an important role in availing optimum moisture content to plants' water and nutrient absorption. It is often easy to confuse pore volume with porosity, but the former is a measure of macro-pores that get filled up when soil is saturated with water. Porosity is normally expressed as a percentage of total sample volume:

$$\phi = \frac{V_v}{V} * 100$$

Where  $\phi$  is porosity, in %,  $V_v$  is the volume of voids and  $V$  is the total volume of the sample (Rai *et al.*, 2017).

Porosities of the sand sample and the two biochars was tested in a simple lab experiment. The three samples of equal volume were weighed and then saturated with water to determine saturation water weight (volume). The samples were then oven dried at 109 °C for 22 h and weighed again to calculate the total pore volume, which is saturated mass less oven dried mass. Pore volume as a fraction of total volume is sample porosity.

It is worth noting that higher pyrolysis temperatures could possibly increase the risk of creating hydrophobicity if too small pores diameters were produced (<10 Å) (Abel *et al.*, 2013), which would be detrimental for water retention of soils. In order to investigate the hydrophobic nature of the biochar samples the biochar will be examined under a Scanning Electron Microscope (SEM) and additional experimental tests, such as wettability tests will have to be conducted.



Figure 4. Sand and biochar samples saturated with water before drying.

### 2.7. Meteorological data

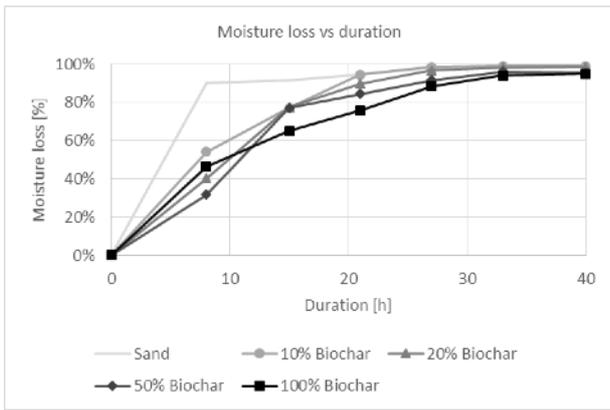
In order to correlate data collected with the environmental conditions during sample exposure to the sun, meteorological data (temperature and humidity) were obtained from (Palapye Historical Weather, 2020). In further testing, however, actual environmental data will be measured in real time together with real time soil moisture and temperature in order to improve correlation.

## 3. Results and discussion

A biochar concentration of 2% (i.e., an application rate of approx. 60 t ha<sup>-1</sup> at a depth of 20 cm) is above the normal range of application rates cited in literature, which typically range up to 20 t ha<sup>-1</sup> (Amoakwah, 2017; Wang *et al.* 2018).

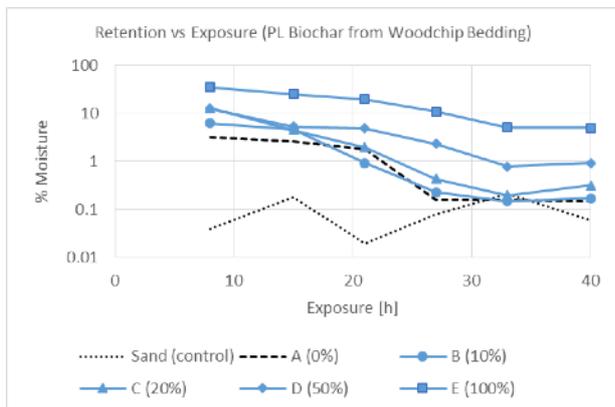
In native sand it is clear from Figure 5 that almost all of its moisture evaporates within the first 8 h of exposure to the Botswana sun. On the contrary, adding even 2% biochar to the sand has a significant effect in retaining the moisture during the initial stages of exposure. Despite a measure of scatter observed in the data during the first 15 h of exposure, it is clear that in the short term (i.e., less than 40 h exposure) there is clear improvement of water retention in the soil as has also been reported (Wang *et al.* 2018). This amount of improvement in water retention could be absolutely crucial during the typical growth stage of a crop in Botswana.

By introducing biochar into the soil, the probability of successfully bridging the time of extreme heat between showers of rain are dramatically improved.

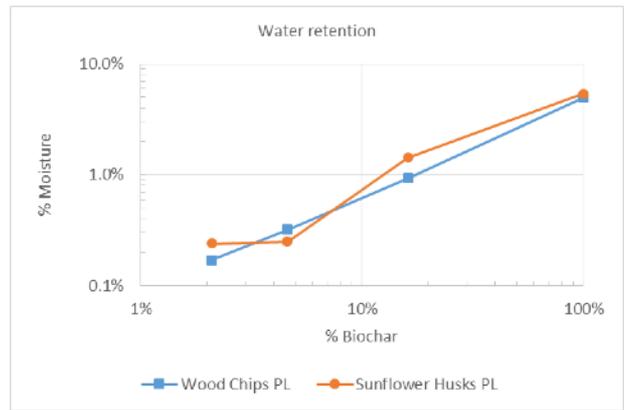


**Figure 5. Moisture loss vs duration**

It is observed in Figure 6, Figure 7, and Figure 8 that the water retention is improved significantly with very high concentrations of biochar. However, the practicality and economics of applying biochar in amounts higher than 2% (>60 t ha<sup>-1</sup>) remains questionable. Figure 7 (woodchip) and Figure 8 (sunflower husk) indicate that, while the soil sample (A) approaches the control sample curve (dry sandy soil), the samples with higher amounts of biochar flattening off with a certain amount of moisture retained. This could be indicative that some of the moisture may be held within the molecular structure of the biochar (inherent moisture), which means that it will only be released at temperatures above 100 °C and would therefore be retained indefinitely. It should also be noted that the soil depth for these test was only 5 cm and it is expected that water retention at greater depths could be more significant. Further testing using deeper soil and longer exposure times are therefore scheduled and will be reported on in the future. The absorption of water as inherent moisture in biochar and the ability of various plants species roots to access the inherent moisture within biochar are also to be determined.

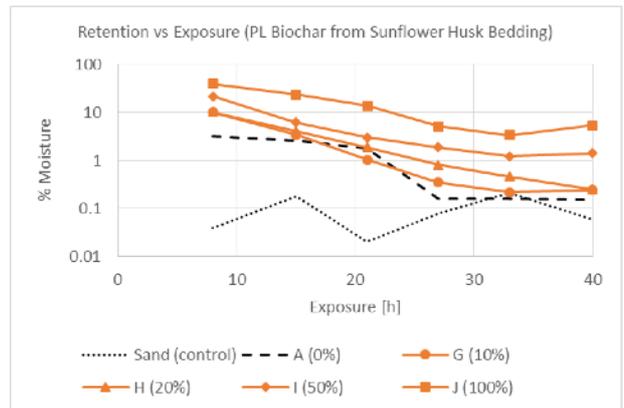


**Figure 6. Water retention vs biochar content in sand after 40 h of exposure to the sun**



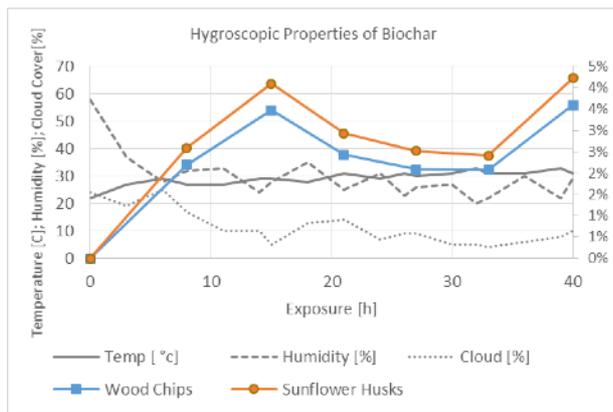
**Figure 7. Water retention vs exposure duration for biochar derived from PL with woodchip bedding**

It can be also observed from Figure 6 that the ability of biochar to retain water varies between the types of PL. The biochar which is derived from sunflower husks generally seems to be able to retain more moisture than that derived from wood chips.



**Figure 8. Water retention vs exposure duration for biochar derived from PL with sunflower husk bedding**

It has been reported that pore size distribution plays a significant role in both the water retention characteristics as well as the hydrophobic nature of biochar (Abel et al., 2013). This may explain the variation between the water retention characteristics between biochar derived from PL with wood chip bedding and sunflower husk bedding respectively. This can be attributed to the difference in porosity between the two types of biochar shown in Table 4 and reported in literature (Phillips et al., 2019). However, the microstructure of the biochars needs to be studied during further investigation to gain a better understanding of the effects of pore size distribution. A SEM investigation would provide valuable information in this regard.



**Figure 9 Hygroscopic properties of biochar**

Dry biochar (0% moisture) from the pyrolysis reactor increased in moisture content (>2%) within 8 hrs of exposure to the atmosphere with relative humidity of around 30% (Figure 9). It is clear that there is not enough data to explain the cause of fluctuations in the moisture content in the biochar, however, it is clear that the biochar does display hygroscopic characteristics (which is beneficial for water retention).

It is also observed that the sunflower husk-derived biochar is superior to the woodchip-derived biochar with regard to hygroscopic properties (shown in Figure 9) can be attributed to its high porosity properties. This also explains why evaporation losses are slightly less compared to its woodchips counterpart.

**Table 4. Porosity of woodchip bedding biochar (K), sunflower husks biochar (L) and soil (F).**

Sample ID	Volume of voids	Porosity %
K	22.8	57
L	31.2	78
F	15.7	39

It also follows that hydrophobicity due to the high occurrence of very small pore sizes is not dominant in these biochar samples.

It should be noted that the meteorological data presented in Figure 9 are 3-hourly average values and not real-time data. This could explain why there is no direct correlation with the hygroscopic properties of the biochar. In order to perform a deeper investigation would require real-time measurement of meteorological data over a longer period of time.

## 4. Conclusions

The initial testing performed during this study has revealed very interesting and promising results for the potential of utilizing biochar to enhance agriculture in Botswana. Detailed follow-up testing will be conducted

on the effects of biochar on Botswana soil, which will include determination of the variables described in sections 2.3, 2.4 and 2.5. This will also be complimented by extensive tests on actual plant growth, and soil chemistry.

The results obtained from this work show strong evidence that PL-derived biochar affects water soil retention. Taking into consideration that Botswana's sunny and hot climate (the major contributor to water losses) combined with mostly dry land agriculture and low (and intermittent) rainfall is the main reason for frequent crop failures, the intensive study of how PL biochar can minimize this effect is of national interest to the country.

These preliminary results indicate that addition of biochar (at as little as 10%) can significantly reduce water loss by evaporation.

There is also evidence that biochar can absorb water into its molecular structure.

Based on these initial indicators, further study should be performed at laboratory and field scale to determine optimum conditions of biochar application in the quest to improve food security for Botswana, as well as improve employment and environmental goals of the country.

## 5. Acknowledgement

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