University of Sao Paulo
"Luiz de Queiroz" College of Agriculture

Biochar and its influence on soil physical and hydraulic properties

Sara de Jesus Duarte

Thesis presented to obtain the degree of Doctor in
Science. Area: Soil and Plant Nutrition

Piracicaba
2019

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Biochar and its influence on soil physical and hydraulic propertie
versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:
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To my mother, who is an exemple of life and determination.

I DEDICATE

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Everything is possible when we believe

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RESUMO

Influência do biochar nas propriedades físicas e hidráulicas do solo

O biocarvão (BC) é um produto promissor para a melhoria da qualidade química, física, e hidráulica do solo. No entanto, faltam estudos sobre a influência da dose de BC, tamanho de partícula, profundidade de aplicação, efeitos sobre a textura do solo e tempo de interação em condições de clima tropical. Este é um dos primeiros trabalhos que avaliam essas propriedades em solos sob condições tropicais. O objetivo deste estudo foi analisar o efeito da dose de BC e do tamanho de partículas nas propriedades químicas, físicas e hidráulicas do solo em condição tropical. Avaliou-se o efeito da dose de BC (6,25; 12,5 e 25 Mg ha⁻¹) em solo franco argiloso e arenoso, em condições de laboratório sobre as propriedades químicas (C, N e C/N), físicas (densidade do solo, porosidade e distribuição do tamanho dos poros) e hidráulicas do solo (capacidade de retenção de água e teor de água disponível). Em condição de campo foi estudado o efeito da torta de filtro e dose de BC (6,25, 12,5 e 25 Mg ha⁻¹) mais torta de filtro (TF) em duas profundidades (0-10 e 10-20 cm) e em dois tempos de interação (9 e 18 meses) sobre as propriedades físicas (densidade do solo, porosidade, distribuição do tamanho dos poros e estabilidade de agregados) e hidráulicas do solo (capacidade de retenção de água, teor de água disponível e condutividade hidráulica). Afim de verificar o melhor tamanho de partícula de BC a ser aplicado ao solo foi desenvolvido um terceiro estudo no qual foi avaliado o efeito do tamanho de partículas de BC (<0,15; 0,15-2 e > 2mm) em solo franco argiloso e arenoso sobre as mesmas propriedades químicas, físicas e hidráulicas do solo avaliadas no primeiro estudo. No estudo de influência de dose de BC em condição de laboratório, foi verificado efeito positivo da dose de BC na disponibilidade de água, microporosidade e retenção de água, especialmente para solo franco argiloso com alta aplicação de BC, mas essa influência não ocorreu, para solos arenosos, possivelmente devido ao curto período de interação. No segundo estudo (efeito da dose de BC+TF) verificou-se que a densidade diminuiu ligeiramente e a porosidade aumentou após nove meses de interação com TF + BC 25 Mg ha⁻¹ e após 18 meses, a quantidade de BC+TF alterou a distribuição do tamanho dos poros aumentando a quantidade de microporos, melhorando a estabilidade do agregado e o conteúdo de água disponível (CAD). O efeito da dose não foi verificado para condutividade hidráulica (Kfs), porém o tempo de interação contribuiu para aumentar os Kfs. Além disso, uma redução de Kfs foi encontrada com o aumento da taxa de BC + TF, especialmente na maior quantidade de TF + BC (25 Mg ha⁻¹) de biocarvão. No terceiro estudo, (efeito do tamanho das partículas de BC nas propriedades químicas, físicas e hidráulicas), o teor total de carbono aumentou principalmente em solo arenoso comparado ao tratamento controle, a maior quantidade de carbono foi obtida no tamanho do BC 0,15-2 mm em solo argiloso e <0,15 mm em solo arenoso, enquanto o teor de TN e a relação C/N aumentaram ligeiramente com a redução do tamanho das partículas de BC em ambos os solos. Estes resultados demonstraram que o tamanho das partículas de BC é crucial para a retenção, disponibilidade de água, distribuição de tamanho de poros e sequestro de carbono. Esses estudos demonstraram que é possível economizar água de irrigação e melhorar as propriedades químicas e físicas do solo por meio da aplicação do biocarvão.

Palavras-chave: Física do solo; Dose de biocarvão; Tamanho de partícula do biocarvão; Biocarvão de *Miscanthus*

ABSTRACT

Biochar and its influence on soil physical and hydraulic properties

The biochar is a promissor product for the soil improvement as physical, chemical and hydraulic properties. However, there is a lack of information about the influence of biochar rate, particle size, depth, soil texture and time of interaction on tropical climate. This is one of the first studies that analyse these properties under tropical condition. The objective of this study was analyze the effect of biochar (BC) rate and particle size on soil chemical, physical and hydraulic properties on tropical condition. Was acessed the effect BC rate (6.25, 12.5 and 25 Mg ha⁻¹) in Clay loam and sandy soil under laboratory condition on chemical properties (C, N and C/N ratio), physical properties (bulk density, porosity and pore size distribution) and hydraulic properties (water holding capacity and water available content). In field condition, the effect of the Filter cake (FC) and FC + BC rate (6.25, 12.5 and 25 Mg ha⁻¹) was studied in two depth (0-10 and 10-20 cm) in two times of interaction (9 and 18 months) on soil physical (bulk density, porosity and pore size distribution and aggregate stability) and hydraulic properties (water holding capacity and water available content and hydraulic conductivity). To verify the best BC particle size to be applaied on the soil, a third study was developed to test the effect of BC particle size (<0.15; 0.15-2 and >2mm) in clay loam and sandy soil and to analyze its effects on soil chemical, physical and hydraulic properties. In the frist study (effect of BC rate on laboratory condition) a positive effect of BC rate on water availability, microporosity, and on water retention was found, especially for clay loam soil at high BC application, but this influence did not occur for sandy soil, possibly due to the short time of interaction. In the second study (effect of BC rate and FC on physical, chemical and hydraulic properties) the bulk density slightly decreased, and the porosity increased after nine months of interaction upon FC + BC 25 Mg ha⁻¹. However, after 18 months, the FC + BC amount altered the pore size distribution with an increase of micropores, aggregate stability, available water content and its alteration was dependent on the FC + BC rate. Nevertheless, this effect was not verified in the hydraulic conductivity (K_{fs}). The time of interaction contributes to increasing the K_{fs} , and the reduction of K_{fs} was found with the increase of FC + biochar rate, especially in higher amount FC + BC (25 Mg ha⁻¹) of biochar. In the third work (effect of biochar particle size on chemical and physical and hydraulic properties) total carbon content increased mainly in sandy soil compared to control treatment, the highest carbon amount was obtained in the biochar size 0.15-2 mm in loamy soil and < 0.15 mm in sandy soil, while TN content and C/N ratio increased slightly with reduction of the biochar particle size in both soils. These results demonstrated that biochar particle size is crucial for water retention, water availability, pore size distribution and C sequestration. It is evident that is possible to save irrigation water and improve soil chemical and physical properties by applying biochar.

Keywords: Soil physics; Biochar rate; Biochar particle size; Biochar *Miscanthus*

1. GENERAL INTRODUCTION

Every farmers wish to have a fertile soil, with good physical, chemical and hydrological properties, from which is possible to obtain high productivity. This soil exists and is known as *Terra Preta*. Worldwide, the biggest part of this soil are in Amazon, Brazil. Compared with regular adjacent soils, the *Terra Preta* has 18% more water retention and higher fertility than adjacent soils. Because of its good properties, the biggest part of the researches in the world had developed studies about it. Recent studies showed that the main constituents of this soil is the biochar, almost 50 Mg ha⁻¹ at the first 30 cm of depth. This is ten times more than adjacent soil that have only 4 Mg ha⁻¹ at the same depth (Glaser et al., 1999). It is evident that the main ingredient that confer the good properties in the *Terra Preta* is the biochar.

Biochar is a product rich in carbon, produced by thermochemical decomposition. The addition of the biochar on the soil has been verified in many studies by increase carbon sequestration, soil fertility and plant productivity. This effect can be associated with biochar physical and chemical properties.

The potential of the biochar to promote improvement in the soil physical and hydraulic properties is related with its porosity. In general, biochars have about 80% in volume of pores, being 95% of the pores inferior to 20 nm of diameter (mesopore and micropore) and about 5% with diameter ranging from 1000 to 10.000 nm (macropore) (Major et al. 2009).

When added to the soil biochar can modify soil chemical, physical and hydraulic properties. However, there is a lack of information about the biochar and its influence on soil physical and hydraulic properties especially on tropical climate.

Thus, there is still doubts about the behavior and the results of biochar application to the soil physical (aggregate stability) and hydric properties (water holding capacity and water available content). For example, some researches found improvement on the soil physical and hydric properties, others found no significant effect and some of them found negative effect. Moreover, the biggest part of these studies were developed on temperate soils. As far as we understand, this is one of the first studies that evaluate the soil chemical and hydraulic properties in tropical soil. To understand the effect of the biochar on soil physical and hydric properties we developed three studies on laboratory and field conditions.

The first study was developed on laboratory condition, was analysed the effect of biochar rates on soil chemical, hydric and physical properties. The second study was carried out under field conditions, from which we analyzed the effect of filter cake and biochar rates plus filter cake additions on soil physical and hydraulic properties at two times of interaction. The third study was also developed in laboratory condition, we analyzed the effect of biochar particle size on soil chemical,

hydrical and physical properties. The objective of these studies was to analyze the effect of biochar rate, biochar rate plus filter cake and particle size on soil chemical, physical and hydraulic properties under tropical condition.

2. CHEMICAL, PHYSICAL, AND HYDRAULIC PROPERTIES AS AFFECTED BY ONE YEAR OF *MISCANTHUS* BIOCHAR INTERACTION WITH SANDY AND LOAMY TROPICAL SOILS

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Abstract

Biochar application has improved soil properties contributing to crop growth. This study evaluates the effect of biochar amount on soil physical, chemical and hydraulic properties in sandy (SD) and clay loam (CL) soils under tropical conditions. An incubation experiment was installed under laboratory conditions with eight treatments (control, two kinds of soils, SD and CL, and three biochar doses (6.25, 12.5, and 25 Mg ha⁻¹). Analyses of soil water retention, bulk density (BD), total porosity (TP), pores size, total carbon (TC), and N were performed after one year. The BD slightly decreased by 0.035 and 0.062 Mg m⁻³ and TP increased by 1.87 and 2.31% in CL and SD soil respectively, upon 6.25 to 25 Mg ha⁻¹ biochar application. TC increased in CL and SD by 6.5 and 4.2 kg kg⁻¹, respectively, compared to control. The total nitrogen content increased upon biochar addition in CL soil than in SD soil. We found a positive effect of biochar on water availability, microporosity, and a small effect on water retention, especially for CL soil at high biochar application, but this influence did not occur for SD, possibly due to the short time of interaction.

Keywords: Biochar amount; Soil physics; Soil fertility; Soil water

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2.1. Introduction

Traditionally, many approaches have been used to increase the agricultural production, such as the application of fertilizers, organic material, and irrigation. Recently, based on the black earth in the Brazilian Amazon region [1], many researchers have studied biochar and its ecological functions in order to increase soil fertility, soil physical properties, and mitigation of greenhouse gas emissions [2]. Due to these functions, biochar is an attractive tool in agriculture for carbon sequestration and soil quality improvement [3].

Diversified functions in one product are possible because the biochar structure is composed of condensed aromatic groups that give the biochar its black color. Aromatic C groups in the biochar structure provide stability in soils, which makes biochar a good option for long-term C storage in soils [4]. Biological degradation of biochar leads to partial oxidation of biochar functional groups, resulting in the formation of functional groups on the edges of biochar, causing reactivity in the soil such as nutrient retention and mineral-organic stabilization [4,5]. In addition large porosity and specific surface area, and small density of biochar contribute to increased soil water storage and porosity and decreased bulk density of soils, which are particularly important in compacted and degraded soils [6,7].

When biochar is present in a soil system, it can enhance water storage by modifying the portion of the soil pore size distribution associated with aggregation improvements [8]. Water retention is possible because biochar is a porous material and has the potential to absorb and retain large amounts of water [9]. The capability of biochar to retain water is a function of the combination of its porosity and surface functionality. Glaser et al [2] demonstrated that 18% higher water retention capacity in biochar-amended soils relative to adjacent soils containing low amounts of biochar. Additionally, other soil physical properties can be improved, such as bulk density, porosity, soil aggregation, and soil compaction [10]. These effects may enhance the water availability to crops and decrease soil erosion.

Biochar may not only change soil physical properties but also affect soil chemistry by improving soil fertility and long-term C storage, thus leading to multiple benefits regarding climate change mitigation and adaptation [2]. Due to these beneficial effects, biochar can be used as a soil amendment for improving the quality of agricultural soils [2].

The application of biochar to soils is considered as a win-win strategy to increase soil C sequestration [11]. Biochar is a key component of a potentially sustainable integrated agronomic-biomass-bioenergy production system [11]. Improving soil fertility and soil physical conditions that influence soil hydraulic parameters as water retention [6,7,12,13].

Although there is a wealth of studies concerning the effect of biochar on ecosystem functions [2,14–16], relatively little is known on the effect of biochar on soil physical and hydraulic conditions and the influence of biochar amount. The hypotheses of this paper is that with increase of biochar amount the physical, chemical and hydraulic properties will be improved. The purpose of this paper is to evaluate the effect of biochar amount on the soil physical, chemical, and hydraulic properties of sandy and clay loam soil under tropical conditions.

2.2. Material and Methods

2.2.1. Biochar Preparation

Biochar was commercially produced from agricultural residues of *Miscanthus giganteus*. This biochar was used because it is a co-product of the production of cellulosic ethanol and has been widely applied because of its increasing availability as a product of the growing biofuels industry. The production of biochar involved drying of the *Miscanthus* grass at 120–130 °C in a reactor, followed by pyrolyzation in a second reactor at 450 °C for about 15 min.

2.2.2. Experimental Setup

The factorial experimental design was completely randomized and comprised the factors biochar rate (0, 6.25, 12.5, and 25 Mg ha⁻¹) and soil texture (sand and clay loam), totaling eight different treatments, with four replicates, resulting in a total of 32 pots that were incubated for 12 months at temperatures of 30 °C under laboratory conditions. Each container was composed of 100 g of soil and the respective dose of biochar.

2.2.3. Sample Preparation, Incubation, and Sampling

Biochar was incorporated into the soil, based on pre-calculated bulk densities (biochar and soil), which included the contribution of the biochar to the final bulk density. The incorporation occurred into a container of 0.5 L with 100 g of soil and biochar rate 0, 0.24, 0.48 and 0.96 g of biochar representing (0, 6.25, 12.5, and 25 Mg ha⁻¹), during all period of the experiment the moisture was adjusted to the 60% of field capacity the interaction soil-biochar occurred in one year, after this, the soil was sampled. For the sampling, a ring of approximately 7 cm³ was used. The collection of the sample occurred with the insertion of the ring in the soil and the removal of the sample with the advice of aluminum similar to one shovel.

2.2.4. Biochar and Soil Analysis

2.2.4.1. Biochar Analysis

The elemental analyses as well as pH and electrical conductivity and yield were performed following the methods recommended by the International Biochar Initiative Guideline [17], labile and stable carbon [18], moisture content [19], volatile matter [20] and ash content [21], and specific surface area [22].

2.2.4.2. Fourier Transform-Infrared Spectroscopy (FTIR)

This analysis was conducted in order to verify absorption bands associated with hydrophobic and hydrophilic groups of biochar. FTIR was used as a suitable tool to visualize and quantify aromatic, carboxylic and phenolic groups at the biochar surface. The biochar was ground until the particle size less than 0.149 mm, the biochar and KBr were dried 24 h at 105 °C and 700 °C, respectively. Sonogel pastilles were prepared at 0.1% of biochar and 99.9% of KBr. In this study, a Nicolet Nexus 670 FTIR (Thermo Electron Corporation, Verona Road Madison, WI, USA) was used. All samples were analyzed in transmittance. FTIR imaging mode while collecting all FTIR spectra in the mid-infrared range from 400 to 4000 cm^{-1} , using 4 cm^{-1} spectral resolution, and 100 scans for each single point collection.

2.2.4.3. Hydrophobicity

Considering that water wets soil material with a 90° contact angle, we used an index of water repellency (molarity method of ethanol drop MED) proposed by [23]. This procedure employs the concept that a liquid can only completely enter the soil if the theta (θ) is less than 90°. The procedure evolved drying the biochar in air and putting approximately 2 g of the sample on the ring (50 mm × 10 mm) with the surface of the biochar planed. Solutions of $\text{H}_2\text{O}:\text{EtOH}$ with 95% of ethanol were prepared with concentrations of EtOH: 100, 50, 30, 20, 10, and 0. One drop (0.05 mL) of these solutions was applied on the surface of the biochar at a height greater than 5 mm. The time of complete drop penetration in the sample was measured, the temperature at the moment of the test was 25 °C, and the test was repeated with incremented the solution molarity in 1% until that the drop enters in one time smaller than three seconds. Using one graphic which correlates the percentage of the volume of ethanol that penetrate in the biochar less than three seconds with the surface of tension. We found the surface of tension in each sample and the molarity of the ethanol for each sample [24]. We follow the classification of severity of water repellency where, soils with a MED index ≤ 1 not water repellent, 2 very low, 3–5 low, 6–8 moderate, 9–10 severe, and 10–12 very severe [24].

2.2.4.4. Soil Analyses

The soils used were Arenosol (sandy texture) and Ferralsol (loamy texture). The soils were sampled at the 0–20 cm layer from two different native vegetation areas located near Anhembi, Brazil (22°43'31.1" S and 48°1'20.2" W) and in Piracicaba, Brazil (22°42'5.1" S and 47°37'45.2" W), both in Sao Paulo state, Brazil. The samples were air-dried, homogenized, and sieved <2 mm.

Soil chemistry characterization as pH in calcium chloride 0.01 M (CaCl_2), P, K, Ca, and Mg in resin, H + Al potential acidity pH SMP; Al extracted with potassium chloride (KCl, 1M), sulfate (S-

SO₄) extracted with calcium phosphate Ca(H₂PO₄)₂, 0,01M), percentage of saturation by bases (V%) and percent saturation by aluminum (m%) [25], C and N was determined with elemental analyzer [26].

2.2.4.5. Physical Analysis

2.2.4.6 Bulk Density and Particle Density

The bulk density was determined by the method of [27]. For the determination of particle density (PD) we used approximately one gram of each soil treated with biochar and the control (only soil). The soil was placed inside of the instrument and the particle density was determinate using a helium gas pycnometer, model ACCUPYC 1330 (Micrometrics Instrument Corporation, Nacross, GA, USA). The pycnometer determines the volume of solids, by the variation of the pressure of one gas, in a known volume chamber.

2.2.4.7 Soil Texture

Soil texture was analyzed in four replicates, since the maximum dose (25 Mg ha⁻¹) is the one that would be most likely to change the texture of the soil, we tested only that dose and the control treatment (only soil) by the method of [28] that use sodium hexametaphosphate for dispersion. Sand and silt were obtained by wet sieving and clay by sedimentation.

2.2.4.8 Porosity

The total porosity (*TP*) was calculated from the soil bulk density (*BD*) and the particle density (*PD*) [29] using the following equation:

$$TP (\%) = 1 - \frac{BD}{PD} \times 100 \quad (1)$$

The macroporosity, mesoporosity, and microporosity were calculated by soil water retention curve using theoretical values for macroporosity superior to 50 µm, mesoporosity between 15 and 50 µm, and microporosity less than to 15 µm [30].

2.2.4.9. Water Retention Curve

Soil water holding capacity was measured by moisture contents of the samples at different matric potentials (-15.000, -10.000, -3000, -1000, -300, -100, -60, -40, and -20 hPa). The points (-15.000, -10.000, -3000 and -1000 hPa) were measured in Richard chamber, and -60, -40, and -20 hPa in Haines' apparatus. Gravimetric analysis was undertaken to determine the moisture contents and these were

converted to volumetric basis using the corresponding bulk density values [31] and for the curve was used Van Genuchten type [32].

2.2.5. Data Analyses

Statistical analyses and graphics were performed using the language R and the packages: soil physics, agricolae and plotrix [33] and the biochar spectrum in the software Origin Lab version 9.1. The data were checked for normality and homogeneity of variances to meet the assumptions of ANOVA and Tukey's test, and a probability of 0.05.

2.3. Results

2.3.1. Soil and Biochar Characterization

According to Agronomic Institute of Campinas (IAC) and Brazilian Agricultural Research Corporation (Embrapa) the sandy soil has very low amount of K, low of Mg, P, and base saturation (V%), medium of Ca, S, Al, CEC, and aluminum saturation (m%) and very acidic pH. The loamy soil has a neutral pH, low Al, and m%, medium S and CEC, high V% and K, and very high C (Table 1).

Chemical and physical properties of biochar and specific surface area, electric conductivity, pH and total nitrogen and carbon are given in Table 1. Biochar has a high quantity of C, N, Ca, Mg, Na, K, P, and S compared to the soil (Table 1).

Table 1. Physical and chemical characteristics of biochar *Miscanthus*, sandy and loamy soil*.

Property	Biochar	Sandy Soil	Loamy Soil
	------(%)-----		
Sand		90	40.6
Silt		2.2	27.7
Clay		7.8	31.7
pH (H ₂ O)	5.86		
pH (CaCl ₂)		3.90	6.50
Yield 31			
Moisture	3.5		
Volatile material	34.6		
Ash	6.1		
Fixed carbon	57.1		
Total N	0.43		
¹³ C	-13.41		
Total C	66.35	0.86	1.93
N	0.43	0.06	0.17
C/N	155.4	14.3	11.4
Labile C (%)	2.70		
Stable C (%)	50.87		
Lability	0.05		
CEC (mmol _c dm ⁻³)	33	69	138
Specific surface area (m ² g ⁻¹)	371.9		
Electric conductivity ((μS cm ⁻¹)	605		
	------(mg kg ⁻¹)-----		
Na	423		
P	1859	4	28
S	634	5.30	9.50
Fe	1317		
Mn	139		
Cu	59		
Mo	0.66		
Zn	138		
Ni	7.74		
	------(mmol _c dm ⁻³)-----		
Al		5.7	0
H + Al		62	18
SB		6.9	120
V (%)		10	87
m (%)		45	0

* Source: [34]. CEC: cation exchange capacity. H + Al = potential acidity, SB = soma of bases (Ca, Mg, K), CEC = Cation exchange capacity (SB + Al + H), V = Base saturation (SB × 100/CTC); m = Aluminum saturation (100 × Al³⁺/ SB + Al³⁺).

The FTIR spectrum of the *Miscanthus* biochar can be recognized in the first main region and the second region. The first region occurs in the interval between 0 and 2000 cm⁻¹ contains individual signals and the second signal in 3685 cm⁻¹ (Figure 1).

Figure 1. Fourier transform infrared spectrum of *Miscanthus* biochar pyrolyzed at 450 °C.

The first signal in the points 500 can be associated to carbonate (C-O), 860, 894 cm^{-1} can be attributed to cyclic acid anhydrides (C-C; C-O) group; the second one at 644 and 1095 associated with the band 1030 cm^{-1} is due to silicon (Si-O), the signal at 1448, 1484, and 1606 can be assigned to carboxylates asymmetric (CO_2) and at 1700 and 1780 can be attributed to ketones (C=O) and aromatic carbon, respectively. The second region is due to the presence of silanol (Si-O-H) at 3685 cm^{-1} .

Among these compounds, are hydrophobic: Cyclic acid anhydrides (C-C and C-O) carboxylates asymmetric (CO_2), ketones aromatic (C=O), Silicon (Si-O) and hydrophilic carbonates (C-O) and silanol (Si-O-H). Although the hydrophilic compounds (silanol and carbonates) have high intensity, the quantity of hydrophobic compounds with high intensity is larger in this biochar (Figure 1). These compounds may contribute to the high hydrophobicity in this biochar, this hydrophobicity was verified by analyze of the biochar hydrophobicity in which the result was high hydrophobicity (Figure 2).

2.3.2. Effect on Soil Chemical Properties

2.3.2.1. Total Carbon

As expected we found higher amounts of carbon in the loamy soil compared to the sandy soil (Table 1). The total carbon increased with biochar addition in both soils, but for loamy soil, this effect was more accentuated than for sandy soil. In the loamy soil, the total organic C ranged from 23.1 g kg⁻¹ at the control to 29.6 g kg⁻¹ at the highest biochar addition (25 Mg ha⁻¹). This dose increased the amount of carbon by 6.6 g kg⁻¹ in loamy soil (Figure 3a). For the sandy soil, the total organic C ranged from 5.7 g kg⁻¹ at the control treatment to 10 g kg⁻¹ at 25 Mg ha⁻¹ of biochar addition from the soil. Therefore, this increase was of 4.2 g kg⁻¹.

Figure 2. Hydrophobicity *Miscanthus* biochar pyrolyzed at 450 °C the scale 0–12 is indicative of degree of hydrophobicity (≤1 not water repellent; 2: Very low; 3–5: Low; 6–8: moderate, 9–10: Severe; 11–12: very severe).

Figure 3. Effect of biochar amount on soil physical and chemical properties in clay loam and sandy soil. C: carbon; N: nitrogen; C/N: atomic ratio; TP: total porosity; BD: bulk density. (A) Carbon content; (B) Nitrogen content; (C) Carbon and Nitrogen ratio; (D) Total porosity; (E) Bulk density.

2.3.2.2. Total Nitrogen

Total N (TN) content ranged between 2.4 g kg⁻¹ and 2.6 g kg⁻¹ for the loamy soil and between 0.58 and 0.70 g kg⁻¹ for sandy soil. (Figure 3b). The increasing amount of biochar application tended to increase soil TN contents compared to the control, but this difference was not statistically significant ($p > 0.05$).

2.3.2.3. C:N Ratio

For the loamy soil the C/N ratio ranged between 9.4 (control) and 11.4 (25 Mg ha⁻¹ of biochar; Figure 3c); for the sandy soil, C/N ratio ranged between 11.6 (control) and 15.9 (25 Mg ha⁻¹ of biochar; Figure 3c). Increasing biochar amounts increased the C/N ratio, but this increase was not statistically significant ($p < 0.05$).

2.3.3. Effect on Soil Physical Properties

2.3.3.1. Porosity

The biochar amount increased the porosity in both soils. Although the difference is not significant it is possible to note that in both soils the biochar amount increased the total porosity. Compared to the control treatment in the loamy soil, the 25 Mg biochar ha⁻¹ increased the porosity from 47 to 49% and for sandy soil from 44 to 47% (Figure 3d).

2.3.3.2. Bulk Density

There is no significant difference ($p > 0.05$) between loamy and sandy soil and biochar doses on bulk density. In both soils, the total bulk density decreased with increasing of biochar, but for sandy soil, this effect was more accentuated than for loamy soil. In the loamy soil, the bulk density ranged from 1.46 g cm⁻³ at the control to 1.39 g cm⁻³ in 25 Mg ha⁻¹ (Figure 3e) and for sandy soil between 1.51 g cm⁻³ (control) and 1.42 g cm⁻³ (25 Mg ha⁻¹).

2.3.3.3. Texture

The biochar addition did not change the soil texture in both sandy and clay loam soil, even when applied 25 Mg ha⁻¹ of biochar (Table 2).

Table 2. Influence of biochar amount on soil texture in sandy and clay loam soil.

Treatment	Sand	Silt	Clay	Textural Class
------(%)-----				
Control	40.6	27.7	31.7	Clay Loam
Biochar 25 Mg ha ⁻¹	34.7	27.0	38.3	Clay Loam
Control	90	2.2	7.8	Sandy
Biochar 25 Mg ha ⁻¹	91	5.8	3.3	Sandy

Control = only soil.

2.3.4. Effect on Soil Hydraulic Properties

2.3.4.1. Water Retention Curve

In the loamy soil at low biochar doses (6.25 and 12.5 Mg ha⁻¹), low tension was enough to reduce the water content of the macropores. However, in control treatment, this decrease occurred from 100

hPa and, for the highest biochar amount (25 Mg ha⁻¹), was necessarily approximately 1000 hPa, for the decrease the water content. We checked that the higher biochar amount increased the water retention and was higher than the other treatments up to 1000 hPa and from that potential water retention was similar for all treatments (Figure 4a).

The biochar amount did not affect the water retention in sandy soil, little increase in the soil water retention in low potential (1–10 hPa) was checked in 12.5 Mg ha⁻¹. From of potential (10 hPa), the biochar dose did not affect the soil water retention, the curve behavior was similar in all treatments and the difference between the treatments in the water retention was very little and insignificant (Figure 4b).

Figure 4. Effect of biochar amount on soil water retention in clay loam and sandy soil. (a) Clay loam soil; (b) Sandy soil

2.3.4.2 Plant-Available Water Content

Comparing loamy and sandy soil, the clay loam soil has higher water available content than the sandy soil. In clay Loam soil and sandy soil the higher biochar dose increased the water available content compared to control treatment in 0.05 cm³cm³ in clay loam and 0.03 cm³ of water per cm³ of soil in sandy soil (Figure 5).

Figure 5. Effect of biochar doses on plant-available water content in clay loam and sandy soil. AWC Plant available water content.

2.3.4.3. Effect of Biochar rate on pore size distribution and its relation with the water Retention Curve

Biochar application not only increased the total porosity but also alters soil pore size distribution and water retention. The biochar doses affected the macroporosity, mesoporosity, and microporosity in both soils, the changes in the porosity altered the behavior in the water retention curve for both soil and in all treatments (Figure 6).

In the loamy soil, in the treatments control and 25 Mg ha⁻¹, the total porosity was approximately 48 and 49% respectively. The very low quantity of macropores kept the same behavior in the curve. The variation occurred only in the microporosity range from 100 hPa, the high water retention in these treatments could be attributed to microporosity in the control and 25 Mg ha⁻¹ of biochar. Different behavior in the water retention curve occurred for 6.25 and 12.5 Mg ha⁻¹ of biochar; the macroporosity was higher compared to other treatments. In the 6.25 Mg ha⁻¹ dose, 61% of the pores comprised approximately, 38% of macropores, 9% mesopores, and 53% micropores, and the high quantity of macropores was responsible for the high drainage of water at a low potential. In the 12.5 Mg ha⁻¹ dose, 59% of the total porosity comprised 21% of macropores, 12% mesopores, and 67% micropores.

The intermediate doses of biochar (6.25 and 12.5 Mg ha⁻¹) increased the macroporosity and mesoporosity and decreased the microporosity. This porosity affected the curve in low potential. From 100 hPa, the field capacity increases the water retention with an increase of the tension in all treatments of the clay loam soil (Figure 6).

In sandy soil, the macroporosity was high in all treatments. This macroporosity contributed to high drainage at low matric potential, up to 100 hPa the low quantity of micropores promoted little changed in the water retention curve. In control treatment, 44% of the pores was controlled by macroporosity, 17% by mesopores, and 35% by micropores. In the 6.25 and 12.5 Mg ha⁻¹ doses, the volume of approximately 24% of micropores contributed to the low variation in the water content when increased the potential. The addition of 25 Mg ha⁻¹ of biochar increased the microporosity to approximately 30% (Figure 6).

Figure 6. Effect of biochar amount on macropores (>50 μm); mesopores (15–50 μm) and micropores (<15 μm), and its relation with water retention.

2.4. Discussion

During temporal biochar exposure to the environment, hydrophobic moieties such as polycondensed aromatic moieties decrease while hydrophilic functional groups such as carboxylic acids increase [2,5].

Both soils have low fertility but the added biochar has high fertility (Table 1). Therefore, biochar has a direct positive effect of the investigated tropical soils. It was already stated by [2] that a potential fertilization effect of biochar is high. Laird et al [14] observed significant increases in plant-available P, K, Ca, and Mn upon 5 and 10 Mg ha⁻¹ biochar addition to the soil after 500 days. This increase was attributed to the presence of these nutrients in the biochar itself that over the time can be available in the soil. Because of chemical and biological biochar stability, the biochar is less reactive in soil than other organic molecules the biochar degradation requires a long time. The study of [35] revealed a biochar degradation of 25% within 100 years, translated into a biochar turnover of around 300 years.

2.4.1. Biochar Effects on Soil Nutrient Storage Capacity

2.4.1.1. Total Carbon

The addition of 25 Mg ha⁻¹ of biochar increased the total carbon in both soils but this difference was significant only for clay loam soil compared to lower doses and the control. A similar result in clay loam soil was verified by [15] after one year of interaction (Figure 3a). Similarly, [14] verified that the addition of biochar to the loamy soil increased the total C content after the 500 days incubation by 17.6, 37.6, and 68.8%, respectively, for the 5, 10, and 20 g kg⁻¹ biochar treatments in relation to control treatment (only soil).

Sandy soil has a tendency to increase carbon content with biochar addition (6.25 to 25 Mg ha⁻¹), but this difference was not significant (Figure 3a). Liu et al [6] reported a three-fold increase of soil organic carbon upon 20 Mg ha⁻¹ biochar addition to sandy soil. Weber et al [36] reported higher C and N contents three years after compost with biochar application from municipal waste in the range of 30 to 120 Mg ha⁻¹ at a field trial with Dystric Cambisol.

The increase of carbon concentration of 6.6 kg kg⁻¹ in the loamy soil and 4.2 kg kg⁻¹ in sandy soil with addition of 25 Mg ha⁻¹ (Figure 3a) can contribute for increase of aggregation stability, water retention, water available content, and reduction of soil bulk density, these soil physical properties are essential for the soil physical quality and, therefore, for plant development.

2.4.1.2. Total Nitrogen

Increase in the quantity of nitrogen with an increase of the biochar doses was also verified by [2,15] in clay loam soil. As well as we found in this experiment, that occurred increase but the

difference was not significant with one year of interaction, [12] verified that the difference was not significant in the first year of soil-biochar interaction.

The time required for the increase of the nitrogen in the soil with biochar addition can be attributed to the N in the biochar is present in a stable form [14]. Therefore, the increase of 0.2 and 0.12 g Kg⁻¹ for loamy and sandy soil respectively (Figure 3b), can increase with the time of interaction. The increase of nitrogen amount in the soil is essential for the plant productivity, the biochar addition can increase the amount of nitrogen in the soil without the need of the farmer spend a lot of money with fertilizers.

2.4.1.3. C:N Ratio

Independent of biochar amount, the loamy soil has lower C:N ratio compared to sandy soil, which can be attributed to the high quantity of nitrogen in clay loam soil, the increase in the biochar dose increased the C:N ratio, for sandy soil, increased 4.3% and for clay loam soil 2%. This increase can be attributed to the high quantity of carbon in biochar (Figure 3c). As well, in this article, Zhang et al [15] verified that the high amount of biochar amendment of 40 Mg ha⁻¹ induced a high C:N ratio 14–16 under 40 Mg ha⁻¹ as compared to 13 under 20 Mg ha⁻¹. The low increase in the C:N ratio can be associated with low dose in both soils. The increase in the C:N ratio decreased the decomposition of the material if the C:N ratio is superior to 35, the decomposition is low, in every treatment the C:N ratio was inferior to 21, indicated that we do not have problems with decomposition and nitrogen immobilization [37].

2.4.2. Biochar Effects on Soil Physical Properties

2.4.2.1. Total Porosity

Similar to our results, many studies have proved that biochar addition increased the porosity in clay loam and sandy soil [7]. The increase of the porosity with an increase of biochar amount occurred because the biochar is a material with high total porosity, composed by approximately 80% of pore volume, with normally, 95% of these pores are less than a 20 nm of diameter [38], when the biochar is putted in the soil the total porosity increase (Figure 3d). The high porosity in biochar can be a strategy for increasing the porosity, aeration and water movement, water holding capacity, heat and gases in degraded soils, and with compaction problems [12]. The alteration in the porosity of the soil is reflected in the bulk density, but it is important to consider that the low bulk density and high total porosity may not be always beneficial for plant growth, because of slight compaction can increase root-soil contact and pore connectivity, allowing higher nutrient and water transport and supply to plant roots [39].

2.4.2.2. Bulk Density

Biochar addition to soil reduced the bulk density even at low amount (Figure 3e), in a few cases, biochar application at rates $<10 \text{ Mg ha}^{-1}$ [40] may not reduce bulk density. However, in most research even in small quantities biochar reduces bulk density, and with increase the biochar amount the decrease in the bulk density is more expressive [12,41–43]. Omondi et al [7] reviewed studies on biochar and soil bulk density prior to 2016, and found that the biochar application reduced bulk density by 3–31% in 19 out of 22 studies, indicating that bulk density generally decreases with biochar application.

The magnitude of the biochar effect on bulk density can be explained by simple dilution of the soil with the low bulk density of the biochar [14]. This is so important for the reduction of bulk density and increases soil porosity that contributes directly to the plant development. Similar to this result (Figure 3e), Blanco-Canqui [12] found that the effect of biochar on a reduction of bulk density on clayey soils can be smaller than sandy soil, because of larger differences in size and density between biochar and sand particles being larger than those between biochar and clay particles. The biochar could also reduce bulk density in the long term by interacting with soil particles and improving aggregation and porosity favoring the water retention and availability of water for the plants and promoting a suitable means for the plant development [12]. These results proved that in clay loam and sandy soil the farmers can use biochar for improve the soil physical properties such as bulk density and porosity, properties necessary for the increase the soil quality and consequently plant productivity.

2.4.2.3. Texture

Our results suggest that in clay loam and sandy soil, biochar addition up to 25 Mg ha^{-1} did not modify soil texture. Similarly, Githinji [43] found the same result up to 25 Mg ha^{-1} , but with 50 Mg ha^{-1} he verified that the soil texture shifted slightly from 'loamy sand' to 'sand'. This can occur due to the presence of many larger particles in the range of sand in the biochar.

2.4.3. Biochar Effects on Soil Hydraulic Properties

2.4.3.1. Water Holding Capacity

The fact that the biochar has been produced from Si-enriched raw feedstock (Figure 1), can increase the water retention in the soil because the Si reacts with water molecules in polymerizations reactions causing phytolith or silica hydrogel formations, which are essential structures used in plant biochemical and biophysical reactions [44]. The result is that the biochar may express the same tendency to react with soil water by physically adhering water molecules or trapping water vapor in

internal pores [45]. Soon, assuming that water-binding pathways of Si-enriched biochar operate in soils, the Si content of biochar may be an important characteristic to increase soil-water storage, and therefore, the feedstock switchgrass can be used for improving the soil water retention [12]. Though the hydrophobicity in this biochar can contribute to the reduction of the efficiency in the increase of soil water retention, the contact with water by means of the saturation process for the production of the retention curve and the maintenance of the field capacity of the samples during one year of soil-biochar interaction can reduce this hydrophobicity. Kinney [46] affirmed that the exposition of the biochar in water can reduce its hydrophobicity.

Considering that the biochar is hydrophobic when the contact angle is higher than 90° [47] observed a 69.5% decrease of the contact angle of biochar after one year of its addition to soil suggesting that initial biochar hydrophobicity disappeared within one year. This decrease in hydrophobicity will increase soil water retention [46]. Based on these results it is possible that the hydrophobicity of this biochar used in this experiment was not a negative factor for water retention.

The effect of biochar on water retention is dependent on soil texture [48]. In the loamy soil, the water retention at low doses (6.25 and 12.5 Mg ha^{-1}) of biochar was smaller than the treatment with no addition of biochar (Figure 4). Two reasons can explain this behavior. The first one is that smaller biochar doses inferior to 20 Mg ha^{-1} have no effect in the water retention [49] or can reduce the water retention because of fine-textured soils may be less responsible to biochar application and larger amounts of biochar may be needed to increase water retention which can result in increased plant available water [12]. Medium (20 Mg ha^{-1}) and high (100 Mg ha^{-1}) biochar applications can increase water-holding capacity as verified by [50]. The second reason is that in those doses (6.25 and 12.5 Mg ha^{-1}) the organic material was higher and differed from the control treatment. Peake et al [50] affirmed that soils rich in organic material responded less or not to biochar amendment. Devereux et al [42] showed that an increase in biochar amount results in an increase in soil water content for a given matric potential, suggesting that as matric potential increases, biochar retains more water within pores as compared to biochar-free sandy loam soil.

The high water retention at 25 Mg ha^{-1} of biochar can be explained by the high dose applied also the high specific surface area in biochar (Figure 4) that associated to the high the electric conductivity can contribute for increasing the water retention in biochar and consequently increase the soil water storage. Blanco-Canqui [12] found in the literature review that the biochar increases the ability of the soil to retain water in 90% of cases but the large amounts of biochar can be required to increase water retention consistently. Finally, in the control treatment, the high microporosity can be associated with high soil bulk density (Figure 3e), which can contribute for the increase in water retention in this treatment.

In sandy soil, with pour organic material, we not verified increase in the soil water retention, the no effect of biochar on the soil can be attributed to the biochar that was applied alone. Laird et al [14] and Christensen [50] verified that the biochar has no effect in sandy soil if applied alone and suggest the application with organic compost and the incorporation of biochar in the subsoil. Another reason is that the increase of soil water retention can occur in coarse texture soil or soils with a large number of macropores if large amounts of biochar are applied [51, 52]. Gaskin et al [53] reported improvements in soil-moisture storage after biochar was added at high rates (88 Mg ha⁻¹) in Ultisol with a coarse texture. In addition, the time of interaction, Salinas et al [54] verified that for increasing the water holding capacity of soils is required a longer period. However, Liu et al [6] reported a two-fold increase of plant-available water holding capacity upon 20 Mg biochar ha⁻¹ plus 30 Mg ha⁻¹ compost addition to a sandy soil when combined with 30 Mg ha⁻¹ compost addition alone.

In the loamy soil, the farmers can use the biochar in the dose 25 Mg ha⁻¹ for increase the soil water retention and in sandy soil the same dose is necessary, however, to obtain one good increase in the soil water retention is necessary more than one year of interaction soil-biochar. The increase in the retention of the water is essential for agriculture, ambient and plant productivity. With more water in the soil, the farmers can reduce the frequency of irrigation, reducing the use of water so necessary for the environment. In areas of familiar agriculture that do not use irrigation, the biochar can be used for provided water in a period drought. With a continuous supply of water to the plants, production tends to grow significantly.

2.4.3.2. Relation between water and pore size distribution

We found that the biochar application with different particle size changes the soil pore size distribution. This occurred due to intrapores (pores inside biochar particles), most of them having diameters <1 µm (micropores), and the different biochar particle size change the pore space between biochar particles and soil (interpores). The contribution with interpores and intrapores create heterogeneity in pore size distribution, as verified in our results in clay loam and sandy soil. In clay loam soil, intermediate doses (6.25 and 12.5 Mg ha⁻¹), increased the macroporosity and mesoporosity and decreased the microporosity, for the control and 25 Mg ha⁻¹ the total porosity was dominated by micropores. However, in sandy soil, the macroporosity was high in all treatments, the mesoporosity increased with increase of biochar amount but the microporosity decrease (Figure 6).

The low amount of biochar (6.25 and 12.5 Mg ha⁻¹) contributed to increase the macroporosity as verified by Gaskin et al [55]. In sandy soil, similar results were found by [56] who verified that biochar addition increased macropores between 5% and 20%. The increase of macropores (>50 µm) contribute to drainage and aeration of the soil and heat flow [12,48], and the drainage corresponds to decreasing

values of water retention and do not hold available water for the plants [56,57] but increases the soil aeration contributing for aerobic microorganisms and plant respiration and the heat flow contributes to warming the soil and the atmosphere near to the soil.

In clay loam soil the mesopores increase only in intermediate doses (6.25 and 12.5 Mg ha⁻¹ and decrease in 25 Mg ha⁻¹. In sandy soil, only in the high amount 25 Mg ha⁻¹ reduced the mesoporosity. The increase in the mesoporosity pores with a diameter between 15–50 µm is important because contribute to conduction of the water in the soil during the water distribution process that occurs after the infiltration, when the macropores are emptied [58].

We found mainly micropores in clay loam soil, at the control treatment and in 25 Mg ha⁻¹. The high microporosity, can be associated to high density in the control and high biochar amount in 25 Mg ha⁻¹. Due to high microporosity the water retention was high compared to smaller doses (6.25 and 12.5 Mg ha⁻¹). Studies have found that biochar can reduce the proportion of drainable pores and increase the quantity of mesopores and micropores (Petersen et al., 2016). The fact that biochar application contribute with pores inside particles (intrapores) less than 1 µm is favorable for the water retention in the soil when matric potential is lower than -165 hPa [58] can explain why only loamy soil with 25 Mg biochar ha⁻¹ retained high quantity of water after -165 hPa. However, biochar with a high quantity of pores between biochar particle and soil (intraporosity) is more effective in the water retention at lower soil water potential, these interporosity control water retention when soil water potential (ψ) is less than -1.65 hPa [58].

The micropores, besides the water retention, increase the plant-available and nutrient storage [59, 60]. Cation retention was observed when mixing soil with biochar [2] However, the underlying mechanism for this observation is still unclear. However, the nutrient retention mechanisms, such as pores, surface adsorption, cationic and anionic interaction, are determined by the physical and chemical structure of biochar [2, 59,60].

Water availability, storage, and nutrient are crucial for plant productivity. Biochar has the potential to alter soil hydrology and to drive shifts for water stored in soils and increase plant-available water under dry conditions [59,61]. Instead, it would provide more storage of water on the landscape under wet conditions [61]. However, the low quantity of biochar can be favorable for water flow, aeration, soil water retention and water available content for the plants [12, 43].

2.4.3.3. Plant-Available Water Content

Similar to this paper, Tryon [61] reported that application of biochar increased plant-available water content in sandy soil and no effect in a loamy soil. Similarly, Blanco- Caqui [12] found that biochar application consistently increased plant available water in 21 out of the 29 soils, suggesting

that plant-available water increased when biochar was applied in 72% of cases such a response may be attributed to the high microporosity of the biochar. Due to the soil moisture, retention may only be increased in coarse-textured soils, a careful choice of biochar/soil combination needs to be taken into consideration.

The increase in plant-available water with biochar suggests that the application of biochar to croplands could contribute to the reduction of the frequency of irrigation. This can be particularly important in water-limited or semiarid regions [2,6].

2.4.3.4. Implications for Farmers in Brazil

It is clear from the present study that high rate of biochar (25 Mg ha⁻¹) in clay loam soil can be beneficial for the chemical and physical properties (e.g., C and N concentrations, C/N ratio, plant available water, porosity, and bulk density) improving the soil water content, reduce plant water stress and increase the amount of C and N. However, the good results in the improvement in soil physical and chemical especially in sandy soil, can be associated with time of interaction because the biochar is a stable material [55]. The Brazilian farmers can use the dose 25 Mg ha⁻¹ for improvement of physical and chemical properties in sandy and clay loam soil.

2.5. Conclusions

The biochar addition contributes to soil C sequestration. In addition, there was an improvement in the physical properties such as bulk density, and porosity for both for loamy and sandy soil. However, the water retention was different between soils, for the sandy soil the addition of biochar did not increase the water retention, but for loamy soil, biochar increased the water retention when applied at 25 Mg ha⁻¹. The maximum dose of biochar altered the pore size distribution, increasing, especially, the mesoporosity and microporosity in clay loam soil and macroporosity in sandy soil.

These results show that biochar can improve soil management in the tropical areas, for example in response to shortages of water. It ought to be possible to recommend to farmers or other land use stakeholders that the biochar with another organic material easily decomposable should be added to a given type of soil with the aim of achieving the desired outcome, e.g., in terms of increase of water retention, the high biochar dose superior to 25 Mg ha⁻¹ could be used in clay loam and sandy soil. However, studies are necessary to indicate which is the better dose superior to 25 Mg ha⁻¹ for these soils and what is the best organic material that is easily decomposable to include with the biochar.

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BIOCHAR AND SUGAR CANE FILTER CAKE INTERACTION ON PHYSICAL AND HYDROLOGICAL SOIL PROPERTIES UNDER FIELD CONDITIONS OF TROPICAL CLIMATE

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Highlights

Biochar plus sugar cane filter cake changes the pore size distribution, increasing micropores with increasing biochar amount and time of interaction, contributing to increasing water available content. With increasing time of interaction, biochar plus sugar cane filter cake improved soil bulk density, porosity, and aggregate stability.

Sugar cane filter cake had no effect on soil hydraulic conductivity while biochar significantly reduced soil hydraulic conductivity when combined with sugar cane filter cake after 18 months in the field condition.

Abstract

Biochar is a solid product produced from biomass pyrolysis under low oxygen conditions. Recently, it has gained wide acknowledgment about its effects on carbon sequestration and soil fertility. However, there is a lack of information about its effects on soil physical and hydraulic properties, particularly under field conditions of tropical soils. We assessed the effects of sugar cane filter cake (FC) and its interaction with increasing amounts of *Miscanthus* biochar (BC) and time of interaction on soil physical and hydraulic properties under humid tropical field conditions. For this purpose, a field experiment was installed at a loamy sandy soil with five treatments: control (only soil), sugar cane filter cake, and sugar cane filter cake plus 6.25, 12.5, and 25 Mg ha⁻¹ *Miscanthus* biochar, respectively, in two soil depths (0-10 and 10-20 cm) and two times of interaction (9 and 18 months), physical (aggregate stability, bulk density, total porosity, pores size distribution) and hydraulic (soil water holding capacity, hydraulic conductivity, water available content) properties were performed after nine and eighteen months of field interaction. The bulk density slightly decreased, and the porosity increased after nine months of interaction but only at the highest biochar application amount in combination with sugar cane filter cake (both 25 Mg ha⁻¹). After 18 months, biochar plus filter cake (B+FC) interaction altered the pore size distribution with an increase of micropores, aggregate stability and plant-available water content, this alteration was dependent on the biochar amount. Saturated hydraulic conductivity was not influenced by sugar cane filter cake. However, biochar significantly reduced saturated hydraulic conductivity when combined with sugar cane filter cake and left in the field for 18 months. We conclude that biochar B+FC modified the pore size distribution, slightly increased plant available water holding capacity and significantly decreased saturated hydraulic conductivity.

Keywords: Water retention; Hydraulic conductivity; *Biochar Miscanthus*; Soil physics

3.1 Introduction

Sandy soils are characterized by a lack of structure, poor water retention, high permeability and low plant-available water holding capacity (AWHC), because of these properties, the sandy soils are considered marginal for agriculture (Sun et al., 1998). Therefore, a considerable amount of

irrigation water is required to meet crop water requirements. However, it is possible to reduce the amount of irrigation and to save water, by increasing the AWHC of sandy soils (Misra, 2014) by addition of organic materials. Previous investigations indicated that the addition of biochar to sandy soils improved their physical and hydraulic properties (Basso et al., 2013; Głab et al., 2016).

The classic example of soil with desirable physical-chemical and hydraulic properties is the *Terra preta* (Glaser et al., 2001). For example, the water retention of *Terra Preta* is 18% higher compared to adjacent soils with similar particle size distribution (Glaser et al., 2002), and its fertility is extremely high. The key to the *Terra preta*'s quality is the biochar and time of interaction. The *Terra preta* contains on average 50 Mg ha⁻¹ of biochar that have interacted for 2000 years in the upper 50 cm soil depth although the adjacent reference soils contain only 70 times less biochar than in *Terra Preta* (Glaser et al. 2001).

Inspired by the *Terra preta* phenomenon, many researchers have studied biochar application in poor agricultural soils such as sandy soil (Blanco-Canqui, 2017; Downie et al., 2009; Duarte et al., 2019a; Duarte et al., 2019b; Glaser et al. 2015). Liu et al. (2012) and Glaser et al. (2015) found that the addition of 20 and 40 Mg biochar ha⁻¹, respectively, in sandy soil in Northern Germany increased its water-holding capacity by 100%.

Due to its high porosity, biochar can ameliorate soil physical and hydrological properties (Atkinson et al. 2010; Hina et al. 2010; Liang et al. 2006). When the biochar is applied in soil, it promotes a modification in the soil pore size distribution (Downie et al., 2009) by contributing with its pores (interporosity) thus and by the creation of new pores between soil and biochar particles (intraporosity), increasing mesoporosity and microporosity in the soil (Liu et al., 2017). In addition to the porosity, the reduced of the biochar particle size increases the specific surface area (Ogawa et al., 2006; Kishimoto and Sugiura 1985; Van Zwieten et al. 2009) and contributes to increasing the water retention and AWHC (Duarte et al., 2019 b; Glab et al., 2016). However, these benefits are dependent on biochar rate of application and the time of interaction as well as the biochar particle size (Alghamdi, 2018; Blanco-Canqui, 2017; Duarte et al., 2019 a; Glab et al., 2016).

According to the literature reviewed, when the biochar rate increases, larger changes in the soil properties occur. For example, in general, bulk density decreases and the porosity, aggregate stability and water retention increase (Alghamdi, 2018; Blanco-Canqui, 2017). The decrease or increase in the biochar rate normally follows a linear function, but in a few cases, the relationship can be quadratic, suggesting that the effect of biochar at higher rates could be smaller or have no effect (Rogovska et al., 2016; Blanco-Canqui, 2017), but this behavior can be variable depending on the time of interaction between biochar and soil particles, (Alghamdi, 2018; Blanco-Canqui, 2017; Joseph et al., 2010), contributing to biochar's decomposition, that is one important factor to improve physical and

hydraulic properties (Glaser et al. 2001). Another additive to the soil that can contribute to improvement of the soil chemical and hydraulic properties is filter cake (Moberly and Meyer, 1978).

Filter cake is a residue obtained by the rotary filter after the extraction of sucrose and it replaces a mineral fertilizer because it presents high concentration of phosphorus, among other nutrients, that is essential for a better crop yield. Research on alternatives to the use of waste from the sugar-energy sector is of fundamental importance for modern agriculture. These can be reused for better production, greater economy and environmental quality, aiming at sustainable agriculture. In addition, due to its characteristics like high moisture, filter cake can promote improvement not only of soil fertility but also on soil hydraulic properties.

According to Lugo Lopes et al., (1954), filter cake can absorb a large amount of water. Normally, filter cake contains 60 to 80 percent water, and this high water holding capacity can increase the moisture, water retention and soil plant available water. Lugo Lopes et al., (1954) verified increase in water retention and organic matter after they applied 8, 24 and 32 Mg ha⁻¹ of filter cake in the soil, and Moberly and Meyer (1978) reported increase in water retention with filter cake application. Molina (1995) suggested that the application of FC contribute to increase the aggregate stability. In addition, due to high fertility in the filter cake some companies from energy sector are using filter cake to improve the soil fertility.

The recommended rate of FC are 20 to 40 Mg ha⁻¹ to apply in groove (Nunes JR. et al., 1988; Cardozo et al., 1988 and Donzelli and Penatti 1977. Due to high concentration of the nutrients and the FC can replace at specific conditions the application of fertilizers when used in rates superior to 20 Mg ha⁻¹ (Nardin, 2017). Filter cake has been applied by the sugar cane industry in a recommended rate of 25 Mg ha⁻¹.

Because of these functions, the interaction of biochar and filter cake can potentially be used as soil amendments for improving the soil physical and hydraulic properties. However, as far we understand this is the first study about B+FC interaction and its influence on soil physical and hydric properties (Glaser et al. 2002a, 2002b; Lehmann et al., 2003; Moberly and Meyer (1978).

The effect of biochar on temperate soils has been discussed in the literature and most of these studies have been conducted under laboratory or greenhouse conditions (Blanco-Canqui, 2017; Barnes et al., 2014; Chen et al., 2018; Novak et al., 2012). However, there is a lack of information about the impacts of biochar on soil physical and hydraulic properties under tropical conditions and especially on field conditions (Blanco-Canqui, 2017). The present study, as far as we understand, is the first research that presents data on the B+FC rates on the physical and hydraulic properties in tropical soil.

We hypothesize that B+FC rate 25 Mg ha⁻¹ can improve the soil physical and hydrological properties than lower rates (6.25 and 12.5 Mg ha⁻¹), and its improvement is greater after 18 months of interaction. Therefore, the objective of this study is to evaluate the effect of B+FC amounts and time of interaction on soil physical and hydrological properties under field conditions of tropical climate.

3.2 Material and Methods

3.2.1 Biochar and filter cake production and characterization

Biochar was commercially produced out of biomass from agricultural residues of *Miscanthus giganteus*. This biochar was used because it is a co-product of the production of cellulosic ethanol and has been widely applied because of its increasing availability as a product of the growing biofuels industry. The production of biochar involved drying of the *Miscanthus* grass at 105 °C in a greenhouse, followed by pyrolyzation in reactor type stationary, with capacity of 60 liters at 450 °C for about 15 min, the reactor was hermetically sealed, this pyrolysis process was performed by SPPT Research and Technology Company Mogi Mirim, SP, Brazil (Conz et al., 2017).

The elemental analyses, as well as pH and electric conductivity, were performed by Conz et al. (2017), following the methods recommended by the International Biochar Initiative Guideline (IBI, 2015), the labile carbon and stable carbon and lability per Chan et al., (2001), moisture ASTM, (2007 a), and specific surface area Cerato & Lutenegeger, (2002) (Table 1).

Table 1. Physical and chemical properties of *Miscanthus* biochar used in this study.

Properties of biochar	Unit	Value	Reference
pH in H ₂ O	-	5.9	IBI (2015)
Electric conductivity	μS cm ⁻¹	605	IBI, 2015
Moisture	%	3.5	ASTM, 2007a
Cation Exchange Capacity	mmol·dm ⁻³	33	IBI, 2015
Specific surface area	m ² g ⁻¹	371	Cerato & Lutenegeger, 2002
Labile C	%	2.7	Chan et al., 2001
Stable C	%	50.9	Chan et al., 2001

Adapted: Conz et al., (2017)

Filter cake was obtained from a commercial sugarcane mill in Sao Paulo State. The company uses sugarcane to produce energy and sugar. One of the sub products is the filter cake, normally applied in the field to increase soil fertility. The recommended application rate is 25 Mg ha⁻¹ of filter cake during the sugar cane planting activity. Commercial sugar cane sector indicated that biochar would be applied together with filter cake during the plantation. Therefore, we used filter cake plus biochar to evaluate the potential increase in water retention and soil fertility.

3.2.2 Soil and climate characterization

The experiment was installed in Ipeúna, Sao Paulo state, Brazil, the climate is Cwa (Köppen-Geiger) Cwa-subtropical climate / tropical climate, with concentrated rainfall in summer (October to march) and dry period on the (April to September). The mean precipitation is 1336 mm per year; the average of annual temperature is 20, 2 °C with minimum at 16, 3 °C and maximum at 23 °C (Figure 1).

Figure 1. Monthly minimum, average, and maximum temperature and average monthly precipitation at Ipeúna, SP, Brazil.

The soil is classified as Typic Hapludox, with texture Loamy sand (sand 78%, silt: 7% and clay: 15%). The soil chemical characterization was performed at the layer 0-20 cm before than treatments application. We determined: pH, Al^{3+} , $\text{H}+\text{Al}^{3+}$, Ca^{2+} , Mg^{2+} , K^+ e P; S, C e N (EMBRAPA, 1997) by the dry combustion and fractionation of soil organic matter by the method Feller, (1979) (Table 2).

Table 2. Chemical properties of the Typic Hapludox under study

Properties of soil	Value
-----(mg kg^{-1}) -----	
Al	1
H+Al	26
SB	28.30
Al saturation	367
Base saturation	555
pH (CaCl_2)	5.05

H+Al= potential acidity, SB= soma of bases (Ca, Mg, K),

Physical and chemical characterization for biochar and soil are found in table 1, 2 and 3. The high content of sand is responsible for the low soil fertility (Table 1). According to Brazilian Agricultural Research Corporation-Embrapa, a pH 5 indicates that this soil is moderately acidic (Embrapa, 2015), also this pH indicates the presence of exchangeable Aluminum that can inhibit the

root development, affect the availability of other nutrients and mineralization of organic matter. The contents Ca, Mg, K, and Na were high, these high values of exchangeable bases indicate that this soil is little weathered. This high values contributed to the high value some of the base (SB) and aluminum saturation (V), resulting in eutrophic characteristic ($V > 50\%$). According to Embrapa, (2015) classification, the quantity of phosphorus (P) is medium. The value of CEC in 5 ($\text{cmol}\cdot\text{dm}^{-3}$) indicate the presence of low clay content or presence of minerals 1:1 such caulinite (Embrapa, 2015).

As expected, comparing the chemical properties between soil and biochar, the fertility of biochar is much higher compared to the soil. For example, total N, P and K contents of biochar are 7, 14, 137.7 and 2.7 times the quantity of the Nitrogen, Phosphorus and Potassium in the soil (Table 3).

Table 3. Physical and chemical characteristics of biochar *Miscanthus* and Loamy sandy soil

Properties	Unit	Biochar*	Filter cake	Soil
P	mg kg^{-1}	1859	8.5	13.5
K	mg kg^{-1}	8615	1.2	3.2
S	mg kg^{-1}	634	-	5.3
Ca	mg kg^{-1}	3361	-	14
Mg	mg kg^{-1}	2133	-	7.5
Total N	%	4.3	6.9	0.6
Total C	%	664	-	8.6
CEC	$\text{mmol}\cdot\text{dm}^{-3}$	33	-	52

*Adapted from Conz et al., (2017). CEC= Cation exchange capacity (SB+Al+H)

The *Miscanthus* biochar was characterized by Duarte et al. (2019) using FTIR and found hydrophobic groups as Cyclic acid anhydrides (C-C and C-O) carboxylates asymmetric (CO_2), ketones aromatic (C=O), Silicon (Si-O) and hydrophilic Carbonates (C-O) and Silanol (Si-O-H). Analyzing the biochar hydrophobicity, Duarte et al. (2019) found high hydrophobicity. The high hydrophobicity and the Silanol of the biochar can influence the water retention in the soil.

Filter cake was characterized concerning to Nitrogen, phosphorus and potassium concentration. The N was analyzed using Elemental analysis (Vario Micro CHNS, Elementar, Hanau, Germany) and the P, and K was performed by the Spectrometry technique of Atomic Absorption (Table 3).

3.2.3 Experimental setup and sampling

The experimental area has been cultivated in the last 50 years with sugar cane, and in the period of the installation of the experiment, the area was cultivated with sugar cane ratoon, after replanting of the previously reformed area.

The experiment constituted of 20 parcels with 4.5 m^2 (5 m of length and 0.9 width) plus borders (2 m length and 1.5 m width). Each parcel encompassed by two rows with five plants each, totaling 10 plants by parcel. The factorial experimental design was completely randomized blocks and

comprised five treatments in four fold field replication, comprising a control (only soil, no amendment) and a constant amount of sugar cane filter cake (25 Mg ha⁻¹) for the remaining treatments to which four different amounts of biochar were added (0, 6.25, 12.5, 25 Mg ha⁻¹). These biochar rates was based on experiment of Woolf et al., 2010 who established the maximum rate of 50 Mg ha⁻¹, these rates are 50% of the maximum recommended. Soil samples were taken in two depths increments (0-10 and 10-20 cm) and two sampling dates (after 9 and 18 months), resulting in a total of 80 samples. The installation of the experiment occurred with manual incorporation of the sugar cane filter cake and biochar until 20 cm of depth using a grubber.

The samples were collected in two soil depths 0-10 cm and 10-20 cm, and analyzed for aggregate stability, bulk density, particle density, and total porosity, pore size distribution, hydraulic conductivity, water retention curve, and water available content.

3.2.4 Physical analysis

3.2.4.1 Bulk and particle density

The bulk density (BD) was performed using the volumetric ring with approximately 5 cm of high and 5 cm of diameter. The BD was determined by the method of Black and Hartge (1986) by the ratio between dry mass and soil volume.

For the determination of particle density (PD) we used approximately one gram of each soil. The soil was put inside of the instrument and the particle density was determined using Helio gas pycnometer, model ACCUPYC 1330 (Micrometrics Instrument Corporation). The pycnometer determines the volume of solids, by the variation of the pressure of Helium, in a known volume chamber.

3.2.4.2 Porosity

The total porosity (*TP*) was calculated from the soil bulk density (*BD*) and the particle density (*PD*) (Flint and Flint, 2002) using the following equation (1):

$$TP (\%) = 1 - \frac{BD}{PD} \times 100 \quad (1)$$

The macroporosity, mesoporosity, and microporosity were performed by soil water retention curve using values for macroporosity superior to 50 μm , mesoporosity between 15 and 50 μm and microporosity inferior to 15 μm (Koorevar, Manelik and Dirsén, 1983).

3.2.4.3 Aggregate stability

We collected soil monoliths of 10 x 10 x 10 cm, in the depths 0-10 and 10-20 cm, these samples were wrapped by plastic film and taken to the laboratory carefully. In the laboratory, the monolith and aggregates larger than 9.52 mm were broken manually following the weak points until it passes through the sieve of 9.52 mm. For analysis of aggregate stability, we dried the samples at ambient temperature for three days. After this, the soil was sieved and was obtained the fraction between the sieved 8 mm and 4 mm. From this fraction was withdrawn one sample of 75 g that was homogenized and separated equally into three portions of 25 g. One sample of 25 g was putted for drying at 105 °C by 24 hours, and the other two portions of 25 g each one was used for aggregate stability analysis.

The samples were put on a ring (previously with fabric and rubber on the bottom of the ring) and were moistened per capillarity during eight hours. The fractionation was performed using a set of sieves: 2; 0.25 and 0.053 mm. The set of sieves was immersed in water excluding all air of the sieves (Yoder, 1936). The moistened soil aliquot was placed into the first sieve. The equipment was adjusted to 30 rpm and the sieving occurred for 10 minutes. After this, the soil retained in each sieve was transferred into aluminum containers and dried at 105 °C during 24 hours.

For quantify the aggregate stability only for the soil, the organic material (roots, filter cake, biochar) was retained in the sieve was quantified by the dispersion method (Six et al., 2000). For this purpose, we put 15 ml of hexametaphosphate for each five grams of soil. This mixture was agitated at 180 rpm by eight hours. After this, each suspension was putted in the same sieve mesh, the residue retained in each sieve was putted for dry in greenhouse at 105 °C during eight hours (Six et al., 2000).

The aggregate stability and its weighted average diameter were calculated according to (Van Bavel, 1949) by equation (2) where the larger the aggregate diameter, the greater the aggregate stability.

$$WAD = \sum_{i=1}^n (x_i \cdot w_i) \quad (2)$$

Where: WAD= weighted average diameter w_i = mass of each class in grams; x_i = average diameter of the classes expressed in mm.

3.2.4.4 Hydraulic conductivity

The saturated soil hydraulic conductivity (K_s) (cm h^{-1}) was determined in the field by a Simplified Falling Head method (SFH) (Bagarello et al., 2004). The measurements were conducted between the rows of sugar cane, using a steel cylinder with dimensions of 21.2 cm (diameter) x 9.4 cm (height); the area of the base (A) was 353 cm^2 . The measurement site was prepared by removing any organic material (straw, sugar cane filter cake, biochar particles) from the soil surface, the steel

cylinder was then inserted into the surface of the exposed soil to a depth of 5 cm. A fixed volume of water ($V = 0.5$ L) was then evenly applied to the soil across the entire area encircled by the steel ring. The infiltration time of the water into the soil (ta) was measured as the time from the start of the application of the water to the soil to the moment at which water was no longer visible on the soil surface. A sample soil dry was collected from an area adjacent to the steel ring and a sample of saturated soil was collected from inside the ring after the complete infiltration of the water into the soil. The difference in the volumetric water content ($\Delta\theta$) between the saturated soil (sample collected from inside the ring after infiltration) and non-saturated soil (dry soil sample collected from outside the ring) was obtained from measurements of volumetric moisture. Following the acquisition of the raw data, K_{fs} was calculated according to the following equation (3) provided by (Bagarello et al., 2004):

$$K_{fs} = \left[\frac{\Delta\theta}{(1 - \Delta\theta) ta} \right] \times \left[\frac{D}{\Delta\theta} - \left\{ \frac{D + (1/\alpha^*)}{(1 - \Delta\theta)} \right\} \times \ln \left\{ 1 + \frac{(1 - \Delta\theta) D}{\Delta\theta (D + (1/\alpha^*))} \right\} \right] \quad (3)$$

In equation (3), $D = V / A$ is the ratio of the volume of water applied to the area of the steel ring inserted into the soil. This ratio determines the depth of the water in the ring above the soil at the start of the measurement of the infiltration time ta in seconds. α^* is a constant which depends on the texture and structure of the soil; α^* varies between 4 and 36 m^{-1} (Elrick and Reynolds, 1993). Within the experimental area, the texture of the soil was Loamy sand, a value of 12 m^{-1} was accordingly adopted for the constant α^* .

3.2.4.5 Soil water holding capacity

Soil water holding capacity was measured by moisture contents of the samples (rings of 5x5 cm) at different matric potentials (-15.000, -10.000, -3000, -1000, -300, -100, -60, -40, and -20 hPa). The points (-15.000, -10.000, -3000 and -1000 hPa) were measured in Richard chamber, and -60, -40, and -20 hPa in Haines' apparatus. The moisture content was performed by the multiplication of gravimetric moisture by bulk density (Klute et al., 1986). For the determination of curve parameters (θ_s , θ_r , α , n) we used Van Genuchten (1980) model. The Van Genuchten equation was used to describe the soil water retention curve.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + |ah|^n]^m}$$

Where, θ is the soil water content ($\text{cm}^3 \text{cm}^{-3}$), θ_r is the soil residual water content ($\text{cm}^3 \cdot \text{cm}^{-3}$), θ_s is the soil saturated water content ($\text{cm}^3 \text{cm}^{-3}$), h is soil water potential (hPa), α is a scale parameter inversely proportional to mean pore diameter (cm^{-1}), n and m are the shape parameters of soil water characteristic, $m = 1 - 1/n$, $0 < m < 1$.

3.2.4.6 Pore size distribution and plant-available water holding capacity

The pore size distribution was determined by the water retention curve. We selected the potentials up to 29 hPa to macropores ($>50 \mu\text{m}$) and the potential below 96 hPa to micropores ($<15 \mu\text{m}$), the range between macropores and micropores we obtained mesopores.

The plant-available water holding capacity was determined from the water retention curve by the difference between field capacity (pF 1.8) and the permanent wilting point (pF 4.2).

3.2.5 Data analyses

Statistical analyses were performed using language R (Version1.2) and the packages: soil physics, agricolae and plotrix. The residuals were checked for normality and homogeneity of variances to meet the assumptions of ANOVA and test of Tukey, 0.05 of probability.

3.3 Results

3.3.1 Effect on soil physical properties

3.3.1.1 Bulk density

There is no significant effect ($p > 0.05$) B+FC on soil bulk density (Fig. 2A). We did not find effect of the time and soil depth on soil bulk density, in all treatments the bulk density was similar (Fig. 2 A). The same behavior was found for the layer 10-20 cm, in this depth, the bulk density was higher than at the surface layer (0-10 cm).

3.3.1.2 Total porosity

We did not find a significant effect ($p > 0.05$) B+FC, time of interaction and sampling depth on total porosity (Fig. 2 B and E). However, sugar cane filter cake slightly increased the soil total porosity at least in the short term; after 18 months, this effect was leveled out (Fig. 2B). Biochar applications between 6 and 25 Mg ha^{-1} had no measurable additional effect on soil total porosity (Fig. 2B, E).

3.3.1.3 Aggregate stability

There is no significant effect of B+FC on soil aggregate stability represented by weighted average diameter (WAD) ($p>0.05$; Fig. 2C and F). However, FC tendentially decreased the soil aggregate stability after nine months at the 0-10 cm soil depth and increased it slightly at 10-20 cm soil depth (Fig. 2C and F). These effects were levelled out after 18 months (Fig. 2C and F). Biochar had not effect on aggregate stability after 9 months in the field but slightly increased soil aggregate stability after 18 months (Fig. 2C and F). This latter effect increased with increasing biochar amount in both soil depths (Fig. 2C and F).

Figure 2. Effect of Filter cake plus biochar rate, filter cake and time of interaction on soil physical properties in Loamy sandy soil. BD= Bulk density; TP= Total porosity; WAD= weighted average diameter; 0= control (only soil); FC= Sugar cane filter cake; FC+6.25= Sugar cane filter cake plus 6.25 Mg ha⁻¹ of biochar; FC+12.5 = Sugar cane filter cake plus 12.5 Mg ha⁻¹ of biochar; FC+25= Sugar cane filter cake plus 25 Mg ha⁻¹ of biochar. A,B,C (0-10 cm); D,E,F (10-20 cm) of depth.

3.3.2 Effect on soil hydraulic properties

3.3.2.1 Hydraulic conductivity

According to Tukey test we did not find significant ($p>0.05$) difference between the treatments at 9 and 18 months of interaction (Fig. 3). However, while sugar cane filter cake slightly increased saturated soil hydraulic conductivity, biochar slightly decreased it after nine months in the field (Fig. 3). After 18 months, saturated soil hydraulic conductivity was higher compared to nine months measurements (Fig. 3).

Figure 3. Effect of sugar cane filter cake (FC) and its interaction with biochar and time of interaction on saturated hydraulic conductivity (K_{fs}) in Loamy sandy soil.

At this time, while there was no significant effect of FC, B+FC reduced saturated soil hydraulic conductivity, independent of the amount of biochar applied (Fig. 3).

3.3.2.2 Soil water holding capacity

Soil water retention characteristic curves were similar for all treatments but for the highest biochar amount was better (Fig. 4). In the first layer, the BC 25 Mg ha⁻¹ plus FC slightly increased the soil water retention after nine months. While after 18 months, the water retention was much higher compared to the nine months measurements Figure 4). This increase occurred at higher potential (>1000 hPa) in the range of micropores (<0.15 μm), pores responsible by water retention and water availability. In low potential (0-1000 hPa), the range of macropores and mesopore there is no difference between treatments (Figure 4).

Figure 4. Effect of FC+biochar rate, Filter cake (FC) and time of interaction on water retention curve in Loamy sand soil.

In the second layer (10-20 cm), after nine and 18 months of interaction in the range of macropore, mesopore and micropore we did not find a difference between treatments (Figure 4).

3.3.2.3 Pore size distribution

The behavior of the pore size distribution is related to the water retention curve. After nine months of interaction, FC+BC 25 Mg ha^{-1} contributed to increase the microporosity and consequently decrease mesoporosity and macroporosity in the first layer (0-10 cm) (Figure 5 A). However, the pore

size distribution was similar in other treatments, the microporosity increase a little bit in the control treatment, but this increase was not reflected in the water retention curve (Figure 4 A).

Figure 5. Effect of sugar cane filter cake and sugar cane filter cake plus biochar rate, time of interaction and depth on pore size distribution and water retention curve in the loamy sand Typic Hapludox under study. MA= Macropore, ME= Mesopore, MI= Micropore.

Figure 6. Effect of sugar cane filter cake and increasing amount of biochar interacting with sugar cane filter cake, time of interaction and depth on available water holding capacity (AWHC) of the Loamy sand Typic Hapludox. A: 0-10 cm of depth; B: 10-20 cm of depth. 0= control (only soil); FC= Sugar cane filter cake; FC+6.25= Sugar cane filter cake plus 6.25 Mg ha⁻¹ of biochar; FC+12.5 = Sugar cane filter cake plus 12.5 Mg ha⁻¹ of biochar; FC+25= Sugar cane filter cake plus 25 Mg ha⁻¹ of biochar.

In the second layer (10-20 cm) after nine months of interaction, there is a similarity between the treatments and this similarity was reflected in the water retention curve (Figure 4 C). After 18 months of interaction in the first layer (0-10 cm), increased the microporosity in all treatments (Figure 4 B), consequently, the water retention also increased in all treatments (Figure 4 B). The treatment FC+BC 25 Mg ha⁻¹ was highlighted among other treatments, their microporosity increased by 40% and this contributed to increase the water retention. Filter cake also increasing the microporosity compare to the control treatment.

In the second layer (10-20 cm) after 18 months of interaction, increase in the microporosity in all treatments was evident. Independent of the treatment, the microporosity was similar.

Comparing the surface with subsurface layer after 9 months, the mesoporosity and macroporosity decreased and there was no alteration in the microporosity (Figure 5 A and C). However, after 18 months of interaction in the second layer, the macropore and mesopore reduced and there is a predominance of micropores (Figure 5 B and D).

3.3.2.4 Plant-available water holding capacity

Independent of the time of interaction and depth there is no significant difference between the treatments ($p>0.05$). However, some behaviors can be observed. For example, after nine months of interaction, in the first layer (0-10 cm), FC alone reduced the plant-available water holding capacity (Fig. 5). However, with increase of BC rate the AWHC slightly increased after nine months and after 18 months diminished (Fig. 5 A, B).

3.4 Discussion

3.4.1 Effect on soil physical properties

3.4.1.1 Bulk density

In our study, there is no significant effect of B+FC and time of interaction on bulk density, compared with the control treatment. However, soil bulk density slightly decreased after nine months but only at the BC+ FC (both 25 Mg ha⁻¹). Similarly, Moragues-Saitua et al. (2017) studying 0, 10 and 20 Mg ha⁻¹ of *Miscanthus* biochar pyrolyzed at 450 °C (the same biochar of this study) the rate 0; 3.5; 10 Mg ha⁻¹ in Loamy soil and in Loamy sandy soil (the same soil that we are studying) did not find significant difference in the reduction of bulk density after 15 and 30 months of interaction, respectively. However, some studies have shown a decrease in the bulk density (~13%) with biochar addition (Alghamdi, 2018). Hardie et al., (2014) verified reduction in soil bulk density with addition of 47 Mg ha⁻¹ of biochar. Biamonte et al. (2018) didn't find significant difference in the reduction of soil bulk density and Duarte et al. (2019) verified a tendency of reduction in soil bulk density with an increase of biochar application amount (from 0.035 to 0.062 Mg m⁻³), although the difference was not significant.

The reduction of the bulk density with addition of B+FC is associated with the interaction between one material with high bulk density, sand soil (1.6 g cm⁻³), with two materials of low bulk density, biochar (~0.6 g cm⁻³) and FC (0.64 g cm⁻³), the big difference between bulk densities could allow decrease in the final soil bulk density (Alghamdi, 2018; Blanco-Canqui, 2017; Duarte et al., 2019; Laird et al., 2010). In addition, B+FC are highly porous (about 95% in pores) (Hina et al. 2010; Liang et al. 2006a, b), while sand soil has a low porosity (43%); their interaction could lead to an increase in porosity of sandy soil as well as a decrease in bulk density. Due to bulk density is an indicator of compaction and soil health, the addition of sugar cane filter cake plus biochar can contribute to reduce the root penetration resistance, water infiltration, increase aeration and plant available water these parameters are key for the soil processes and productivity (Alghamdi, 2018).

3.4.1.2 Total porosity

No significant effect ($p > 0.05$) on total porosity with the rate of biochar application, similar to the findings in this research, was verified by Duarte et al. (2019a,b); Hardie et al., (2014) and Moragues-Saitua et al. (2017). Aversely, some researches had shown increase in the soil total porosity with biochar application. For example, Jien and Wang (2013) found an increase of 24% soil porosity with the application of 47 Mg ha⁻¹ biochar after 105 days of interaction. Alghamdi (2018) affirmed that the increase in soil porosity ranged from 13 to 52%, for example, Głab et al. (2016) reported high

increment (35%) following application of 4% biochar to a loamy sand soil. Regarding the effect of the addition of FC, comparing the control treatment to FC treatment, we verify increase of 5% at the layer 0-10 cm on total porosity. The high total porosity in filter cake can contribute to increase the soil total porosity (Ripperger et al., 2012). However, comparing FC with biochar rate plus FC there are no alterations in the total porosity.

Increase on the soil porosity with FC+BC addition can be attributed to high porosity of both materials, biochar porosity (70 to 90%) and FC. Probably due to B+FC can settle between the soil particle matrix creating new pores to increase the macroporosity (Steiner et al. 2011). According to Hardie et al. (2014), there are three mechanisms that contribute to increasing of porosity in the soil with biochar addition: (1) pore contribution from the high-porosity biochar material, (2) modification of the pore system by creating packing or pores, and (3) aggregate stability improvement. In this study, the last effect has been probed.

Increase in the soil porosity can be associated with decrease of soil bulk density (Alghamdi, 2018; Blanco-Canqui, 2017; Duarte et al., 2019; Laird et al., 2010) and aggregate stability improvement (Hardie et al., 2014) factor key for creation of a suitable environment for root growth (Andrenelli et al., 2016) and microbial activities that result in high productivity of the soil.

3.4.1.3 Aggregate stability

We did not find a significant effect ($P>0.05$) on aggregate stability upon sugar cane filter cake and biochar addition. Hardie et al. (2014), who applied 47 Mg biochar ha⁻¹ and Wang et al. (2017), who added 0.5 and 1% biochar to a loamy sandy soil, reported similar results. The lack of significant changes in wet aggregate stability observed in some studies suggests that biochar's effects depend on several factors as site-specific characteristics as interactions among texture, soil slope, organic C, biochar properties, climate, and others could dictate the extent to which biochar application can change soil aggregate stability (Blanco Canqui, 2017). Another reason is sandy soils generally not aggregate very well. Liu et al. (2012) reported that biochar did not increase dry aggregate stability in soils with a sand content greater than 17.3%. The sand content of the soil in our study had even 42% sand. Therefore, due to low interaction between soil and biochar the aggregation of the soil under study is generally very unlikely (Figure 7), but this aggregation can be increased with time of interaction.

In this context, the reason that explain the lack of effect on aggregation is site-specific characteristics and time of interaction. The reduction in the aggregate stability, especially after nine months of interaction at the layer 0-10 cm, can be associated with desegregation provoked by incorporation of the biochar with soil, also the biochar particle size that the majority are > 2mm can

contribute to desegregation due to this particle size is superior to sand's grain this factors associated with slow biochar decomposition (Sohi et al., 2010).

After 18 months of interaction, we verified increase on the aggregate stability (Figure 7) with increase of the BC rate application in both layers (Blanco-Canqui, 2017) biochar application increased wet aggregate stability in 14 soils of the 24 soils analyzed. For example, Wang et al. (2017) verified in Entisol increase in the aggregate stability with rates of 0.5; 1% after 15 months of interaction.

Blanco-Canqui (2017), attributed the increase of the aggregate stability to biochar particles that oxidize and react with soil particles. This reaction can increase with time of interaction, contributing to increasing the aggregate stability as we verify in our research after 18 months of interaction (Figure 2 C and F). In addition, the inorganic particles can bind and form soil aggregates through physical, chemical, and biological forces with the organic core (biochar particles) forming aggregates (Hua et al., 2013).

Figure 7. Difference between soil, and soil treated with 25 Mg ha⁻¹ of biochar plus filter cake after 18 months of interaction under field condition.

Improvement on soil aggregation can result in increased on soil water holding capacity, reduction of water erosion and increase of the plant-available water holding capacity necessary to increase the soil quality and plant productivity. In our study, the FC+BC 25 Mg ha⁻¹ contributed to increase the diameter of the aggregate in 0.146 mm, this increase contributed to improve the water retention on the field capacity in 0.7 m³m³ and the water available content in 5 mm. This result is important for region with changing dry periods followed by heavy rainfall, especially in these regions,

the biochar plus filter cake can contribute to retain water and increase the plant-available water holding capacity.

3.4.2 Effect on soil hydraulic properties

3.4.2.1 Hydraulic conductivity

Comparing only the time of interaction, was verified increase on the hydraulic conductivity, this increase can be associated to the precipitation that is higher on January (after 9 months of interaction) than on November (after 18 months), the low precipitation on November contributed to increase the hydraulic conductivity. There is no significant effect ($p>0.05$) in the first time of interaction, the effect of the biochar plus filter cake was more evident in the reduction of the hydraulic conductivity after 18 months of interaction.

Reduction on the hydraulic conductivity was verified in 12 coarse textured soils (coarse sand, sand, fine sand, and sandy loam soils) of 15 studied soils (Blanco Canqui et al., 2017). The decrease in saturated hydraulic conductivity ranged from seven to 2270% (Blanco Canqui et al., 2017). Similarly, Barnes et al., (2014) found biochar amendment decrease hydraulic conductivity on average 92% in sandy soil. Uzoma et al. (2011) found that the wood biochar application reduced unsaturated hydraulic conductivity with increasing soil water content and suggested the addition of biochar at 20 Mg ha⁻¹ can be more effective in this reduction than at a rate of 10 Mg ha⁻¹ and Githinji (2014) found a gradual decrease in water infiltration with an increase in the biochar application rate after ~2 months of interaction under greenhouse conditions.

The reduction in the hydraulic conductivity as verified in our study probably is not related to biochar hydrophobicity, because of during 18 months of temporal biochar expose the environment, hydrophobic moieties such as polycondensed aromatic moieties decrease while hydrophilic functional groups such as carboxylic acids increase (Glaser et al. 2000; Glaser et al. 2002), as verified by Ojeda et al., (2018), that verified reduction of the biochar hydrophobicity within one year.

After 18 months, the particle size of the biochar can be reduced due to some unstable biochar particles that may rapidly disintegrate when is to exposure the environment, this disintegration can occur due to the presence of water that major role in processes such as dissolution, hydrolysis, carbonation and decarbonation, hydration, and redox reactions, affecting biochar weathering in soil, as well as interactions with soil biota (Joseph et al., 2010). This favorable condition for biochar dissolution was found in our experiment after eight months of interaction (Figure 1) the high precipitation and temperature and can contribute for the smaller biochar particle after 18 months of interaction.

The reduction in the hydraulic conductivity could be associated to filling or clogging soil macropores with fine biochar particles. Where, the small particles can fill the pore space and interact

with soil inorganic particles, altering the porous media of the soil (Figure 2 B and E and Figure 5), which directly influence the rate of water flow.

The reduction in the hydraulic conductivity due to biochar application especially in the rate of 25 Mg ha⁻¹ could be a strategy to reduce water losses in runoff (Blanco Canqui, 2017).

3.4.2.2 Soil water holding capacity

As we verified most studies reporting increase on soil water holding capacity (WHC) when more than 25 Mg ha⁻¹ of biochar was applied and smaller amount of biochar may not significantly increase the soil water holding capacity (Blanco-Canqui, 2017). In the current study, the recommended rate of 25 Mg ha⁻¹ of filter cake was applied with biochar, since that would be the management practice to be used during the sugar cane planting under commercial conditions. Although Lugo López (1954) and Moberly and Meyer (1978) showed in their research the capacity of the sugar cane filter cake to increase the soil water holding capacity, this capacity was lower comparing to filter cake plus biochar 25 Mg ha⁻¹ (Figure 4). The high capacity of the biochar to retain water, can be attributed not only to the high porosity (Atkinson et al. 2010; Hina et al. 2010; Liang et al. 2006a, b) and large inner surface area (Kishimoto and Sugiura 1985; Van Zwieten et al. 2009), but also the ability of the biochar to retain water inside the pores and between the particles (Blanco-Canqui, 2017).

In our research, the BC+FC present in the soil system after 18 months of interaction, contribute to improving WHC (Figure 4), this increase can be associated with the modification of soil pore size distribution (Figure 5 B, D) which is associated with soil aggregation (Figure 2 C, F). Downie et al. (2009) studying biochar rate reported similar results. Another reason that contributed to increase the soil water holding capacity in our experiment was the raw material that has favorable chemical properties. According to Duarte et al. (2019 a), this *Miscanthus* is enriched in Silicon (Si). The Si in the biochar can react with soil water by physically adhering water molecules or trapping water vapor in internal pores increasing the water retention (Pandis et al., 2011).

The farmers can use FC+BC 25 Mg ha⁻¹ in order to increase the 0.04 m³m³ of soil water holding capacity in sandy soil; this increase can be bigger with the time of interaction (18 months) increasing 0.38 m³m³. With the increase of water in the soil, the farmers can reduce the frequency of irrigation contributing to save water and money, due to the water holding capacity of the biochar that stores water and makes it available gradually to plants it is useful also for desert areas and areas with familiar agriculture that is not possible to use irrigation.

3.4.2.3 Relation between water retention and pores size distribution

Biochar plus filter cake application not only increase total porosity (Figure 2 and 5) but also alters the soil pore size distribution and this has a greater effect on water retention (Figure 4). Downie et al., (2009) found similar results. In our study, we verified an increase in micropores with increase of BC+FC rate. The increase of micropores with biochar addition can be associated with the conversion of drainable pores (60–300 μm) into water-retaining pores (0.2–60 μm) provoked by biochar (Petersen et al., 2016). The particles should probably fit into drainable pores in the skeleton of the soil matrix (Petersen et al., 2016). Contributing with micropores (pores inside biochar particles) most of them have diameters $<1 \mu\text{m}$ and due to biochar have different particle sizes they can change the pore space between biochar particles and soil (interpores) (Liu et al., 2017). The contribution with interpores and intrapores, create heterogeneity in pore size distribution converting drainable pore space into water retaining pore space.

An increase in the proportion of mesopores and micropores in sandy soils can increase their ability to retain water. However, the micropores inside of biochar is so small that they retain water not available for the plants (Gray et al., 2014), this behavior can explain why we have a high quantity of micropores and water retention and plant available water is not too high. Despite this, we can verify the positive effect of the rate and time of interaction on water retention (Figure 4).

Sandy soils require a considerable amount of irrigation water to meet crop water requirements. Due to pore alteration, the biochar improved water retention properties of the coarse soil (Petersen et al., 2016), by to reduce the rapid water infiltration and loss of water, increasing the water in the root zone, optimize irrigation management and reducing irrigation needs characteristics important especially in dryland regions, arid and/or desert areas (Misra, 2014).

3.4.2.4 Plant-available water holding capacity

Slightly increased mesoporosity and microporosity at higher B+FC amount (25 Mg ha^{-1}) led to slightly increased plant-available water holding capacity (AWHC). Głąb et al. (2016) and Kameyama et al. (2016) reported that biochar addition at 10 Mg ha^{-1} did not affect the plant-available water holding capacity. Similarly, the no significant increase in the plant-available water holding capacity ($p>0.05$) with the biochar rate was also verified by Herath et al. (2013) that used 7.3 Mg ha^{-1} in Anisofol and Glab et al., 2016 that added 0.5% of biochar *Miscanthus*, in Loamy sand soil didn't find significant effect.

Similar to our results de Melo Carvalho et al., (2014) added biochar 32 Mg ha^{-1} in Sandy loam under field conditions and after 3 years of interaction and verified increased in AWHC, also, Esmaeelnejad et al. (2016), added 2% of Rice husk and wood biochar in Sandy loam soil under

Incubation conditions and after 180 days of interaction and verified increased $\leq 130\%$ in the plant available water content.

The low increase in the AWHC can be associated with the high microporosity that retains the water so strongly that is not available for the plants (Gray et al., 2014). The properties such as specific surface area (SSA) and intraparticle porosity were attributed as the most important factors that increased AWHC (Uzoma et al., 2011). Duarte et al., (2019) verified an increase in the AWHC with the decrease of biochar particle size until 2-0.15 mm and particles inferior to 0.15 mm, the AWHC decreased. In our results, the increase in the AWHC after 18 months of interaction can be attributed to increase in the aggregate stability and water retention (Figure 2 D and 4).

The slight increase in the AWHC with an increase of the B+FC rate can be associated with the high mesoporosity (20%) and microporosity (60%) of the soil with FC+BC 25 Mg ha⁻¹ the biochar could have a positive impact in soil water retention in 0.04 m³m³ (Ogawa et al. 2006) and, thus, increase the plant-available water in 5 mm.

The time of interaction and the B+FC rate makes it an important factor that increases the plant available water-holding capacity of soil when mixed with B+FC. The increase in plant-available water following biochar application is advantageous to reduce the frequency of irrigation, especially where plants fully depend on irrigation. This might in the long run reduce the cost of production.

3.5 Conclusions

The hypothesis that B+FC rate 25 Mg ha⁻¹ improve the soil physical and hydrological properties more than lower rates (6.25 and 12.5 Mg ha⁻¹), and its improvement in the soil physical and hydraulic properties is greater after 18 months of interaction was partially proved. Biochar combined with sugar cane filter cake modified the pore size distribution, slightly increased plant available water holding capacity at the first layer and significantly decreased saturated hydraulic conductivity. However, further studies are encouraged to investigate effects of these agricultural residues on soil physical and hydraulic properties with more time of interaction.

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4 EFFECT OF BIOCHAR PARTICLE SIZE ON PHYSICAL, HYDROLOGICAL AND CHEMICAL PROPERTIES OF LOAMY AND SANDY TROPICAL SOILS

Abstract

The application of biochar is promising for improving the physical, chemical and hydrological properties of soil. However, there are few studies regarding the influence of biochar particle size. This study was conducted to evaluate the effect of biochar size on the physical, chemical and hydrological properties in sandy and loamy tropical soils. For this purpose, an incubation experiment was conducted in the laboratory with eight treatments (control (only soil), two soils (loamy and sandy soil), and three biochar sizes (<0.15 mm; 0.15–2 mm and >2 mm)). Analyses of water content, bulk density, total porosity, pore size distribution, total carbon (TC) and total N (TN) were performed after 1 year of soil–biochar-interactions in the laboratory. We didn't verify effect of the particle size on water retention in both soils, particularly in the loamy soil. Bulk density slightly decreased, especially in the loamy soil when biochar > 2 mm and in the sandy soil with the addition of 0.15–2 mm biochar. Porosity increased in both soils with the addition of biochar in the range of 0.15–2 mm, smaller biochar particles shifted pore size distribution to increased macro and mesoporosity in both soils. Total carbon content increased mainly in sandy soil compared to control treatment; the highest carbon amount was obtained in the biochar size 0.15–2 mm in loamy soil and <0.15 mm in sandy soil, while the TN content and C:N ratio increased slightly with a reduction of the biochar particle size in both soils. These results demonstrate that biochar particle no alter the water retention, but have influence on water availability, pore size distribution, and C sequestration.

Keywords: Biochar particle size; Soil physics; Soil chemistry; Water retention

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4.1. Introduction

The intensification of agricultural production on a global scale is necessary in order to secure the food supply for an increasing world population. However, in most tropical environments, sustainable agriculture faces large constraints due to low nutrient content and accelerated mineralization of soil organic matter (SOM) [1]. Therefore, the low cation exchange capacity (CEC) of the soils further decreases. Under such circumstances, the efficiency of applied mineral fertilizers is very low when the loss of mobile nutrients from the topsoil is enhanced by high rainfall [2]. Additionally, coarse-structured soils with low clay content are characterized by a lack of both water retention and nutrient-holding capacities that are necessary for plant growth [3]. Many farmers cannot afford the costs of regular applications of mineral fertilizers. Consequently, nutrient deficiency is prevalent in many crop production systems of the tropics [4].

In contrast to these deficient soils, the famous *Terra Preta* maintains its fertility, despite its 2000 years of age [5]. This is partly due to the tremendous nutrient levels and SOM stocks that act as a long-

term, slow-release fertilizer [5,6]. The physical and hydrological properties in this soil also contrast with adjacent soils. For instance, Glaser et al [4] verified that the water retention of *Terra Preta* was 18% higher as compared to adjacent soils. The secret of the *Terra Preta* is in the biochar; this type of earth contains on average 50 Mg ha⁻¹ of biochar per hectare in the upper 50 cm soil depth. Adjacent reference soils contain only 4 Mg biochar, which is about 10 times less than that in *Terra Preta* [5]. The existence of *Terra Preta* in Amazonia today proves that it is possible to convert infertile soils' insufficient physical and hydrological properties to sustainable, fertile soils with good physical and hydrological properties. It is evident that biochar is a key ingredient in making *Terra Preta* so special [6] and is the ingredient to improve the soil quality on intensive agriculture.

Biochar as key for *Terra Preta* formation can improve physical and hydrological properties such as water retention, water available content, bulk density, and porosity [7–9]. For example, the addition of 20 Mg ha⁻¹ biochar to sandy soil in northeast Germany increased its water-holding capacity by 100% [10]. At the same time, the incorporation of biochar into soil has been shown to enhance soil capacity to retain plant nutrients, decrease nutrient losses from leaching, and increase soil water holding capacity, pH and SOM [11,12].

Many functions in one product are possible because the biochar is composed of condensed aromatic moieties that give biochar its black color and are responsible for its stability, which makes biochar an interesting compound for C sequestration [13,14]. In addition, biological degradation and consequently partial oxidation results in the formation of functional groups on the edges of biochar, causing reactivity in soil such as nutrient retention or organomineral stabilization [15,16]. The highly porous material leads to enhanced air and water storage in soil [6].

Because of these functions, biochar can be used as a soil amendment to improve the quality of agricultural soils [4]. The application of biochar to soil is considered as a win-win strategy to improve the soil physical conditions that influence soil hydraulic properties and water retention [2, Kameyama et al [17] and increase soil fertility [6,18].

The effects on the chemical and physical properties of soil are dependent on the biochar amount, pyrolysis temperature, biomass type, and biochar particle size [7,19,20]. However, few studies have focused comprehensively on the effects of biochar particle size on hydraulic, physical and chemical properties [7,21]. Understanding biochar particle size is important because it affects the interaction with the soil matrix. The greater and/or lesser interaction of biochar with the soil matrix may have a direct effect on its chemical, physical and hydrological properties [22]. This interaction is dependent of biochar particle size and therefore can influence the physical and hydraulic properties of soil [7].

Small biochar particles can more easily interact with soil particles to form aggregates than large biochar particles [23]. In addition, the greater specific surface area per unit of mass increases the water

retention [7] and plant-available water [24]. In another study, Głab et al [25] found that bulk density decreased, total porosity increased, plant-available water content decreased, and water repellence decreased with an increase in the biochar size from 0.5 to 2 mm.

The role of biochar on temperate soils has been discussed in the literature [7,21,22]. However, for tropical soil conditions, there is a lack of information on this promising soil conditioner. The present study, as far as we understand, is the first research that presents data on the fate of biochar application on the physical, chemical and hydrological properties of tropical soil.

We hypothesize that the biochar application has a positive effect on the physical, chemical and hydrological properties of soil under tropical conditions. However, this effect is dependent on particle size; the reduction of particle size causes an increase in water retention and total porosity and a decrease in available water content and bulk density. Therefore, the objective of this study was to determine the effect of biochar particle size on the physical, hydrological and chemical properties of soil. The knowledge of the relationship between soil's physical, hydrological and chemical properties and biochar particle size is potentially useful in management applications, particularly those concerning irrigation and recovery of degraded areas.

4.2. Methodology

4.2.1. Biochar Production

In our study, we included biochar produced from biomass coming from agricultural residues (*Miscanthus giganteus*) (Table 1). This biochar is commercially produced by drying *Miscanthus* grass at 105 °C in a greenhouse, followed by 15 min of pyrolyzation in a second stationary metallic and cylindric 60 liters reactor at 450 °C. Both reactors were hermetically sealed. The pyrolysis process was performed by SPPT Research and Technology Company (Mogi Mirim, SP, Brazil) in a metal reactor, saturating the sample with N₂ and raising the temperature 10 °C every minute during the first 30 min and 20 °C per minute until reaching the desired temperature [26]. We used *Miscanthus giganteus*, because it is a residue of the growing biofuels industry and its high quantity of silicon can increase water retention in biochar, thus contributing to the high water storage capacity in the soil [27].

Table 1. Chemical characterization of the biochar.

Properties of Biochar	Unit	Value	Reference
pH in H ₂ O	-	5.9	[28]
Electric conductivity	μS cm ⁻¹	605	[28]
Moisture	%	3.5	[29]
Cation Exchange Capacity	mmol·dm ⁻³	33	[28]
Specific surface area	m ² g ⁻¹	371	[30]
Labile C	%	2.7	[31]
Stable C	%	50.9	[31]

4.2.2. Biochar and Soil Characterization

4.2.2.1. Biochar Characterization

Analyses such as pH and electric conductivity were performed by Conz et al [26] following the methods recommended by the International Biochar Initiative Guideline (IBI, 2015). The labile carbon, stable carbon and lability analyses were conducted following the method of [31]. Moisture was measured using the Standard Test Method for the Analysis (ASTM) method, specific surface area was measuring using the method reported by Cerato & Luttenegger [30] (Table 1).

4.2.2.2. Soil Characterization and Sampling

The soils used were Entisol and Oxisol, which were sampled in two different native forest areas located in Sao Paulo state, Brazil. The sampling sites were near Anhembi, Brazil (22°43'31.1"S and 48°1'20.2"W) and Piracicaba, Brazil (22°42'5.1"S and 47°37'45.2"W). Although these areas had never been cultivated, we identified the presence of alterations in the surrounding forest. However, the collection point was chosen in the middle of the forest in a location without alterations. The soils were sampled at the 0–20 cm layer, air-dried, homogenized, and sieved <2 mm.

The soil chemical characterization was performed by Feola Conz et al [26], who followed the methodology proposed by Raij et al [32] and determined the parameters such as pH in Calcium chloride 0.01 M (CaCl₂); P, K, Ca, Mg and K in the resin; Al extracted with potassium chloride (KCl, 1M); sulphate (S-SO₄) extracted with calcium phosphate (Ca(H₂PO₄)₂, 0.01M); percentage of saturation by bases (V%); percent saturation by aluminium (m%); and potential acidity (H + Al). The C and N contents were determined with elemental analyser (LECO CN-Truspec) (Table 2).

Table 2. Chemical and physical characterization of loamy and sandy soil.

Chemical Characteristics	Sandy Soil	Loamy Soil
pH (CaCl ₂)	3.9	6.5
(%)		
Sand	90	41
Silt	2	27
Clay	8	32
Aluminium saturation	10	87
Base saturation	45	0
(mmol·dm ⁻³)		
Al	6	0
H + Al	62	18
SB	7	120
CEC	69	138

H + Al = potential acidity, SB = soma of bases (Ca, Mg, K), CEC = Cation exchange capacity (SB + Al + H), V = Base saturation ($SB \times 100/CTC$); m = Aluminium saturation ($100 \times Al^{3+}/SB + Al^{3+}$).

4.2.2.3. Experimental Setup and Sample Preparation

The design of the experiment was completely randomized with a 3×2 factorial, three biochar particle sizes (>2 mm, $2-0.15$ mm and <0.15 mm) and two soil textures (sandy and loamy), with an additional treatment control (only soil), totaling eight different treatments with four replicates. We used 200 g of soil and 0.92 g of biochar (~ 25 Mg ha⁻¹) for biochar particle sizes of >2 mm; $2-0.15$ mm and <0.15 mm. The biochar fractions were incorporated with soils in jars (500 mL volume) and vigorously mixed into the soil based on pre-calculated bulk densities, which included the contribution of the amendments to the final bulk density, resulting in 32 pots that were incubated for 1 year at a temperature of 30 °C under laboratory conditions. During that year, the moisture of the soil-biochar mixture was adjusted to 60% field capacity and maintained at that level throughout the experiment by weighing the jars three times per week and adding water if necessary. The biochar and soil were filled in the incubation, and after 12 months of interactions, the soil was sampled and physical and chemical analyses were performed.

To obtain the water retention curve, a volumetric ring of approximately 7 cm³ was used to sample inside of the jar without disturbing the sample. First, the ring was inserted into the soil and the sample was removed with an aluminum device similar to a shovel. The soil remaining were used for chemical analysis.

4.2.2.4. Post-Incubation Analyses C, N, and C:N Ratio

Carbon and nitrogen concentrations were determined using an elemental analyzer LECO TruSpec, (LECO Instruments ULC, Mississauga, Ontario, Canada), and it was possible to obtain the atomic ratio (C:N).

Bulk Density and Particle Density

The bulk density was performed by the Black and Hartge method [33]. Deformed samples were used to determine the particle density (PD) in each soil and their different treatments. A helium gas pycnometer, model ACCUPYC 1330 (Micrometrics Instrument Corporation, Nacross, GA, USA) was used to determine the PD values. The principle of this method is based on the determination of the volume of solids by the variation of the pressure of one gas in a known volume chamber.

Porosity

The total porosity (TP) was calculated from the soil bulk density (BD) and the particle density (PD) [34] using the following Equation:

$$TP (\%) = 1 - \frac{BD}{PD} \times 100 \quad (1)$$

The macro and microporosity were performed with a soil water retention curve using theoretical values for macroporosity superior to 50 μm and microporosity inferior to 15 μm [35].

Water Retention Curve

Soil water-holding capacity was measured by the moisture contents of the samples at different matric potentials (-15000, -10000, -3000, -1000, -300, -100, -60, -40, and -20 hPa). The points (-15000, -10000, -3000, -1000, -300 and -100 hPa) were used in the Richard chamber, and -60, -40, and -20 hPa were used in Haines' apparatus. The moisture content was performed with gravimetric analysis. Using the multiplication of gravimetric moisture by bulk density, we converted the gravimetric moisture to volumetric moisture [36]. For the determination of curve parameters (θ_s , θ_s , α , n), we used a Van Genuchten (1980) type.

4.2.3. Data Analyses

Statistical analyses and the graphics were performed using the language R (Version 1.2) and the packages: soil physics, agricolae and plotrix. [37] and Microsoft Excel. The data were checked for normality and homogeneity of variances to meet the assumptions of ANOVA and test of Tukey, with a probability threshold of 0.05.

4.3. Results and Discussion

4.3.1. Soil and Biochar characteristics

The *Miscanthus*-derived biochar had a higher quantity of C, N, Ca, Mg, Na, K, P, and S when compared to both soils (Table 1). Furthermore, the *Miscanthus*-derived biochar was characterized by hydrophobic groups such cyclic acid anhydrides (C-C and C-O); asymmetric carboxylates (CO_2), aromatic ketones (C=O); silicon (Si-O); and hydrophilic groups such carbonates (C-O) and silanol (Si-O-H). With these classifications, this biochar was determined to have a high hydrophobicity [38].

Sandy soil has a very low amount of K; a low amount of Mg and P; a base saturation of Ca; a medium amount of S, Al, CEC and m%; and a high content of sand at a low pH can contribute to the low fertility as compared to loamy soil (Table 3). The low pH (3.5) indicates the presence of exchangeable aluminum that can inhibit the root development and affect the availability of other nutrients and mineralization of organic matter. In addition, the values of Ca, Mg and K were very low, indicating that this soil is highly weathered and base saturation is very low, resulting in cation exchange sites occupied by components of the acidity H or Al [39]. Loamy soil has a low amount of Al, a medium amount of S and CEC, a high amount of V% and K, and a very high amount of Ca at a high pH; there is also no presence of Al, contributing to the low solubility of the Al^{+3} , rendering it harmless to roots and soil processes and increasing the availability of other nutrients (Table 2).

Table 3. Comparison between chemical properties of biochar and two soil textures: loamy and sandy soil.

Properties of Biochar	Biochar	Sandy Soil	Loamy Soil
	(mg kg ⁻¹)		
Ca	3361	5.3	97
Mg	2133	<1	20
K	8615	<0.7	4.1
P	1859	4	28
S	634	5.3	9.5
C	66.4	0.9	1.9
N	0.43	0.06	0.17
C:N	155	14	11

Adapted from Feola Conz et al [26] C:N = ratio between Carbon and Nitrogen.

Comparing the biochar with sandy and loamy soil, the biochar had 7 and 2.5 times more N, 464 and 66 times more P, and 12.3 and 2 times more K in both soils, respectively (Table 3). This large difference can contribute to increasing the fertility in both of the soils. Glaser et al [4] affirmed that the fertilization potential of the biochar is high, especially in tropical soils. This affirmation has been proven by Laird et al. [12] who observed a significant increase of P, K, Ca, and Mn after 500 days of biochar addition.

4.3.2. Biochar Effect on Physical Properties

4.3.2.1. Total Porosity

Naturally, the total porosity is higher in clay soil than in sandy soil. Though there is no significant difference between treatments ($p > 0.05$), the biochar addition (>2 mm) increased the total porosity in both soils. The increase in the particle size reduces the homogeneity of the pore distribution and increases the total porosity; this increase was more evident in loamy soil. Likewise, in a previous study, He et al [8] reported an increase in the total porosity with the addition of biochar 4 mm.

The total porosity in sandy soil was higher when 0.15–2 mm biochar was added (Figure 1a), but this increase was not significant. Similar to our study, Głąb et al [25] did not find a significant difference on total porosity in biochar *Miscanthus* with a different particle size (0.5–2 mm). However, they verified that the total porosity increased with biochar addition in loamy and sand soil, with an increase in biochar size from 0.5 mm to 2 mm. Similarly, in this research, we found that the size 0.15–2 mm sandy soil contributed to increasing the soil porosity.

Figure 1. Effect of biochar size (0: Control (Only soil); >2 mm; 2–0.15 mm and <0.15 mm) on soil physical and chemical properties in loamy and sandy soil, where, TP: Total porosity; BD: Bulk density; C: Carbon; N: Nitrogen; C/N: Carbon and Nitrogen ratio.

The smaller fraction (<0.15 mm) slightly decreased the total porosity. The reduction of the porosity is proportional to the reduction of the particle size; this behaviour is attributed to biochar fragmentation; during the fragmentation process, most of the larger wood pores are destroyed in smaller pieces, thus increasing the number of micropores [40]. As we verify in this study, the reduction in the particle size to <0.15 mm increases the homogeneity in the pore distribution, increasing the micropore volume and reducing the total porosity, particularly in sandy soil [25,41]. In previous work, Glab et al [25] found similar results for the particle size <0.3 mm.

The alteration in the biochar fraction and consequently in the porosity of the soil can influence the different impacts on soil physics and hydraulic properties. For example, wide spaces where water can freely move exist in larger biochar particles (>2 mm). Smaller fractions such as <0.15 mm have pores with the function of storing water [40]. Due to the fractioning process, these particles have a larger surface area and micropore volume.

4.3.2.2. Bulk Density

The high bulk density in sandy soil and low bulk density in loamy soil can be attributed to the soil particle. For both soils, porosity and bulk density are inversely proportional to each other. There was no significant effect ($p > 0.05$) of biochar particle size on soil bulk density (Figure 1B). However, in sandy soil, there is a tendency for reduction of the bulk density with reduction of the particle size until 2–0.15 mm fraction in loamy soil increases in the bulk density with the decrease of particle size.

The magnitude of the biochar effect on bulk density can be explained by simple dilution of the soil with the low bulk density of the biochar [12]. In clay loam soil and in the smaller fraction of sandy soil (<0.15 mm), the increase in the bulk density with a decrease in the biochar particle size can be associated with an arrangement of the particles of biochar in the volume of the soil, where the smaller particles can occupy the pores in the soil, this is not possible if the biochar particle is bigger. With this arrangement, more biochar is located inside the pores of the soil, contributing to a reduction of the total porosity and an increase in the soil bulk density. The reduction in the bulk density is so important for the increase in soil porosity because it contributes directly to root elongation and consequently plant development and production [42].

4.3.3. Biochar Effect on Chemical Properties

4.3.3.1. Total Carbon

The carbon amount in the loamy soil was higher than in sandy soil (Figure 1c). The addition of 25 Mg ha⁻¹ biochar in the >2 mm fraction had a minor contribution to the increase in carbon in the loamy soil and especially sandy soils. In both soils, the carbon content increased significantly ($p < 0.05$) with a decrease in the biochar particle size (2–0.15 mm); the carbon amount for loamy soil increased by 6.6 kg kg⁻¹ and in sandy soil by 4.2 kg kg⁻¹ in the smaller biochar particle size (<0.15 mm) (Figure 1c).

The ability of biochar to increase the quantity of nutrients can be attributed to its large amount of carbon and its large specific surface area, porosity and amount of negative surface functional groups. All of these factors produce an enhanced soil cation exchange capacity [43] that can reduce nutrient leaching while increasing the quantity of the elements in the soil [44].

The increase of carbon content in loamy soil and sandy soil with biochar addition can contribute to an increase in aggregation stability, water retention, plant-available water content, and reduction of soil bulk density. These soil physical properties are essential for the soil physical quality and therefore for plant development [44].

4.3.3.2. Nitrogen

In loamy soil, there is a high amount of nitrogen as compared to sandy soil. The biochar addition contributed very little to an increase in the nitrogen amount. Although there is no significant difference on nitrogen amount with the different biochar particle size, we verified that in loamy soil, the 0.15–2 mm biochar size increased the nitrogen amount 0.12 kg kg^{-1} as compared to the control treatment. For sandy soil, the biochar size does not alter the nitrogen amount (Figure 1D). Similarly, Zhang et al [45] verified that the difference was not significant in the first year of soil–biochar interaction. However, in loamy soil, we can see a little increase in the nitrogen amount in the particle size 0.15–2 mm and in sandy soil $<0.15 \text{ mm}$; this increase can be associated with the specific surface area that can contribute to the nitrogen amount in the soil.

4.3.3.3. C:N Ratio

In loamy and sandy soil, the C:N ratio was different. Though there is a tendency to increase the C:N ratio, for a small biochar particle size (2–0.15 mm), this increase was more evident in sandy soil. This study shows, that in loamy soil with the decrease of the biochar particle size (0.15–2 mm and $<0.15 \text{ mm}$), the C:N ratio increased to 19 and 18, respectively, as compared to the control treatment. However, this increase was not significant ($p > 0.05$). In sandy soil, the difference in the biochar particle size 0.15–2 mm and $<0.15 \text{ mm}$ contributed to an increase in the C:N content of 88 and 64 kg kg^{-1} , respectively (Figure 1E). Zhang et al [45] verified an increase in the C:N ratio with biochar addition. The influence on the biochar particle size on the C:N ratio is associated with alteration of the carbon and nitrogen amount in the soil with biochar. As shown in this work, the C:N ratio is essential for the equilibrium of nutrients and their availability for plants and microorganisms survival. The only exception was in the sandy soil treatments of particle sizes of 0.15–2 mm and $<0.15 \text{ mm}$, where the C:N ratio was inferior to 21 so there were no problems with decomposition and nitrogen immobilization [46].

4.3.4. Biochar Effect on Hydrological Properties

4.3.4.1. Water Retention Curve

There is no significant difference between the treatments (Figure 2) in clay loam and sandy soil. Comparing the addition of 25 Mg ha^{-1} of biochar with the control treatment (only soil), the biochar addition did not promote an increase in water retention in sandy soil. The effect of particle size on water retention properties was not. Similarly, in their experiment on sandy soil, Jeffery et al [47] did not find significant effects of biochar application on soil water retention. Hardie et al [48] verified no increase in soil moisture and water retention characteristics with biochar addition.

Figure 2. Effect of biochar particle size on soil water retention in sandy (A) and loamy soil (B).

In both soils (loamy and sandy soil), we not verified that finer fractions increased water retention. Considering biochar pyrolysis, the increase of pyrolysis temperature causes a decrease in the particle size. This size reduction occurred together with the reduction of the hydrophobicity contributes to the increase of microporosity and consequently an increase in the water retention in the permanent wilting point [49]. This size reduction occurred together with the reduction of the hydrophobicity [49].

The increase in water retention with a decrease in particle size (especially in <0.15 mm) was verified by Ibrahim et al [50] in biochar with particle sizes ≤ 1 mm; this biochar contributed to an increase in the soil moisture content, especially when biochar was applied to the superficial layer (0–5 cm). Głąb et al [25] verified that the increase in biochar size from 0.5 mm to 2 mm caused a decrease in the water retention in sandy soil; this result was found in this study with an effect that is more evident at a high matric potential. The increase of water retention at a high matric potential is attributed to water content that is affected more strongly by the organic carbon as compared to the low water potential [51]. These differents results compare to our research can be attributed to differents raw materials.

The low increase that we verified in the figure 2A in the range 15 -120 hPa in the treatment (<0.15 mm) can be attributed to smaller particles that retain more water than larger particles is due to small biochar particles can more easily mix or interact with soil particles to form aggregates than large biochar particles [23]. These aggregates contribute to an increase in water retention. In addition, small biochar particles have a high specific surface area per unit of mass, and the water retention increases

with an increase in the total specific surface area per unit of mass [7]; when the biochar with a high specific surface area is incorporated into the soil, it contributes to increasing the soil surface area [52]. That can result in the increase of the soil water retention [4,52,53].

The increase in water retention with a reduction in particle size allows the soil to retain additional water, increasing the amount of available moisture in the root zone and permitting longer intervals between irrigations [10,54]. The biochar application increase soil water retention. From this point of view, biochar can be recommended as a valuable amendment that improves soil hydraulic properties. As the addition of biochar increases the volume of stored water in the soil, it may allow for a reduction in the frequency of irrigation [55]. The addition of biochar may have enhanced the effect on the soil water content, resulting in positive impacts on plant growth during periods of water deficit.

4.3.4.2. Plant-Available Water Content

A significant difference in the plant-available water content (AWC) was found for the soil textures. In all treatments, the loamy had more AWC than the sandy soil. For both soils, we found a significant effect of biochar addition on AWC ($p < 0.05$), and between biochar fractions the best treatment was 2–0.15 mm; this treatment differed from <0.15 mm and the control treatment. (Figure 3).

Figure 3. Effect of biochar size on plant-available water content in sandy soil (SD) and loamy soil (CY) AWC.

The plant-AWC is directly related to pore size distribution in different biochar-textured fractions [56]. Similar to our results, the increase in the plant-AWC in sandy and loamy soil with the decrease of the particle size was also verified by Głab et al [25] and Mukherjee & Lal [57].

The high porosity of biochar has a positive impact on soil water retention [58]. This high porosity is associated with a high specific surface area that increases with the decrease of the particle size, these are the essential factors that cause a rise in the soil available water content [59,60]. The sandy soil has a specific surface area $<10 \text{ m}^2 \text{ g}^{-1}$ [61], while that of biochar *Miscanthus* can be as high as $371 \text{ m}^2 \text{ g}^{-1}$ in the fraction ($>2 \text{ mm}$). This property of biochar is verified in the particle size ($0.15\text{--}2 \text{ mm}$) and is therefore an important factor to increase the water-holding capacity of soil when mixed with biochar. However, when the biochar particle size is too small ($<0.15 \text{ mm}$), the specific surface area is so large and retains the water so strongly that the available water content can be reduced. The application of the biochar in the soil with a smaller fraction ($0.15\text{--}2\text{mm}$) is advantageous in reducing the frequency of irrigation, especially where plants fully depend on irrigation [25].

4.3.4.3. Effect of Biochar Particle Size on Pore Size Distribution and its Relation with Water Retention Curve

Comparing only the biochar addition (25 Mg ha^{-1}) in the $>2 \text{ mm}$ fraction with the control treatment (only soil) in both soils (especially in loamy soil), the biochar addition increased the volume of micropores ($<15 \text{ }\mu\text{m}$ diameter) and decreased the volume of mesopores ($15\text{--}50 \text{ }\mu\text{m}$ of diameter) and macropores ($>50 \text{ }\mu\text{m}$ diameter). In the sandy soil, the biochar particle size affected the pore size distribution only slightly; only the fraction $>2 \text{ mm}$ had a larger increase of micropores ($<15 \text{ }\mu\text{m}$) as compared to other treatments (Figure 4A). In loamy soil, comparing only the effect of particle size, smaller biochar particles ($<0.15 \text{ mm}$) increased the volume of macropores ($>50 \text{ }\mu\text{m}$) and mesopores ($50\text{--}15 \text{ }\mu\text{m}$), yet reduced micropores ($<15 \text{ }\mu\text{m}$). However, the treatments with biochar particle size $0.15\text{--}2 \text{ mm}$ and $>2 \text{ mm}$ were similar. Similarity, Głąb et al [25] found that smaller particles of biochar ($0\text{--}500 \text{ }\mu\text{m}$ in diameter) reduced the volume of small pores ($0.5 \text{ }\mu\text{m}$) and fissures ($500 \text{ }\mu\text{m}$) but increased the volume of pores in a diameter range from 0.5 to $500 \text{ }\mu\text{m}$.

Figure 4. Effect of biochar doses on pore size distribution in Clay Loam and Sandy Soil. Macroporosity (A), mesoporosity (B) and microporosity (C).

The increase in the macroporosity and mesoporosity and the decrease in the microporosity under the addition of small biochar particle size (0.15–2 and <0.15 mm) can be associated with the biochar particles, which settle between the soil particle matrix without blocking the existing pores, thereby creating new pores to increase the macroporosity [62]. Moreover, the presence of the micropore was dominant in both soils (Figure 4), contributing to an increase in the soil water retention, as was previously reported by Tseng & Tseng [63] after 295 interactions of biochar and soil in incubation conditions.

In loamy and sandy soil, we found high water retention in smaller biochar fractions (0.15–2 and <0.15 mm (Figure 2). This increase can be associated with a high specific surface area that increases with the decrease of particle size. These particles can contribute to the creation of pores between biochar particles and soil particles (interpores). The pores inside biochar (intrapores) play fundamental roles in soil water retention [10].

Following soil pore classification, the α -type and β -type pores can be also indicated as transmission-like ($\geq 50 \mu\text{m}$), storage-like ($0.5\text{--}50 \mu\text{m}$) and residual-like ($<0.5 \mu\text{m}$) pores. The largest transmission-like pores are responsible for excess water drainage, thus permitting the aforementioned

water. Storage-like pores retain water against gravity and release or diffusion within the biochar pores (from pores whose size belong to the top limit of the 0.5–50 μm interval). Finally, the smallest residual-like pores contain strongly bound water that cannot easily escape from the porous system [56].

The high quantity of micropores in all treatments and in both soils indicates that biochar may not sufficiently shift soil aeration conditions, as was previously reported [10]. However, the reduction in the biochar particle size contributed to an increase in the macroporosity and mesoporosity in sandy and loamy soils. The macropores and mesopores contribute by aeration and water conduction, and micropores contribute by water retention [23]. In loamy soil, the porous biochar particles can improve water flow. On fine-textured soils, biochar particle can also increase water infiltration and hydraulic conductivity by improving soil aggregation, thus increasing macroporosity. Therefore, biochar can be an important amendment to improve water movement in loamy soils [7]. Biochar could contribute to reducing the penetration resistance and increase the water holding capacity in soils, which would be beneficial for plant root elongation and available water [64].

4.4. Conclusions

The physical properties of soil, such as bulk density and total porosity, were dependent on the biochar size, especially in loamy soil. Small particles of biochar reduced the volume of soil pores (<0.15 mm diameter) but increased the volume of mesopores (0.15–0.50 mm diameter) and macropores (>0.50 mm diameter).

Biochar application increase the soil water characteristics by slightly increasing the plant-available , especially when the finest fraction was used in sandy soil. The biochar has a great potential to increase soil water retention in the finest fraction of loamy and sandy soils.

The benefits found in our research show that this material can be recommended for farmers as a soil amendment to increase the chemical, physical and hydrological quality of their soil.

For the farmers to obtain improvement in the chemical, physical and hydrological properties, the biochar can be used in the finest fraction <0.15 mm with rates of 25 Mg ha⁻¹. Moreover, due to the difficulty of applying a small particle size in agricultural soils, the biochar can be co-composted before it is applied to soil.

Further investigations are recommended to better understand the influence of biochar particle size on hydraulic conductivity, rates and time of interaction, as well as cost-to-benefit ratios in sandy and loamy soils.

Supplementary Materials: The soil and biochar characterization are available in Conz et al [26] and Duarte et al [38].

Author Contributions: D.S.J. was responsible for conducting the experiment, writing the manuscript and contributing to the statistical analyses; G.B. contributed to the review and improvement of the paper and C.C.E.P. contributed to the experimental design, experimental conduction, and review of the paper.

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5. FINAL REMARKS

Biochar has been indicated as a promising option to improve soil quality. Some researchers have shown improvement in the soil physical, chemical and hydraulic properties in temperate climate. However, there is a lack of information about the effects of biochar on soil chemical, physical and hydraulic properties under tropical climate conditions. In this sense, the present study provided pieces of information about the effect of biochar rate and particle size on soil chemical physical and hydraulic properties in a tropical climate.

In chapter I, Duarte et al. (2019a) concluded that the biochar addition contributed to soil carbon sequestration and to improved soil physical properties such as reduction of the bulk density and increase porosity in loamy and sandy soils. In addition, the water retention increase only for loamy soil when biochar was applied at a rate of 25 Mg ha⁻¹; this improvement can be attributed to the increase of the mesoporosity and microporosity in Clay loam soil.

In chapter II, the biochar dose of 25 Mg ha⁻¹ plus filter cake 25 Mg ha⁻¹ improved soil physical and hydraulic properties in tropical soils and this effect was greater with the time of interaction. The most promising results were observed after 18 months of interaction, in which the properties as soil aggregation, water holding capacity, plant available water content, and hydraulic conductivity were improved.

In both chapters, we verified that the higher rate of biochar application (25 Mg ha⁻¹) contributed to the improvement of soil physical and hydraulic properties. However, the biochar particle size can alter the behavior of the biochar in the soil. In order to test that, Duarte et al (2019b) carried out the study reported in chapter III, in which they analyzed the effect of biochar particle size (<0.15mm; 0.15-2mm and >2mm) on soil physical, hydric and chemical properties, and verified that the biochar application improved the soil water characteristics by increasing the plant-available, especially when the finest fraction was used (<0.15mm) in loamy and sandy soils.

The differences between control (i.e. no biochar application) and the maximum biochar rate (25 Mg ha⁻¹) in these three studies are presented in Table 1. There was no difference between control and biochar additions (25 Mg ha⁻¹) + Filter Cake for bulk density, total porosity, macro and mesoporosity. Only microporosity increased. However, under laboratory condition, a reduction in the bulk density and an increase of the porosity were observed. The biochar addition contributed to the increase of macroporosity and reduction of the meso and microporosity.

Table 1. Differences between control and biochar rate 25 Mg ha⁻¹ in three experiments: biochar particle size; biochar rate and biochar rate plus filter cake on sandy soil.

Propertie	Unity	BC (> 2mm)	BC+FC (>2mm)	BC (0.15-2mm)
Porosity	(%)	2.31	0	4
Microporosity	(%)	-5	25	4
Mesoporosity	(%)	-6	0	0
Macroporosity	(%)	11	0	0
Bulk density	gcm ⁻³	-0.062	0	-0.1
Water holding capacity	(m ³ m ³)	0	0.03	0.08
Water available content	(m ³ m ³)	0.05	0.1	0.6

BC (>2mm): Biochar 25 Mg ha⁻¹ with particle size >2mm; BC +FC (> 2mm): filter cake plus Biochar 25 Mg ha⁻¹ with particle size >2mm; BC (0.15-2mm): Biochar 25 Mg ha⁻¹ with particle size 0.15-2mm

Analyzing the hydraulic parameters, a similar behavior was observed in both experiments; the available water content and the water holding capacity increased especially under field condition. The difference between these results from laboratory and field conditions showed that even using the same rate of biochar in both experiments, the results were different. In field condition, the filter cake and the effects of the climate and biological factors, plant roots, and microorganisms contributed to increase the efficiency of the biochar plus filter cake on water holding capacity and water available content after 18 months of interaction.

Comparing the contributions of the biochar particle size (25 Mg ha⁻¹) and biochar + filter cake it was verified that the reduction of the biochar particle (0.15-2mm) improved the hydraulic parameters such as water holding capacity and water available content (Table 1). Only by reducing biochar particle size, the water retention increase three times more than filter cake plus biochar > 2mm and 8 times more than biochar > 2mm. These results demonstrated that the reduction of the biochar particle size is crucial for improving water retention and water available content.

Overall, the results presented here showed that the use of 25 Mg ha⁻¹ has a positive effect on soil physical, hydric and chemical properties. However, the studies conducted under field conditions and under laboratory conditions showed different results. This difference can be attributed to the use of filter cake, the longer time (18 months) of interaction and the effect of the climate at the field condition. However, the improvement on the hydraulic parameters such as water holding capacity and water available content can be greater if the particle size is reduced to 0.15-2mm. These results can be used by farmers and company that desire the improvement on soil physical, chemical, and hydraulic properties. They can use the biochar 25 Mg ha⁻¹ with the particle size 0.15-2mm and include filter cake 25 Mg ha⁻¹ to increase water available content, contributing to keep water into the soil for plant uptake and potentially avoiding spending resources with irrigation procedures.

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