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Biochar Amendment and Mulches Techniques Reduce Soil Surface Evaporation Rate

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Abstract: *Crop residues have value when left in the field and also when removed from the field and sold as a commodity. Soil evaporation is the main route of soil moisture loss and often exceeds precipitation in the arid and semi-arid regions. Reducing soil water evaporation is one of the benefits of leaving crop residues in place and essential to maintaining agricultural production in arid and semi-arid areas. The objective of this study was to measure the cumulative soil water evaporation with time under different treatments in a lab experiment and to determine whether biochar and mulches techniques could reduce soil evaporation in dryland areas. The effect of the mulch and two biochars on water evaporation in clayey soils under a lab system has seldom been studied. The relationship between water evaporation and biochar properties is still unknown. Thus, in the present study, cumulative water evaporation under biochar and mulch treatments at the soil surface were measured by the water balance method. Results showed that both biochar and mulch application could inhibit water evaporation in clayey soil under a lab experiment. Plastic mulch showed a better inhibition effect compared with biochar. Covering soil surface reduced the required amount of water. Furthermore, the results showed that biochar addition generally increased the soil average water content and effectively reduced soil cumulative evaporation. However, biochar addition decreased the ratio of evaporative loss. This experiment clearly demonstrates that what might otherwise be agricultural waste can be used to significantly conserve soil moisture, providing more resources for crops and reducing overall costs of production.*

Keywords: Biochar; Bulk density; Crop residues; Soil evaporation; Water content

Introduction

In arid and semi-arid regions, water availability is generally the most important natural factor limiting expansion and development of agriculture. A better understanding of the relationship between transpiration, evaporation and evapotranspiration as affected by mulch (amendment and covering soil surface) for various crops is needed to improve the management of irrigation and water resources. Soil water evaporation is an important component of the surface water balance and the surface energy balance. Accurate and dynamic measurements of soil water evaporation enhance the understanding of water and energy partitioning at the land–atmosphere interface. When not enough water is available to produce full yields, the goal for water management is to maximize transpiration and minimize nonessential water losses. One avenue for reducing nonessential water use is minimizing evaporation.

Soil moisture is fundamental to agricultural construction and a key factor in determining the structure and functioning of ecosystems, particularly in arid and semi-arid regions where strong associations exists among the ecosystem productivity, surface energy balance, and water availability (Wu et al., 2014; Ma and Zhang, 2016; Liu and Shao, 2016). Severe drought may result in further soil degradation, i.e., sandification and desertification, which permanently increases evaporative water loss and decreases soil water retention in these lands. To improve the water use efficiency and soil structure characteristics, enhance soil water retention, and prevent desertification, soil amendments have been widely applied to soil (Agegnehu et al., 2015).

Traditionally, Sudan is an agricultural country and has rich forest resources. Huge agricultural and forestry waste, such as crop straw, sawdust, branches and fruit, are produced by agricultural and forestry activities, representing not only a waste of energy (inefficient burning) but also a disaster to the local environment (Zhang et al., 2016). Therefore, how to renewable use of these waste has been a research hotspot. One method involves pyrolysis them and application of the products (i.e., biochar) to soils.

Biochar is a carbon-rich product of the thermal decomposition of organic materials under a limited oxygen supply and at a relatively low temperature (< 700 °C) (Lehmann et al., 2006; Wang et al., 2017). The application of biochar as a soil amendment or slowrelease fertilizer carrier or for carbon sequestration has recently attracted substantial attention (Marris, 2006; Lehmann, 2007) because biochar has a complex structure, extensive porosity, and a large specific surface area with rich organic functional groups that can improve the physical and chemical properties of soil (Sohi et al., 2009; Lehmann et al., 2011; Li et al., 2011). Increasing numbers of researchers have reported a significant increase in the water holding capacity of soil after biochar addition (Baronti et al., 2014; Zhang et al., 2016). Furthermore, biochar may enhance agricultural production due to its ability to absorb and retain nutrients in soil (Lentz and Ippolito, 2012), reduce the soil bulk density and increase the diversity and abundance of the soil biological community (Herath et al., 2013; Gomez et al., 2014). Biochar can also enhance soil porosity and water permeability, thus improving the soil water holding capacity (Herath et al., 2013; Kumari et al., 2014). Biochar has a moisture absorption capacity that is 1–2 orders of magnitude higher than that of soil organic matter (Accardi-Dey and Gschwend, 2002). The potential of biochar to improve water-holding capacity has been widely recognized (Agbna et al., 2017; Wong et al., 2017).Therefore, biochar may play an important role in improving soil water relationships in agricultural systems, particularly the systems in the Sudan.

The addition of biochar to soil will inevitably alter the physical and chemical properties of the soil (Liu et al., 2012; Herath et al., 2013), thereby affecting soil moisture and evaporation processes. Evaporation is a catenary physical process in which soil moisture flows through the soil surface in the form of water vapour into the atmosphere, and it is an essential part of the transformation of water from soil to surface water vapour in the soil-plant-atmosphere system (Zhao and Wu, 2004; Novák, 2012). In semi-arid environments, soil evaporation can exceed precipitation and limit normal vegetative growth (Onder et al., 2009). Reducing soil evaporation is essential to maintaining agricultural production in arid areas (Raz-Yaseef et al., 2010).

Soil evaporation is characterized by two periods (Lehmann et al., 2008). A period with an initially high and relatively constant rate is termed stage I evaporation, which is supported by internal capillary flow (the constant rate period, CRP) (Yiotis et al., 2006). After a certain period (or mass loss), this CRP is followed by a period with a lower and gradually decreasing evaporation rate (stage II), reflecting a transition to diffusion-limited vapour transport (the falling rate period, FRP) (Bond and Willis, 1969; Or et al., 2013). Recently, increasing numbers of researchers have begun to consider the influence of biochar characteristics, such as the feedstock, pyrolysis temperature, particle size, amount added, intra-particle porosity, shape, and plasticity on soil evaporation (Eibisch et al., 2015; Hardie et al., 2014). Ibrahim et al. (2017) applied conocarpus biochar in sandy loam soil and found the cumulative evaporation was the lower (32.2–35.5 mm) in the biochar treated soil than in the non-treated soil (40.9 mm), which suggested that biochar can reduce soil evaporation. But Zhang et al. (2016) found that adding biochar powder to sandy soil did not decrease the water evaporation loss, it may be related to soil texture and biochar particle size. Xu et al. (2016) reported that biochar effectively restricted soil evaporation at a low addition amount (5%) but promoted it at a high addition amount. Therefore, it is not clear whether the increase in water holding capacity after biochar addition can be maintained through the entire evaporation processes (Karhu et al., 2011). Furthermore, the effects of the particle size and addition amount of biochar on soil evaporation are also unclear. Evaporation is a comprehensive function that involves multiple soil properties, such as the soil texture and particle size distribution (Qiu et al., 1998), applying the biochar affects these properties, especially the soil porosity and its distribution via biochar's particle size, different particle sizes and addition amounts will thus differentially affect the evaporation process.

Crop residues reduce the evaporation of water from soil by shading, causing a lower surface soil temperature and reducing wind effects (Klocke et al. 2009; van Donk et al. 2010). A number of studies from both irrigated and rain-fed regions around the United States where no-tillage is used have reported annual irrigation savings of as much as 4 to 5 inches (10 to 13 centimeters) (Klocke et al. 2009). Crop residues are left in the feld under mechanized overhead irrigation systems. When irrigation wets the soil surface, evapotranspiration (ETc), which is the combination of transpiration and soil water evaporation, occurs. Transpiration, water moving into and through crop plants to the atmosphere, is essential for growth and crop production. Soil water evaporation, on the other hand, is generally not useful for crop production, although it does slightly cool the crop canopy microenvironment (Klocke et al. 2009). The type of residue, though, is important, as residues from crops such as cotton and grain sorghum, which produce less material, would need to be concentrated to impractical levels to achieve evaporation decreases comparable to those obtained by typical residues from irrigated wheat (Unger and Parker 1976).

Plastic mulch is a product used in a similar fashion to mulch, to suppress weeds and conserve water in crop production. Certain plastic mulches also act as a barrier to keep methyl bromide, both a powerful fumigant and ozone depleter, in the soil. In plastic mulching crops grow through slits or holes in thin plastic sheeting. Plastic mulch is also used in conjunction with drip irrigation to increase WUE. Nowadays use of plastic mulch becomes standard practice for all vegetable farmers. Polyethylene film was first used as mulch in the late 1950's in USA for high value crops (Schales and Sheldrake 1965). It conserves moisture efficiently because water that evaporates from the soil under the plastic film condenses on the lower surface of the film and falls back to the soil as droplets. It accelerates plant growth by increasing the soil temperature and stabilizing soil moisture. Plastic mulches directly affect the microclimate around the plant by modifying the radiation budget of the surface and decreasing the soil water loss (Liakatas et al., 1986).

Based on above mention literature, there are no reports regarding the effects of biochar and mulch on soil evaporation in Sudan. Therefore, we investigate the effect of millet and groundnut biochars applied at various rates and plastic mulch to a clay soil on soil water evaporation. It was predicted that the type (i.e., feedstock source) of biochar added to soil at varying rates would differentially affect soil water-evaporation. Specifically, it was hypothesized that millet and groundnut biochar applied at the greatest rate would alter soil water-evaporation more than at lower rates of biochar addition. Moreover, the present study could offer a comprehensive evaluation of the effect of biochar and mulch on soil water evaporation in clay soil and a possible alternative method for saving irrigation in dryland cultivation. It would play an important role in guiding the use of biochar as a kind of soil amendment in decreasing soil water evaporation.

The objectives of this study were to **(1)** determine whether biochar addition and mulch could reduce or increase soil evaporation, and **(2)** compare the effect of two type of biochar and two mulch materials, i.e., plastic mulch (white polythene) and organic mulch (calotropis procera residues) on soil water evaporation.

Materials and Methods

Site description

The study was performed during the autumn of 2019 in a laboratory of the college of agricultural studies Sudan University of Science and technology, Khartoum North, Shambat, which lies between longitudes (32-32′E) latitude (15-40′N). The soil at the site was a clay, the surface soil bulk density was 1.5 g cm^{-3}, and the topography was relatively flat (slope <2%). Climate in the study site was a semi-desert with short rain period and sunshine hour ranging from 9-11 hour per day. The average temperature was 35 ^{0}C, the relatively humidity increase in the rainy season and reaches maximum in August 66% on someday.

The laboratory experiment

Prior to mulch and biochar application, soil was collected from approximately the top 20 cm soil layer in the experimental site and clods were broken up with a rubber pestle and then taken to the laboratory, and then soils were dried at room temperature before being passed through a 2 mm sieve. Biochar was mixed with soil material uniformly by hand at the same rates (2% w/w) for the lab experiment.

In total, two types of biochar (Bm and Bg, which were millet and peaundnut pyrolysis at 350 -500 ◦C, respectively), and two types of mulch (Pm and Cm, which were plastic mulch and, calotropis procera residues, respectively and one treatment as a control (CK) were used in the present experiment. All types of biochar used in this study were produced in the farm of the college of agricultural studies Sudan University of Science and technology. Biochar was produced at 350 - 500 ◦C pyrolysis temperature based on the recommendation of Lehmann (2007). The dry millet and peanut were packed into a barrel container which was covered with a lid to generate biochar. It has been thought that pore size distribution in biochar particles is dependent on both raw materials and pyrolysis temperatures. The particle size of the biochar was about 5–8 mm in diameter after pyrolysis.

In total, five treatments were established (2 types of biochar at proportions of 2% *w*/*w*, named as Bm and Bg.) with no biochar applied as control (CK) and two types of mulch (Pm and Cm, which were plastic and calotropis procera). Each treatment had 3 replicates. An aluminum column (pot) with 29 cm diameter and 5 cm height was used to conduct the experiment. Two thousand grams of soil with a relative proportion of biochar and organic mulch were completely mixed before being filled into columns. The samples columns from the same soil treatment were packed according to its field bulk density. All the columns were incubated in the laboratory with the room temperature. A randomized complete block design was used, comprising five pots, each receiving a different level of biochar and mulches treatments. The experiment was conducted with the soil columns (pots) without human disturbance in an indoor laboratory environment.

Collecting Data

Soil moisture loss was monitored every 2 - 3 days, beginning one day after saturation, and ending when no significant difference in weight was measured. This was accomplished by weighing the total container weight. The weight was recorded, and subtracted from the previous weight to determine total soil moisture loss for that period of time. The observation was continued until the weight difference between two observations was less than 0.2 g. After incubation, columns were dried to a constant weight. The volume of soil in each column was recorded to calculate soil bulk density (BDs).

Data Analysis

According to soil water balance method, the cumulative evaporation (CE_i) was calculated as follows:

$$CE_i = W_0 - W_i \qquad (i = 1, 3, \ldots 33)$$

where W_0 is the initial weight of the soil column in the beginning of the experiment, and W_i is the weight of the soil column on the i^{th} day.

Since the initial soil water content of each treatment was different and increased with biochar and mulch addition, the data were averaged to evaluate what biochar type or mulch addition were most useful for inhibiting soil evaporation. We used the ratio of evaporative loss (the proportion of the final CE to the initial water content of the soil, (Li and Li, 1991) as a more appropriate index to illustrate evaporative effects. If the ratio is high, the treatment is relatively prone to water evaporation. The evaporative loss ratio (R) was calculated as follows:

$$R = \frac{M_1}{M_2}$$

where M_1 is the final CE of water (g) and M_2 is the initial water content (g) absorbed by the soil column (pot).

After all of the data were collected, the water loss for each experimental unit at each sampling was divided by the weight of the saturated soil to obtain percentage water loss. The data analysis was conducted using the Microsoft excel and graph prism 2010 software package to compare the means of the measured values at $P < 0.05$ for each treatment.

Results and discussion

The effect of two different mulch types (plastic mulch and calotropis procera residues) and two biochar types (peanut and mille residues biochar) on soil surface evaporation and soil physical properties were determined from soil trays filled with 2 kg of soil. The control trays contained no mulch or biochar amendments. The trays were weighed every two to three days to determine the percentage water loss.

The changes in soil water content (WC) in the 0–0.5 m soil layer during the incubation experiment under the five treatments are shown in Figure 1. The results of soil water content for each treatment, clearly illustrating that mulch and biochar addition can increase the soil water content: average water content in the plastic mulch treatment was higher than that in the biochar and control treatment. The greatest WC value occurred under the plastic mulch (T1) while the smallest value occurred under the control treatment in the absence of mulch and biochar (CK). At the both biochar type, all soil water contents increased with biochar addition.

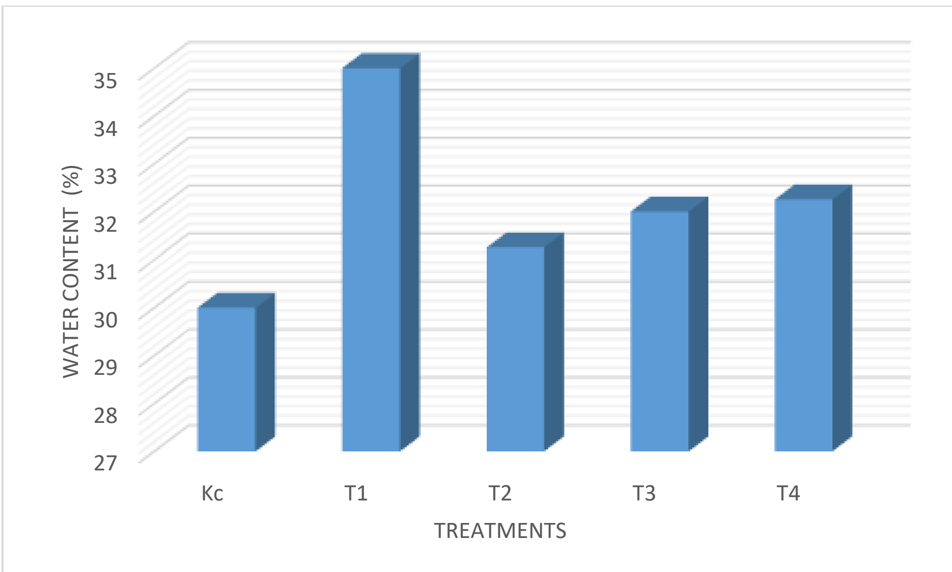

Figure 1: Soil water content of each treatment. CK is control treatment, T1 is plastic mulch, T2 is calotropis procera residues, T3 is peanut residues biochar and T4 is mille residues biochar treatments.

The influence of covering soil surface and amendment soil with biochar and mulch are presented in Figure 2. In general, increasing water applied increased water use and soil evaporation in open soil surface treatments, and vice versa in covered soil surface treatments. Covering soil surface reduced the amount of water that should be added at each time. The result showed that the amended and covered soil surface treatments (mulch and biochar) reduced the application of water amount compared to water applied in the same open soil surface treatment (control, Ck). Moreover, soil available water in covered soil surface treatments remains higher than soil available water in open surface treatments, due to the high loss of water by evaporation in the earlier days after water applied in the open soil surface treatment (Ck). Our observations showed that the evaporation reached a high rate at the beginning and declined gradually to a new balance (Figure 2). Biochar application reduced the evaporation rate compared with CK. During the midterm of observation, the evaporation rate of both biochar application were significantly lower than CK. Furthermore, as shown, the mulch and biochar treatments significantly decreased the soil evaporation values during the experiment. The highest values of evaporation were recorded at Ck treatments. The lowest evaporation values were recorded at T4, T3, T2 and T1 treatments, respectively.

Figure 3 clearly shows that mulch and biochar were reduced soil evaporation in all treatments because the ratios of evaporative loss in the control treatment was the highest among all of the treatments. The evaporative loss ratio decreased under mulch and biochar addition, suggesting that a higher addition amount could enhance the inhibition of soil evaporation by biochar and mulch.

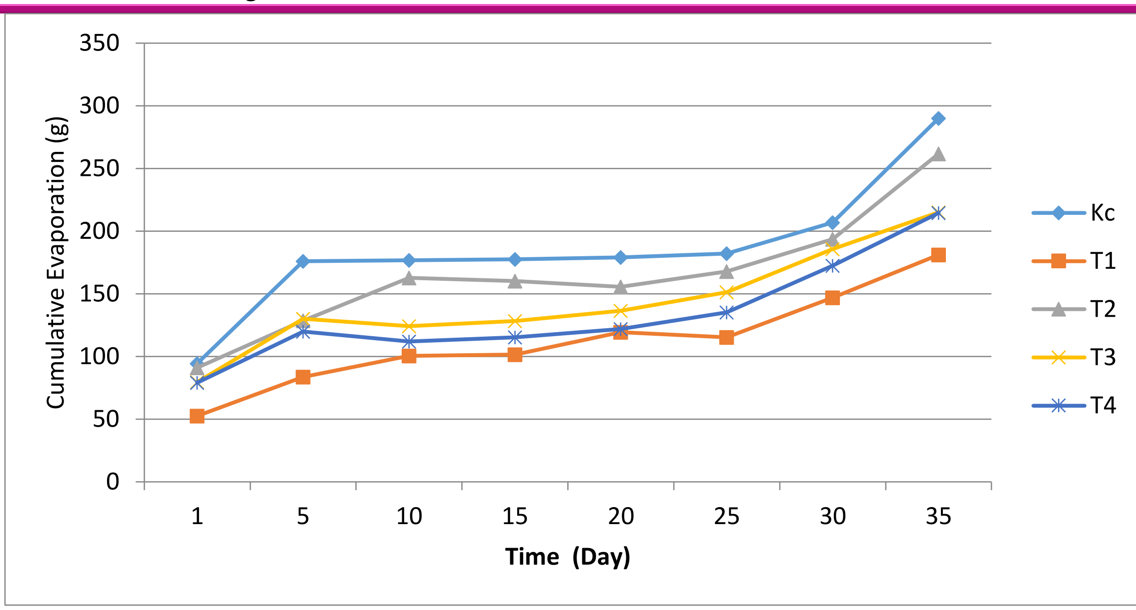

Figure 2: Cumulative soil evaporation under different treatments. CK is control treatment, T1 is plastic mulch, T2 is calotropis procera residues, T3 is peanut residues biochar and T4 is millet residues biochar treatments.

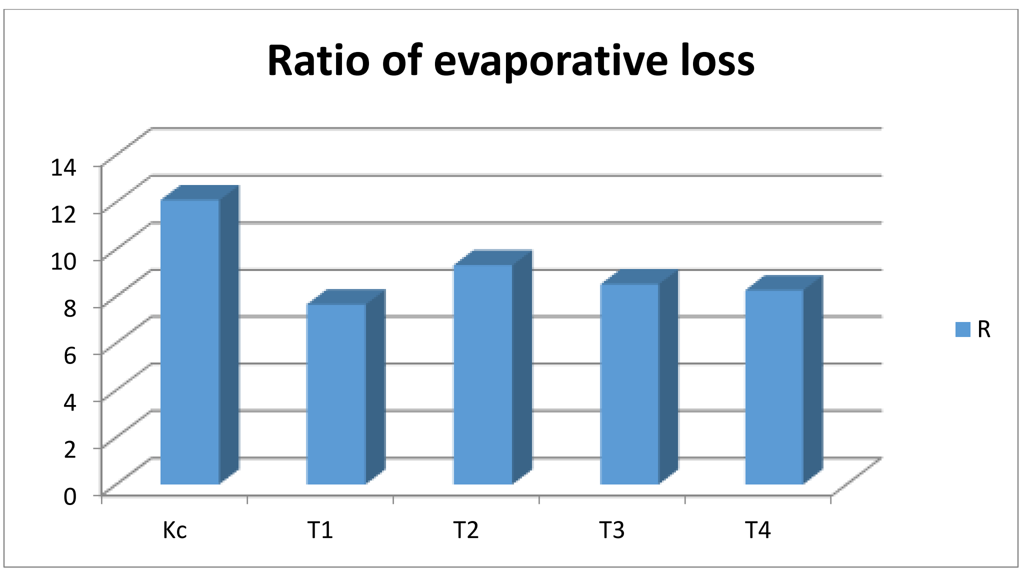

Figure 3: The evaporative loss ratio as a function of mulch addition amount. CK is control treatment, T1 is plastic mulch, T2 is calotropis procera residues, T3 is peanut residues biochar and T4 is millet residues biochar treatments.

At the end of the incubation experiment, the soil bulk density (BD) was measured.

Clayey soil is always heavy textured with large BD. In the present study, both biochar type and calotropis procera residues application reduced BD (Figure 4). Significant changes were occurred under T4, T3 and T2 treatments, respectively. While there was no significant deferent between T1 and control (Ck). The soil BD was significantly decreased under biochar treatments compared to non- biochar treatments, while there was no significant difference observed among both biochar type treatments. The result was mainly due to the low BD of biochar. In the present study, BD of both biochar types treatments were significantly lower than plastic mulch and calotropis procera residues tretments. Thus, biochar showed a better bulk density reduction compared with plastic mulch and control. However, feedstock showed no effect on BD. Results of the present study showed that biochar application, reduced BD, and further improved soil structure and affected soil evaporation of clayey soils.

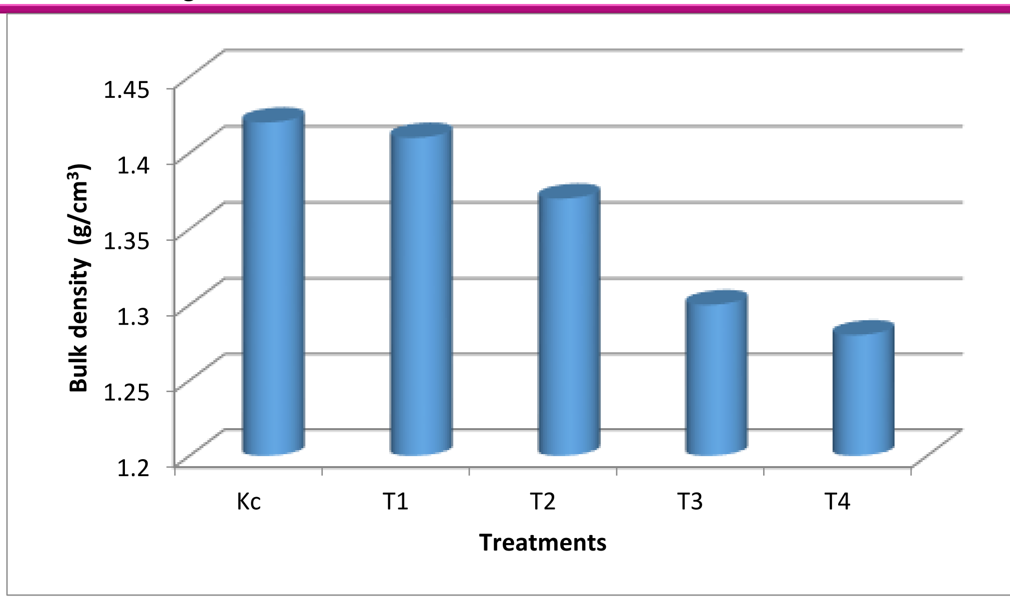

Figure 4: Soil bulk density of each treatment. CK is control treatment, T1 is plastic mulch, T2 is calotropis procera mulch, T3 is peanut residues biochar and T4 is mille residues biochar treatments.

Due to the high porosity and large surface area (Zhang et al., 2016), biochar application improved soil aggregation by binding to other soil constituents (Lehmann et al., 2006). Therefore, biochar significantly improved soil water retention capacity. In addition to the improvement on water retention, there are other factors that contribute to the effect of biochar application on soil evaporation. On the one hand, biochar application increased soil porosity and hydraulic conductivity, which enhanced soil evaporation. On the other hand, biochar showed a water adsorption capacity, which inhibited soil evaporation (Lehmann et al., 2008). The effect of biochar application on soil evaporation is also closely related to soil properties. Former researches showed that biochar was a good soil amendment for sandy soil by enhancement of water retention and inhibit soil evaporation (Zhang et al., 2016). Results of the present study further demonstrated that biochar was beneficial to clayey soil. Nevertheless, whether the results of the present study on clayey soil could be extrapolated to other soils, such as sandy soil, is still unclear. Even if biochar application inhibited soil evaporation for both sandy and clayey soils, their mechanism should be different.

Conclusion

Biochar addition changed the soil physical properties and subsequent water evaporation dynamics. Our study found that biochar addition can generally increase the soil water content and effectively reduce soil evaporation, and the inhibition of evaporation was enhanced with biochar addition. The result of the present study showed that both biochar type and mulch application to clayey soil reduced bulk density of soil and inhibited soil evaporation compared with CK. Soil evaporation inhibition of plastic mulch is significantly better compared with that of biochar. The soil evaporation inhibition of biochars was closely related to the bulk density of biochar, rather than other biochar properties. The result of the present study indicated mulch and biochar application, could save irrigation by inhibiting soil evaporation in clayey soil, which showed a great potential for water conservation and water use efficiency improvement under protected cultivation. Moreover, our research reinforces the study direction about the effects of biochar on soil hydraulic properties and demonstrates that the effect of biochar addition on soil evaporation processes for clay soil in Sudan.

Recommendations

1. Further experiments should be conducted to investigate the optimal biochar type and application proportion for open field cultivation.
2. The combined effects of biochar properties and soil properties on soil evaporation still need to be further investigated.

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