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Effect of Biochar Particle Size on Physical, Hydrological and Chemical Properties of Loamy and Sandy Tropical Soils

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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. The smaller particle size <0.15 mm increased 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 size is crucial for water retention, water availability, pore size distribution, and C sequestration.

Keywords: biochar particle size; soil physics; soil chemistry; water retention

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 [2,17] 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, Głąb 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.

2. Methodology

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 N_2 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_2O	-	5.9	[28]
Electric conductivity	$\mu S\ cm^{-1}$	605	[28]
Moisture	%	3.5	[29]
Cation Exchange Capacity	$mmol_c dm^{-3}$	33	[28]
Specific surface area	$m^2\ g^{-1}$	371	[30]
Labile C	%	2.7	[31]
Stable C	%	50.9	[31]

2.2. Biochar and Soil Characterization

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 & Lutenegge [30] (Table 1).

2.2.2. Soil Characterization and Sampling

The soils used were Entisoland 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 ($CaCl_2$); P, K, Ca, Mg and K in the resin; Al extracted with potassium chloride (KCl, 1M); sulphate ($S\text{-}SO_4$) extracted with calcium phosphate ($Ca(H_2PO_4)_2$,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
($mmol_c dm^{-3}$)		
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 ($100 \times Al^{3+}/SB + Al^{3+}$).

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 cm^3 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.

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, Missossauga, Otario, 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:

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

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 (−15, −10, −3, −1, −0.3, −0.1, −0.06, −0.04, and −0.02 bar). The points −15, −10, −3, −1, −0.3, and −0.1 bar were used in the Richard chamber, and −0.06, −0.04, and −0.02 bar 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 (θs, θs, α, n), we used a Van Genuchten (1980) type.

2.3. Data Analyses

Statistical analyses and the graphics were performed using R studio Version 1.1 [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.

3. Results and Discussion

3.1. Soil and Biocharcharacteristics

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).

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.

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.

3.2. Biochar Effect on Physical Properties

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.

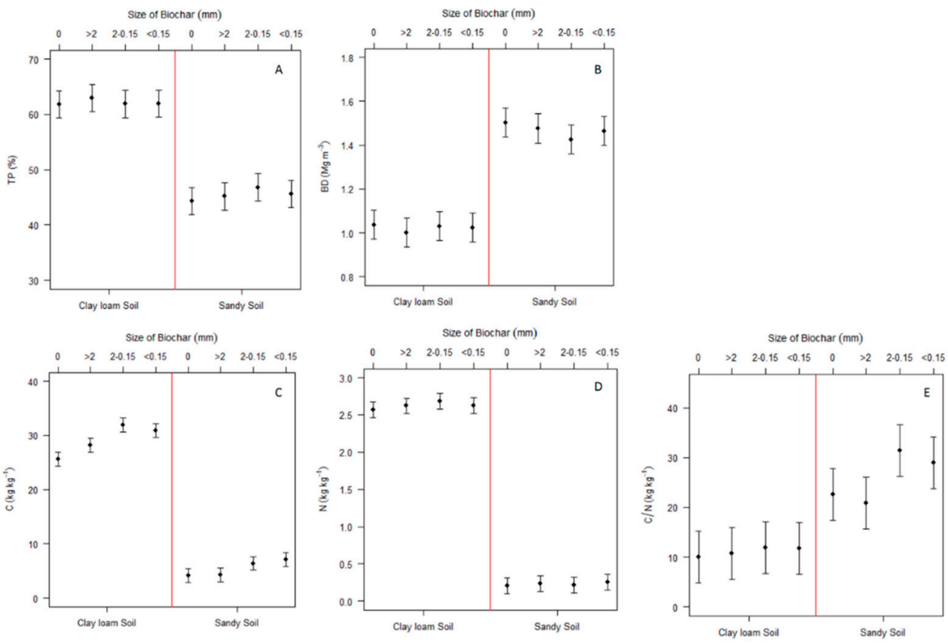

Figure 1. Effect of biochar size (0: Control (Only soil); >2 mm; 2–0.15 mm and <0.15 mm) on soil physical and chemical properties in loamy and sandy soil, where, TP: Total porosity; BD: Bulk density; C: Carbon; N: Nitrogen: C/N: Carbon and Nitrogen ratio.

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 that contributes to increasing the water retention. Therefore, the addition of smaller biochar particles could be beneficial to improving its ability to retain water. However, larger particles can increase aeration and drainage.

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 the 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].

3.3. Biochar Effect on Chemical Properties

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 improve 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].

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 um; this increase can be associated with the specific surface area that can contribute to the nitrogen amount in the soil.

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 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 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 mm, where the C:N ratio was inferior to 21 so there were no problems with decomposition and nitrogen immobilization [46].

3.4. Biochar Effect on Hydrological Properties

3.4.1. Water Retention Curve

According to a Shapiro–Wilk normality test at 5% of significance, 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. Although the effect of particle size on water retention properties was very low when the particle size decreased (<0.15 mm), the water retention increased in moderate (100 hPa) and in dry conditions (15000 hPa); the range of these conditions represents the variation between mesopores and micropores, respectively (Figure 2A). Similarly, in their experiment on sandy soil, Jeffery et al. [47] did not find significant effects of biochar application on soil water retention. Similar results were observed by Hardie et al. [48] with no improvement in soil moisture and water retention characteristics.

Biochar application improved water retention in wet and dry conditions in the loamy soil, as compared to the control. However, the scale of this effect is dependent on biochar particle size (Figure 2B). The biochar particle size (0.15–2 mm) contributed to an increase in water retention in wet (5 hPa) to dry (<10,000 hPa) conditions. The smaller particle size <0.15 mm held water more strongly than the larger particles.

In both soils (loamy and sandy soil), we verified that finer fractions increased water retention. For example, the particle size (0.15–2 mm) was responsible for an increase of 0.08 m^3; of water per m^3; of soil in both sandy and loamy soils [25].This increase occurred because small biochar particles often have more micropores than large biochar particles, holding more water than large particles [7]. For example, when considering biochar pyrolysis, the increase of pyrolysis temperature causes a decrease in the particle size. This size reduction contributes to the increase of microporosity and consequently an increase in the water retention in the permanent wilting point [49].

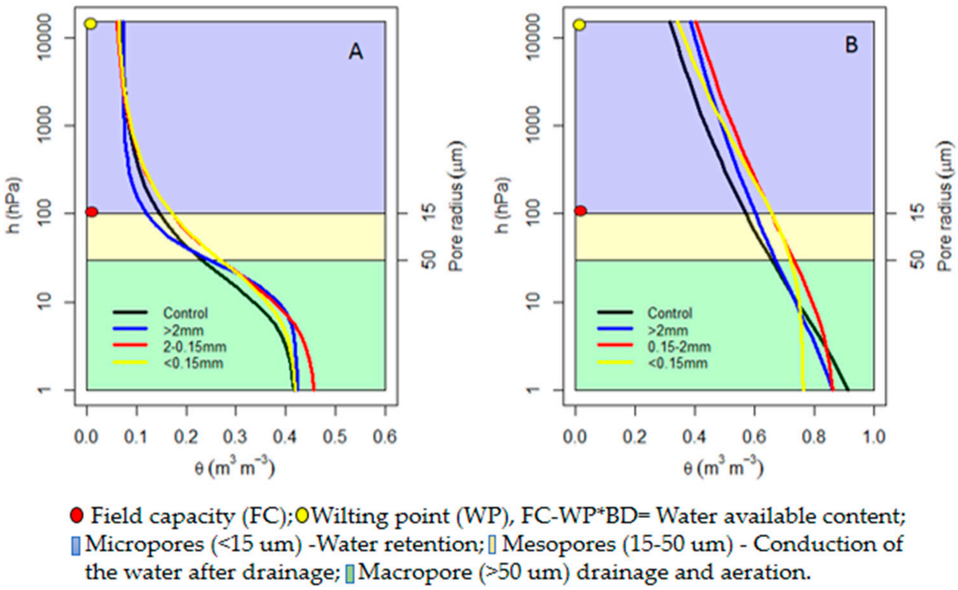

Figure 2. Effect of biochar particle size on soil water retention in sandy (**A**) and loamy soil (**B**).

The increase in water retention with a decrease in particle size (especially in <0.15 mm) was also 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].

The fact that smaller particles retain more water than larger particles is due to small biochar particles that 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 improvement 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 improves 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.

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).

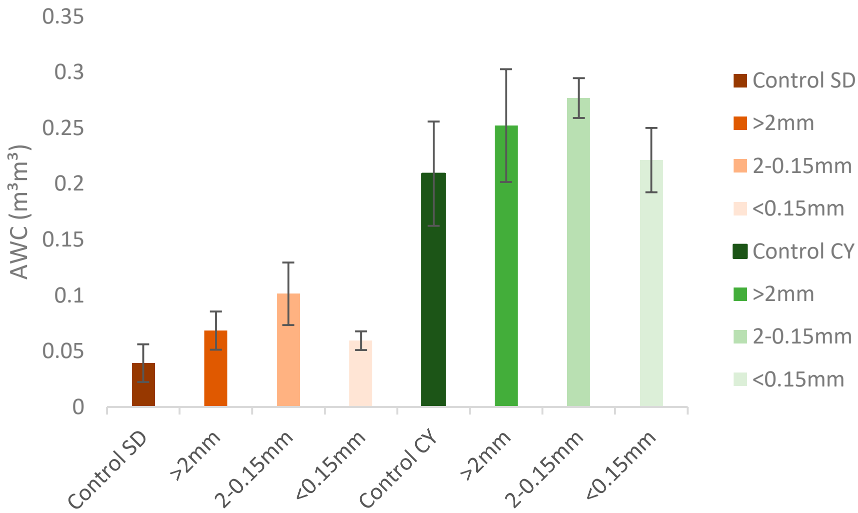

Figure 3. Effect of biochar size on plant-available water content in sandy soil (SD) and loamy soil (CY) AWC.

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 Głąb 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 m^2 g^{-1} [61], while that of biochar *Miscanthus* can be as high as 371 m^2 g^{-1} in the fraction (>2 mm). This property of biochar is verified in the particle size (0.15–2 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 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 (0.15–2mm) is advantageous in reducing the frequency of irrigation, especially where plants fully depend on irrigation [25].

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

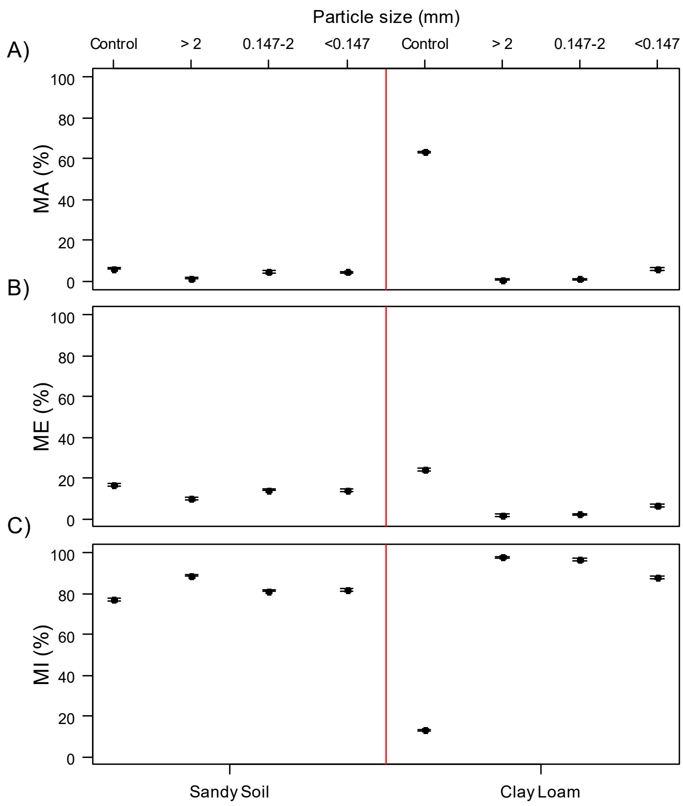

Figure 4. Effect of biochar doses on pore size distribution in Clay Loam and Sandy Soil. Macroporosity (**A**), mesoporosity (**B**) and microporosity (**C**).

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 (≥50 μm), storage-like (0.5–50 μm) and residual-like (<0.5 μm) 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. 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 improved the soil water characteristics by slightly increasing the plant-available water storage capacity, especially when the finest fraction was used in sandy soil. The biochar has a great potential to improve 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 improve 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.

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