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Biochar and its impact on soil properties, growth and yield of okra plants

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Abstract
Applying biochar to the soil can mitigate problems that hinder agricultural production, such as water scarcity and low fertility soils. The objective of this research was to evaluate the impact of dry coconut husk biochar and sewage sludge combinations on soil chemical characteristics, growth, yield and water productivity of okra crop. The experiment was arranged in randomized blocks, with 6 treatments (CHB + BSS - coconut husk biochar + biochar of sewage sludge, CHB + RSS - coconut husk biochar + raw sewage sludge, BSS + RSS - biochar of sewage sludge + raw sewage sludge, CHB - coconut husk biochar, BSS - biochar of sewage sludge, WB - without biochar (control)). Plant height, number of fruits per plant, yield and water use productivity were evaluated. To evaluate the effect of biochar on soil, soil samples were taken to determine pH, CEC, P, K, Ca, Mg concentrations after incorporation of biochar into the soil. The BSS + RSS and BSS treatments provided better results on okra production and growth characteristics with a 421.15% and 419% productivity increase, respectively, compared to the control treatment. The BSS and BSS + RSS treatments provided better water productivity, with values of 14.5 and 13.3 kilogram produced for each cubic meter of water applied, respectively. All soil chemical characteristics analyzed were modified when the biochar was incorporated into the soil. The results provide valuable insight that okra growers can embrace the use of the combination BSS+RSS and BSS, providing better yields and lower water use in growing this plant.
Keywords: biochar combinations; horticulture; soil fertility; water productivity.

Biocarvão e seu impacto nas propriedades do solo, crescimento e produtividade de plantas de quiabo

Resumo
A aplicação de biocarvão no solo pode atenuar problemas que dificultam a produção agrícola, como escassez de água e solos com baixa fertilidade. O objetivo desta pesquisa foi avaliar o impacto das combinações de biocarvão de casca de coco seco e lodo de esgoto nas características químicas do solo, crescimento, rendimento e produtividade de água da cultura do quiabo. O experimento foi organizado em blocos casualizados, com 6 tratamentos (CHB + BSS - biocarvão de casca de coco + biocarvão de lodo de esgoto, CHB + RSS - biocarvão de casca de coco + lodo de esgoto bruto, BSS + RSS - biocarvão de lodo de esgoto + lodo de esgoto bruto, CHB - biocarvão de casca de coco, BSS - biocarvão de lodo de esgoto, WB - sem biocarvão (controle)). Foram avaliados a altura da planta, número de frutos por planta, produtividade e produtividade de uso da água. Para avaliar o efeito do biocarvão no solo, foram coletadas amostras de solo para determinação das concentrações de pH, CEC, P, K, Ca, Mg após incorporação do biocarvão no solo. Os tratamentos BSS + RSS e BSS proporcionaram melhores resultados nas características de produção e crescimento de quiabo, com um aumento de produtividade de 421,15% e 419%, respectivamente, em comparação com o tratamento controle. Os tratamentos BSS e BSS + RSS proporcionaram melhores valores de produtividade da água, com valores de 14,5 e 13,3 quilos produzidos para cada metro cúbico de água aplicado, respectivamente. Todas as características químicas do solo analisadas foram modificadas quando o biocarvão foi incorporado ao solo. Os resultados fornecem informações valiosas de que os produtores de quiabo podem adotar o uso da combinação BSS + RSS e BSS, proporcionando melhores rendimentos e menor uso de água no cultivo desta planta.
Palavras-chave: combinações de biocarvão; horticultura; produtividade da água; fertilidade do solo.

Introduction

Okra (*Abelmoschus esculentus* L. Moench) is a crop that can be grown in several regions that have mainly tropical and subtropical climates (EMUH *et al.*, 2006). It has economic importance (FARIAS *et al.*, 2019), reaching in 2017 the value of the ton that varies from US $ 236.8 (Mexico) to US $ 3870.6 (Fiji) worldwide (FAOSTAT, 2017). Okra has several benefits for human consumption, being a good source of carbohydrates, proteins, fats, minerals and vitamins, which aroused interest in growing this vegetable on a large scale (JAIN *et al.*, 2012; SINDHU; PURI, 2016). In order to increase the productivity of crops such as okra in the tropics, inorganic fertilizers were encouraged to be used to improve the low fertility of soils belonging to these locations (ADEKIYA; AGBEDE, 2009), however, these fertilizers have high value (AGBEDE *et al*., 2008) which makes it necessary to find alternative sources such as biochar to provide this improvement in the soil and increase crop productivity.

The use of biochar as a soil conditioner has been encouraged due to its potential to improve soil structure, chemical characteristics (DOWNIE *et al.*, 2009) and plant growth (GONZAGA *et al.*, 2017; 2018; 2019). Biochar is produced by slow pyrolysis (thermal degradation under limited oxygen conditions) of biomass (PANEQUE *et al.*, 2016). As it is a carbon rich material, its application to soil can significantly increase the soil organic matter content leading to improved soil quality (DOWNIE, 2009; LIU *et al.*, 2014).

Laboratory and field-scale studies have shown that biochar assists in soil water availability and maintenance (AGEGNEHU *et al.*, 2016) and nutrients (AGEGNEHU *et al.*, 2016; PANDIAN *et al.*, 2016; SMITH, 2016), promoting the development of important plant parts such as the roots (ABIVEN *et al.*, 2015; MADARI *et al.*, 2017; OBIA *et al.*, 2016), it also provides better conditions for the development of important soil microorganisms (SHENG; ZHU, 2018; ULYETT *et al.*, 2014). These parameters help to stimulate plant growth, ultimately generating better crop yields (NAIR *et al.*, 2017; NOVAK *et al.*, 2016).

Due to the great variability of the available biomass, different types of biochar can be obtained and, for this reason, their effect on soil properties and agricultural production is also very variable (BORCHARD *et al.*, 2014; JEFFERY *et al.*, 2015). Therefore, a prior assessment of each type of biochar is necessary, as well as its effect on the soil and plants, in order to identify which raw material is ideal to guarantee the highest productivity.

The study of the impact of biochar on agricultural production has been studied by many researchers (PETTER *et al.*, 2012; KRASKA *et al.*, 2016; WIN *et al.*, 2019), mainly regarding irrigation water use productivity, aiming to mitigate problems with lack of water and low fertility soils (AKHTAR *et al.*, 2014; AGBNA *et al.*, 2017).

Most biochar studies are carried out under greenhouse and vessel conditions. Little has been studied about combinations of biochar and different raw materials and how this addition affects the productivity of water use in field crops. In addition, few studies have been carried out with okra plants in relation to the application of biochar in the soil. Therefore, we evaluated the impact of biochar combinations of dry coconut shell and sewage sludge on the chemical characteristics of the soil, development, yield and water productivity of the okra culture.

Material and Methods

Experimental site

The experiment was conducted in the field at the experimental station of the Federal University of Sergipe (UFS), located in the municipality of São Cristovão / SE, Northeast Brazil (about 10° 55 '46 " S; 37° 06' 13" W). The local climate according to Köppen's classification is *As* type, ie rainy tropical with dry summer and annual rainfall around 1200 mm, concentrated between April to September months. The soil is classified as Yellow Red Argisol according to Santos *et al.* (2013), Ultisol, according to Soil Survey Staff (2014), and presented the following physicochemical characteristics: pH = 4.64; P = 2.82 mg dm^{-3}; K = 0.65 mmol dm^{-3}; Ca^{2+} + Mg^{2+} = 0.73 mmol dm^{-3}; Al^{3+} = 0.45 mmol dm^{-3}, effective cation exchange capacity (CEC) = 1.83 mmol dm^{-3} and effective base saturation (V) = 75.40%. Physical properties were: Sand: 71.57%, Silt: 13.43%, Clay: 15%. The sample was collected in the 0-20 cm depth layer.

Experimental set up

The experiment was arranged in randomized blocks, with 6 treatments (CHB+BSS - combination of coconut husk biochar and biochar of sewage sludge, CHB+RSS- combination of coconut husk biochar and raw sewage sludge, BSS+RSS - combination of biochar of sewage sludge and raw sewage sludge, CHB - coconut husk biochar, BSS - biochar of sewage sludge, WB - without biochar (control)) and four replicates. The blends were made in the ratio of 1:1 (v:v). The equivalent of the 30 t ha^{-1} dose of each biochar and combinations was incorporated at a depth of 5 cm in soil. The experimental unit consisted of three plants. The biochar was applied and incorporated manually into the soil, with the aid of a shovel, 30 days before sowing. The sowing of the okra cultivar Santa Cruz was carried out, with 3 seeds per hole, with spacing between plants of 0.30 m, and the thinning was performed after emergence. The weeds were removed weekly by hand with the aid of a hoe. The cultivation was carried out between June and July 2016.

Production, chemical characterization, and feedstock of biochar

Biochar was produced in a furnace adapted and produced at the Federal University of Sergipe using a model developed by IBI (International Biochar Initiative), the TLUD (Top Lid Updraft). Coconut residue (dry coconut husk) and sewage sludge collected at a sewage treatment plant were used as feedstock. The biomass accumulated in the inner chamber of the TLUD furnace was transformed into biochar by slow pyrolysis which lasted approximately 40 minutes for the coconut husk and 2 to 3 hours for the sewage sludge at temperatures ranging from 350-450 °C in the internal compartment and around 650 to 700 °C in the outer compartment. The biochar was submitted to laboratory analysis where the chemical characterization followed the methodology used in the determination of soil fertility (Silva, 2009). The characteristics of biochar are shown in Table 1.

Table 1. Characteristics of biochar's.

	pH	EC	N	P	K	C
	1:2.5	mS m^{-1}		%		
CHB	10.55	3.14	9.93	0.02	1.6	60.47
BSS	7.28	10.39	16.13	1.06	3.25	34.04

EC - electrical conductivity, CHB - coconut husk biochar, BSS - biochar of sewage sludge.

Crop evapotranspiration and irrigation

Irrigation was done based on crop evapotranspiration (ETc), determined according to the product between the reference evapotranspiration (ET_0) by the crop coefficient (Kc). The cultivation coefficients for each phenological phase of the culture were those found by Farias *et al.* (2016). The reference evapotranspiration was calculated by the Penman-Monteith method (ALLEN *et al.*, 1998). The daily values used to determine ET_0 were collected at the local weather station. The irrigation method used was dripping with spacing of 0.30 m and flow rate of 1.2 L h^{-1}, with daily irrigation.

Chemical characteristics of soil

The chemical characterization of the soil occurred after incorporation of biochar into the soil. Chemical analyses were performed (pH, CEC, P, K, Ca, and Mg concentrations), following the methodology proposed by Silva (2009). The pH values were obtained through the electrochemical measurement of the effective concentration of H^+ ions in the soil solution, by means of a combined electrode immersed in soil / water suspension in the ratio of 1: 2.5.

Agronomic variables

The first harvest occurred at 64 days after sowing (DAS) and the last at 92 DAS, totaling 12 harvests, the same ones being made 3 times a week. In each harvest, the fruits were weighed on an analytical balance to two decimal places. The average yield per plant was obtained by harvesting the fruits per plant and then weighing, using average values according to the number of harvests. The values were converted in kilogram (kg) and the productivity was obtained considering the production of the useful area of each plot with subsequent conversion to t ha^{-1}. The height of the plants was measured using a ruler graduated in centimeters in each experimental plot. The number of fruits per plant accumulated until the end of the harvest was obtained. The water use productivity (WUP) was calculated for each treatment, in kg m^{-3}, according to Payero *et al.* (2009), as follows:

$$WUP = \frac{Y}{ETc} \quad (1)$$

wherein, Y = yield (kg m^{-2}), ETc = seasonal crop evapotranspiration (mm).

Data analysis

Data were analyzed using the R statistical software version 3.6.3 (R CORE TEAM, 2013). The analysis of variance (ANOVA), homogeneity and normality of the data was performed. The data were submitted to the Tukey test for mean comparison ($p \leq 0.05$).

Results and Discussion

Biochar combinations on soil chemical properties

The pH values were significantly influenced ($p \leq 0.05$) by the different treatments (Table 2). Soil pH increased in all biochar treatments, with a 14.30%, 13.4% and 10.04% increase in CHB, BSS, CHB + BSS treatments respectively.

The addition of biochar showed significant effect ($p \leq 0.05$) for Ca, Mg, P and K parameters (Table 2). Ca content was increased by 216.66% in BSS treatment. For Mg there was a 311.1% increase in CHB + BSS treatment. P was high when CHB treatment was used, increasing 28.48%. There was an increase of 1092.6% of K in the CHB + BSS treatment.

The values of base sum (SB), cation exchange capacity (ECC) and base saturation (V) were significantly influenced by the different treatments (Table 2). In general all treatments had increment of these parameters when compared to the control treatment. There was a 200% increase in SB in the CHB + BSS treatment. For the CEC parameter, two treatments stood out: BSS, with an increment of 12.43% and CHB + BSS, with an increase of 10.73%. The base saturation was modified by the treatments, however, the largest increase was found in the CHB + BSS and CHB treatments, with an increase of 269.83% and 269%, respectively.

Table 2. Chemical properties of soil with different biochar and combinations.

Treatments	pH	Ca	Al	Mg	P	K	SB	CEC	V
	--	cmol dm^{-3}			mg dm^{-3}		cmol dm^{-3}		%
CHB+BSS	4.93a	0.61b	0.47bc	0.37a	1.93e	96.6a	1.23a	3.92a	31.3a
CHB+RSS	4.89ab	0.49c	0.56a	0.13c	2.07e	21.6c	0.68c	3.49c	19.3c
BSS+RSS	4.89ab	0.68b	0.60a	0.19b	4.20c	8.5d	0.89b	3.69b	24.1b
CHB	5.12a	0.39d	0.39c	0.22b	6.00a	44.6b	0.72c	2.32d	31.2a
BSS	5.08a	0.95a	0.43c	nd	3.74d	10.1d	0.98b	3.98a	24.5b
WB	4.48b	0.30d	0.65a	0.09c	4.67b	8.10d	0.41d	3.54bc	11.6c
CV (%)	3.21	6.22	6.84	9.57	3.16	6.19	4.94	1.94	9.61

SB – sum of bases; CEC – cation exchange capacity; V – base saturation. Values followed by the same letter within a column are not significantly different at $p \leq 0.05$ level based on Tukey test.

The treatments with coconut shell, sewage sludge and their combination, provided an increase in soil pH (Table 2), promoting an alkaline behavior. Large differences in soil pH can be seen depending on the raw material that is used for biochar production. The alkalinity of biochar is an important factor in controlling its liming effect (YUAN; XU, 2011). Table 1 shows that the biochar CHB and BSS feedstock have a high pH value, which probably led to their increase in soil. The increase in pH is consistent with other studies found in the literature (SHACKLEY *et al.*, 2012; UZOMA *et al.*, 2011). The modification of pH in the soil is dependent on the raw material that the biochar was made, for this reason it is noted that each biochar and combinations presented different values.

Ca levels were modified in the soil (Table 2), so adding biochar to the soil may increase the calcium available to the plants. This fact is related to the negative charges present in biochar that attract positively charged ions like Ca, and make it available to plants (ABDUL; ABDUL, 2017). The biochar can then be used to increase the calcium content available to plants. Some researchers found positive responses to the Ca parameter in the soil (SACKETT *et al.*, 2015; PAVLÍKOVÁ *et al.*, 2014).

Mg in the soil was modified by incorporating biochar (Table 2). The combination CHB + BSS, BSS + RSS and CHB promoted increase of this nutrient. This is important for regions where predominant tropical and subtropical soils are generally Mg deficient due to extensive leaching (MASUD *et al.*, 2014). Other researchers found similar results and attributed this event to the raw material used for biochar production (MARTINSEN *et al.*, 2015; CARTER *et al.*, 2013).

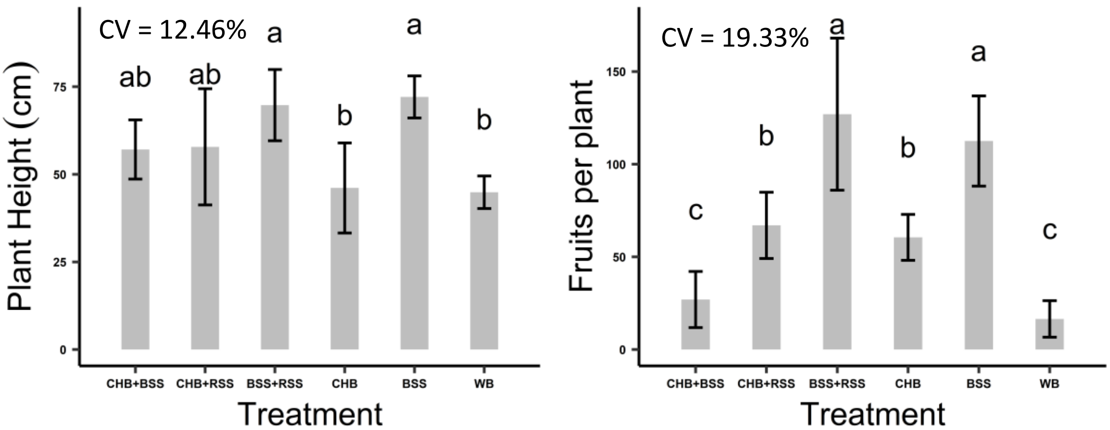
The incorporation of CHB increased the level of P in the soil (Table 2). This may have been due to the fact that the increase in pH provided by the biochar may have improved the availability of P that was already present in the soil, since the P content in this biochar is low (Table 1). Gonzaga *et al.* (2017) observed the same effect as biosolid derived biochar. Logically this is related to the biochar raw material and its efficiency in the adsorption and availability of this nutrient to plants. According to Chintala *et al.* (2014) and Zhang *et al.* (2016), biochar's ability to increase P retention in soils is quite variable, and this variation is due to P concentration in the soil solution. The CHB + BSS combination increased the soil K level. Some studies have shown that increasing K by adding biochar to soil can improve crop development (ORAM *et al.*, 2014; ABU ZIED AMIN, 2016). Robertson *et al.* (2012), found an increase in soil K content when biochar was used in a greenhouse experiment. This proves that biochar can be an important source of this nutrient as K is linked to much of the development of agricultural crops.

Soil CEC was modified through treatments, and the highest value was found in CHB + BSS and BSS treatments. The increase in CEC is related to surface area, negative surface charge and biochar charge density (LI *et al.*, 2018). In addition, there is the presence of oxygenated functional groups on the biochar surface that may influence the increase of soil CEC (GLASER *et al.*, 2003; SOHI *et al.*, 2010). Increase in CEC has been found in other studies (MARTINSEN *et al.*, 2015; HILIOTI *et al.*, 2017; CORNELISSEN *et al.*, 2018; HAILEGNAW *et al.*, 2019). There was an improvement in soil V values in the use of biochar, with an increase in all treatments, with the highest values found in the CHB + BSS and CHB treatments. This positive change in V values can be explained by the increase in pH and soil cations (Ca^{2+}, Mg^{2+} and K^{+}), and it is also related to changes in soil CEC and type of residue (CARMO *et al.*, 2016).

Growth and water productivity of okra

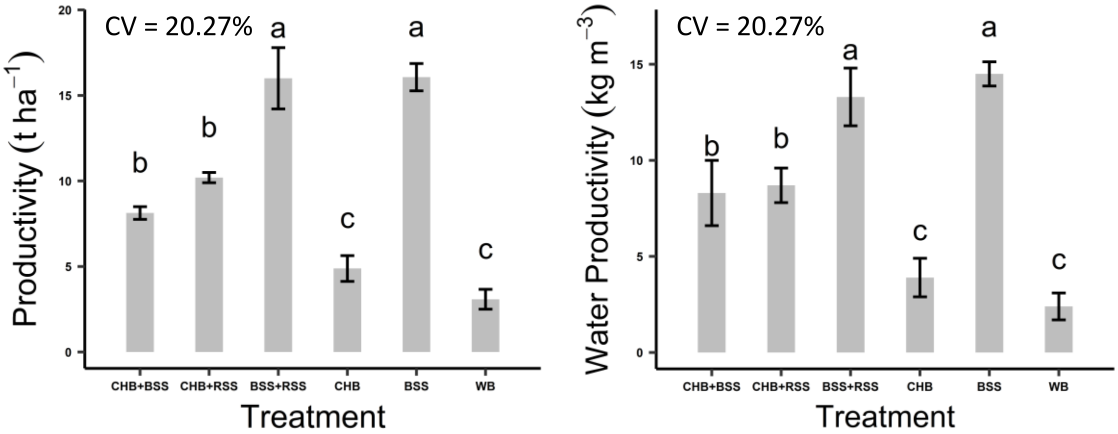
The results of okra growth parameters can be seen in figures 1 and 2. Growth variables, plant height (cm), fruits per plant and yield (t ha^{-1}) were significantly influenced ($p \leq 0.05$). For the plant height variable there was an increase of 60.58% and 55.4% in the BSS and BSS + RSS treatments respectively (Figure 1), in comparison to control treatment. The number of fruits per plant increased in BSS + RSS and BSS treatments, causing an increase of 669.7% and 581.8% respectively, when compared to the control treatment (Figure 1).

Figure 1. Effect of the combinations and type of biochar on average plant height (cm) and fruits per plant of okra. Different letters in bar of each treatment represents significant differences between various treatments following ANOVA (Tukey test, $p \leq 0.05$).



The highest yields were found in the BSS + RSS and BSS treatments with an increment of 421.15% and 419%, corresponding to 13.00 and 12.92 tonnes more than the control treatment (Figure 2). The best results of water use productivity were found in the BSS and BSS + RSS treatments, with values of 14.5 and 13.3 kg produced for each cubic meter of water applied, respectively (Figure 2).

Figure 2. Effect of the combinations and type of biochar on productivity and water productivity of okra. Different letters in bar of each treatment represents significant differences between various treatments following ANOVA (Tukey test, *p ≤ 0.05*).



The different biochar combinations promoted changes in the plant height and number of fruits per plant. Jeffery *et al.* (2011), showed that when there is an increase in soil pH, there is also an increase in the availability of nutrients, which may explain the effect of adding this combination of biochar. This shows that in acidic soils when there is an increase in soil pH, there is also an increase in the availability of the most essential nutrients, except cationic micronutrients, and this is because each nutrient has an ideal pH range that maximizes its absorption by plants. Wong *et al.* (2009), showed that when making changes such as applying organic materials to the soil there may be an improvement in soil characteristics, which implies improved plant development.

The addition of BSS+RSS and BSS significantly improved okra productivity and consequently water use productivity. It is observed that the same treatments showed the best numbers of fruits and plant height, which reflected in the final productivity, that is, there was an increase in productivity with less water use. This is important for regions where water resources are scarce as producers can use these types of biochar to improve soil chemical characteristics and achieve higher yields without using more water. The cause of this improvement in water use productivity may be due to changes in total porosity and soil density, which may have improved soil hydraulic conductivity and its ability to retain water and make it available to plants (FALOYE *et al.*, 2019; AJAYI; RAINER, 2017; SUN *et al.*, 2013).

The present study demonstrated that okra increases its productive characteristics and optimizes the use of water when subjected to biochar application to the soil. The application of different types of biochar promoted changes in the chemical parameters of the soil which increased okra productivity. BSS + RSS and BSS treatments revealed a significant increase in okra productivity and water productivity. It is possible to verify the influence of these treatments on the okra plant and how it behaved during its development. Therefore, this research can serve as a basis for other locations where resources are scarce, thus contributing to increase the productivity of this crop in the most diverse regions of the world.

Conclusions

The results found in this research indicated that the use of biochar incorporated in the soil may be beneficial for increasing okra productivity, optimizing water use and improving soil chemical characteristics. The BSS + RSS and BSS treatments provided the best results of okra production parameters, showing that these types of biochar can be used in okra production, and that the biochar raw material is decisive in deciding whether or not to use it. Soil chemical parameters have been modified as a function of the raw material used in the production of biochar, which may promote the reduction of the application of chemical fertilizers to the soil by farmers.

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