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SHORT COMMUNICATION

Biochar Physical and Hydrological Characterization to Improve Soil Attributes for Plant Production

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Abstract

One of the most important problems in agriculture is water scarcity. Biochar, as a soil amendment, has the potential to overcome this problem by improving soil's physicochemical and hydraulic properties. However, the study of biochar's physical and hydraulic characteristics, its potential to improve soil physical and soil water holding capacity, and its contribution to water saving and reduction in irrigation costs is lacking. The understanding of biochar's characteristics is so important because the effectiveness of biochar as a soil amendment is dependent on biochar properties. Our goal is to determine how biochar's pore volume, pore size distribution, specific surface area, and water uptake by biochar interact with soil's physical and hydraulic properties. The pore volume, pore size distribution, porous network, specific surface area, and water holding capacity (WHC) were evaluated in four biochars produced from elephant grass (*Pennisetum purpureum*), castor bean seeds, soybean seeds, and *Jatropha* sp. cake pyrolyzed at 380 °C. Our results demonstrated that the specific surface area and pore volume do not contribute to water uptake in hydrophobic biochars from castor bean seeds, soybean seeds, and *Jatropha* sp, but the results also demonstrated that these biochars have the potential to reduce soil compaction and increase soil porosity. Interestingly, the macroporosity and low hydrophobicity of the elephant grass biochar contributed to increase in its water uptake; these characteristics make this biochar promisor in increasing the soil water holding capacity and water saving and reducing the irrigation costs.

Abstract Highlights

- Different biochar has different potential to change soil physics and hydraulic properties.
- Biochar from elephant grass is promising to improve soil hydraulic properties.
- Biochar from Castor bean seeds, soybean, and Jatropha sp. are indicated to improve soil physical properties.

Keywords Biochar · Porosity · Specific surface area · Water holding capacity

1 Introduction

Water scarcity is one of the most important problems in the world; actually, ~39% of total croplands experienced water scarcity, and in the near future (2026–2050), this problem will intensify in more than 80% of global croplands (Liu et al. 2022). As a result, agriculture as the main sector that requires water to maintain its production will be affected, and consequently, food security will increase, particularly for the poor. In order to reduce the necessity of water applied by irrigation, strategies to increase the soil water holding capacity are necessary.

Biochar is considered an amendment not only to increase the soil's chemical quality (Suliman et al. 2017;

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Ginebra et al. 2022; de Jesus Duarte et al. 2019, 2020), but also to improve its physical and hydraulic properties (Mollinedo et al. 2015; Adhikari et al. 2022; de Jesus Duarte et al. 2019). These properties, such as porosity, specific surface area, and water uptake, are related to feedstock and temperature of pyrolysis.

While several studies have shown that the low temperature of pyrolysis contributes to increasing biochar hydrophobicity and the high temperature of pyrolysis reduces its hydrophobicity with a direct effect on soil water holding capacity (Gray et al. 2014), few studies exist that are focused on biochar porosity, specific surface area, and water uptake as parameters to improve the soil's physical and hydraulic properties. This lack of information is mostly because the biggest part of these studies has focused on the biochar effect and not on the biochar characteristics that could contribute to this effect (Panwar and Pawar 2022; Ippolito et al. 2020).

These few studies have demonstrated that the plant's available water is present on the macropores and mesopores, with a diameter superior to 10 nm, which according to the IUPAC biochar pore classification, macropores have size superior to 50 nm, mesopores are between 2 and 50 nm, and micropores are inferior to 2 nm (Rouquerol et al. 2009). These pores are inherited from plant cellular structures (Wildman and Derbyshire 1991), which include external and internal porosity; they are important to hydrological processes, and also, for fungal hyphae and bacterial survival (Gray et al. 2014; Suliman et al. 2017; Gul et al. 2015; Lehmann et al. 2011), the two major parts of the biochar pore volume, mesopores and micropores, contribute to the chemical sorption and can store dissolved substances and water, supplying for microbial metabolism (Brewer et al. 2012). Of course, the capability of biochar to retain soil water is a function of the combination between porosity (external and internal porosity) and surface functionality (Suliman et al. 2017); this porosity is also beneficial to reduce the soil bulk density and compaction.

The specific surface area is strongly associated with biochar porosity, of which micropores make the greatest contribution, as well as high surface area which is usually accompanied by many surface sites, giving more chances for microbial colonization as well as nutrients fixation and soil water retention (Gul et al. 2015; Lehmann and Joseph. 2009).

The knowledge already established about the biochar physical properties is necessary to have a base to know how the porosity contributes to water uptake in biochar but is necessary to advance in how much the porosity and biochar water uptake contributes to soil water holding capacity and in the reduction of the water applied by irrigation. In order to advance in this way, it is necessary to understand the biochar porosity and specific surface area; this understanding opens the opportunity to create value-added "designer biochar" for specific soil applications (Novak et al. 2009).

The study of the biochar's physical properties is so important because the effectiveness of biochar as a soil amendment is determined by the biochar's physic-chemical nature (Chan et al. 2007; Gundale and De Luca 2006) and biochar porosity that is considered one of the most important characteristics for water holding applications (Gray et al. 2014). Then, the effect on soil water holding capacity, aggregate stability, soil porosity, and soil compaction is directly associated with biochar physical properties (Blanco-Canqui 2017; de Jesus Duarte et al. 2019; Glaser et al. 2002).

The biochar's effect on soil physical properties may have a direct impact on plant growth because the penetration depth and availability of air and water within the root zone are determined largely by the physical makeup of soil horizons: this is why the understanding of the biochar's physical properties as a parameter to increase water uptake in biochar is necessary to identify the most adequate biochar and produce effective products for an agricultural commodity.

Our goal is to determine how biochar's pore volume, pore size distribution, specific surface area, and water uptake by biochar interact with soil physical and hydraulic properties.

To achieve this goal, we investigated (a) the mechanisms that allow biochar's porosity and specific surface area to retain more or less water; (b) we also tested the biochar's specific surface area, pore network, and water holding capacity in biochar from different feedstock and produced at the same pyrolysis temperature; (c) the contribution of each biochar on water saving and the reduction in irrigation costs were also analyzed. Three hypotheses were considered as follows: (1) the water uptake in biochar will be dependent on biochar's porosity and specific surface area; (2) the contribution with soil water holding capacity is related to biochar's water uptake; (3) the biochar has potential to increase water uptake in soil, favoring the water saving and reducing the irrigation costs.

2 Material and Methods

The biochars were produced from different organic materials such as elephant grass (*Pennisetum purpureum*), castor bean seeds, soybean seeds, and *Jatropha* sp. cake. These materials were oven-dried at 75 °C for 24 h, until a constant mass was achieved, and pyrolyzed at 380 °C for 3 h under an N2 atmosphere in an LTC reactor. Then, it was analyzed: specific surface area, pore volume, pore size distribution, scanning electron microscopy (SEM), and water holding capacity. As the European Biochar Certificate EBC (2015) and the International Biochar Initiative IBI (2015) recommend, we used the Brunauer–Emmett–Teller (BET) method to determine the specific surface area, pore volume, and pore size distribution of biochars. We applied the BET method from N2 isotherms measured at 75.2 K, using a Quantachrome Autosorb automated instrument. The nitrogen will fill all pores when the relative pressure attains a certain value (typically at 0.95), and the total pore volume is calculated based on the volume of nitrogen absorbed at this pressure. For these analyses, samples of 100 mg of each biochar were used.

Considering that microscopic methods are able to give more accurate pore size analysis covering the whole range of mesopores and micropores (Leng et al. 2021), we used analysis of the image with high-resolution scanning electron microscopy (HRSEM) in a JEOL 7600 F with an acceleration of 30 kV and a theoretical resolution of 1 nm. For this analysis, a solid sample, homogeneously dispersed in pure ethanol, was deposited on a Cu grid, previously covered with a thin layer of biochar.

The biochar water holding capacity was measured with a dew-point potentiometer (Decagon Devices). To do so, the biochar samples were put inside the WP4C chamber to measure their water potential by determining the relative moisture of the air above a sample in the closed chamber (an AOAC-approved method; also conforms to ASTM 6836). When the sample comes into equilibrium with the vapor in the WP4C's sealed chamber, the instrument, using the chilled mirror method, found the relative humidity and sample temperature with 0.001 °C accuracies at − 1, − 2, − 12, and − 25 kPa. For the determination of biochar's water retention curve parameters (θr, θs, α, *n*), we used a van Genuchten (1980) model.

Statistical analyses were applied to determine the effect of feedstock on porosity, pore size distribution, and specific surface area. In addition, graphics were made using the software R (R Core Team 2021) to verify the porosity by the adjustment Multipoint BET, pore size distribution by adsorption and desorption isotherm, and the effects of biochar feedstock on biochar water holding capacity. In addition, interpretation and calculations of the results were made using real situation. For example, considering a subsurface drip irrigation system cultivated with sugarcane crop, the flow rate of the drip is 0.001m^3, and the volume of the water is 0.56 m^3 m^{-3}, using the equation of the following flow rate:

$$Q = \frac{\Delta V}{\Delta T}$$

where Q is the flow rate, ΔV is the volume of the water (m^3), and ΔT is the time (s); we found the time reduced in the irrigation of this system when we applied the biochar produced from elephant grass (*Pennisetum purpureum*).

3 Results and Discussion

3.1 Biochar's Physical Characterization and Its Impacts on Soil Physical and Hydraulic Properties

The isotherms of N2 adsorption–desorption indicated the type of pore size predominant in each biochar. According to the isotherms of N2 adsorption–desorption, the biochar produced from soybean seeds had little interaction with the adsorbate (N2) and, therefore, is mainly composed of mesoporous material, with a pore distribution between 3 and 20 nm and a high frequency of pores between 3 and 8 nm (Fig. 1), besides an average pore size of 3.7 nm and a specific surface area of 39.63 m^2 g^{-1} (Table 1).

For the biochar, produced from castor bean seeds, we also found low interaction with the adsorbate (Fig. 1), as well as low specific surface area (Table 1). The distribution of the pore sizes was very large, with most of the pores between 2 and 6 nm and an average pore size of 4.8 nm, thereby characterizing the predominance of mesopores (Fig. 1, Table 1). The specific surface area of the biochar from *Jatropha* sp. cake was also very low (0.67 m^2 g^{-1}), showing low interaction with the adsorbate and hysteresis, indicating the presence of mesopores (2–36 nm) (Fig. 1).

The biochar produced from elephant grass (*Pennisetum purpureum*) has a low specific surface area (4.286 m^2 g^1) (Table 1) and low interaction with the adsorbate; it is a material with a very large pore size distribution, between 300 and 3600 nm, with a different morphology along its surface, characterizing a heterogeneous surface with the predominance of macropores (Fig. 1, Table 1).

Biochars rich in macropores are responsible for increasing the plant's available water and retaining large molecules of phenolic compounds. On the other hand, biochar rich in mesoporous inferior to 10 nm and micropores is capable of retaining nutrients and water-holding capacity with high capillary forces becoming not available for most plants (Suliman et al. 2017). For this reason, understanding the physical properties of biochar is crucial to addressing its agronomical and environmental uses (Conte 2014).

As was verified, the specific surface area of the evaluated biochars varied from 39.63 (soybean seeds) to 0.67 m^2 g^{-1} (*Jatropha* sp. cake) (Table 1). Considering that the specific surface area of sandy soil is generally below 0.1 m^2 g^{-1} (Scheffer and Schachtschabel 2010), the addition of any of these biochars appears suitable to increase the specific surface area of sandy soils and changes the soil porosity, by contributing with mesopores when adding biochar from soybean seeds, castor bean seeds and, *Jatropha* sp, and mesoporosity and macroporosity when adding biochar from elephant grass (*Pennisetum purpureum*) (Fig. 1).

The high proportion of coarse pores and low specific surface area of sandy soils result in high hydraulic conductivity, low water-holding capacity, and low water availability for plants, which, in turn, leads to low plant development and biomass production. Thus, the addition of biochar with a high quantity of mesoporous materials such as castor bean seeds, *Jatropha* sp., but especially soybean seeds (Fig. 1), has been shown to increase the soil mesoporosity and microporosity, consequently increasing

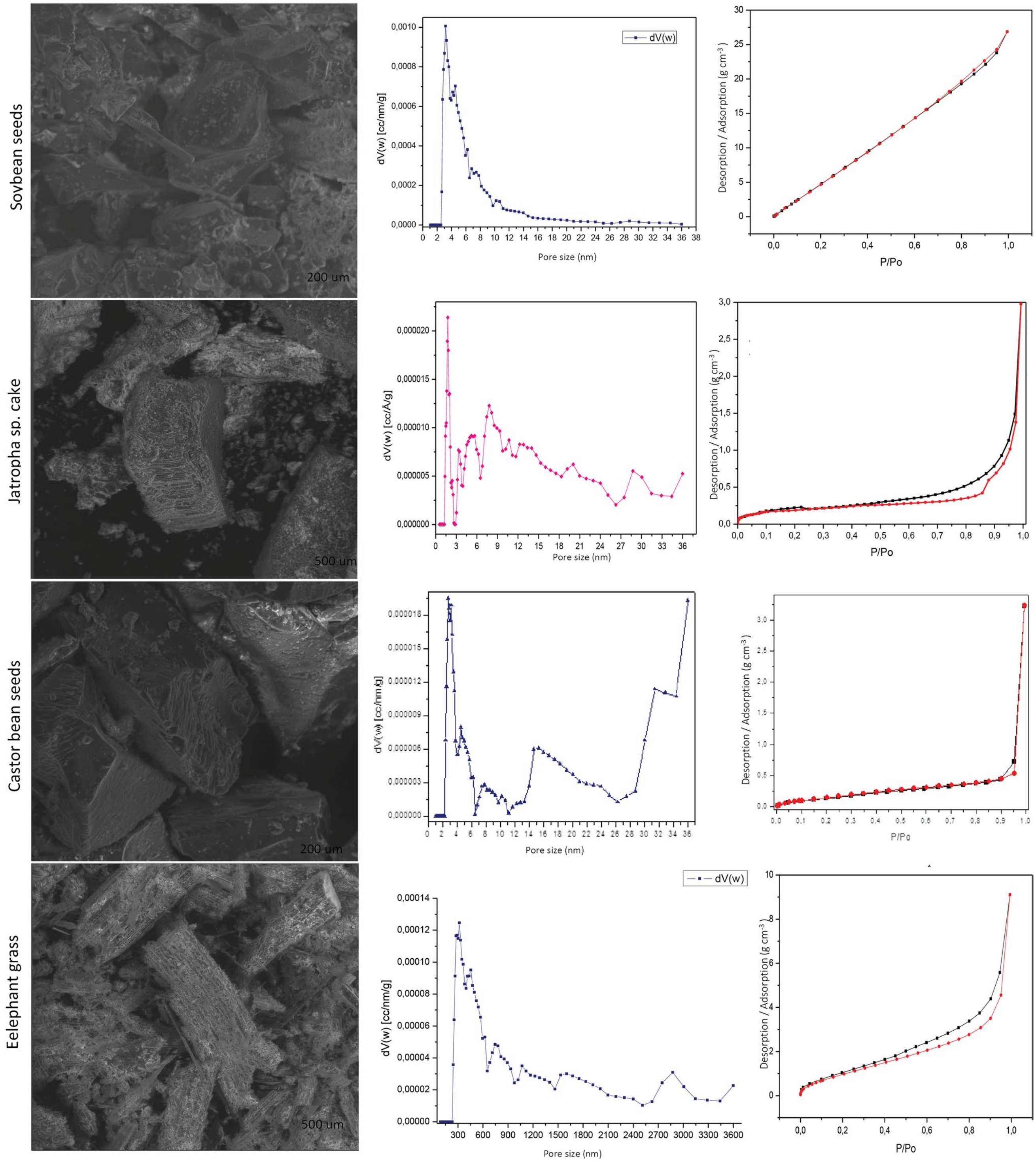

Fig. 1 Scanning electron microscopy (SEM), pore size distribution by volume and volume adsorption (—■—) and desorption (—●—) isotherms of N_2 a 77 K, type III measured in biochars produced from elephant grass (*Pennisetum purpureum*), castor bean seeds, soybean seeds and Jatropha sp. cake

the soil water holding capacity (de Jesus Duarte et al. 2019; Glaser and Birk 2012). However, in this case, the high specific surface area and low pore size distribution may not contribute to improving the soil water-holding capacity due to the hydrophobicity of biochar from the castor bean (Fig. 1).

Table 1 Physical characterization of the biochars produced from elephant grass (*Pennisetum purpureum),* castor bean seeds, soybean seeds and *Jatropha* sp. cake

Type of biochar	Specific surface area m2 g^{-1}	Pore volume cm3 g^{-1}	Pore size nm
Elephant grass (*Pennisetum purpureum)*	4.28	0.007	658.9
Castor bean seeds	0.69	0.001	4.8
Soybean seeds	39.60	0.037	3.7
Jatropha sp. cake	0.67	0.002	9.4

3.2 Biochar's Chemical Characterization and Its impacts on Soil Physical and Hydraulic Properties

Previous analysis of the short-term effects of the same biochars evaluated by Rittl et al. (2015) showed that all of them have aliphatic compounds, corresponding to 37% in castor bean seeds, 33% in soybean seeds, and 19% in *Jatropha* sp. cake. For the elephant grass (*Pennisetum purpureum*) biochar, xylan polysaccharide signals are predominant in the hydroxylated aliphatic side chain (δC) in the spectra of the whole cell walls with a medium concentration of 0.007236% (Haldar and Purkait 2022).

The aliphatic compounds remaining in the pores would render them hydrophobic, providing negative capillary forces in residual macropores and pyrogenic nanopores (Gray et al. 2014). The high concentration of hydrophobic compounds can be mainly associated with the low temperature of pyrolysis (380 °C) that allows the high number of aliphatic drives alkyl functionalities on biochar surfaces (Kinney et al. 2012), but pyrolysis temperatures between 400 and 500 °C destroy these functionalities (Chen et al. 2008).

Hydrophobic biochar can turn hydrophilic soil into water-repellent (Mao et al. 2019). The study of Kinney et al. (2012) found that the use of biochar produced from Magnolia leaf pyrolyzed at 300 °C increased the soil water repellency, but when this biochar was pyrolyzed at 500 °C and applied in the same soil, it was wettable; this hydrophobicity, however, was not able to affect the soil field capacity. In addition, Mao et al. (2019) verified that the addition of 5% of hydrophobic biochar of wood sawdust and orange peel was enough to immediately increase the soil hydrophobicity in red soil (Ferralsol) and yellow soil (Regosol), but not in black soil (Phaeozems). This happens because, when the biochar surface is hydrophobic, it prevents water from infiltrating into the biochar particles, prohibiting its effect on soil water retention and potentially increasing the risk of soil erosion (Dekker and Ritsema 2000; Mao et al. 2019).

The biochar hydrophobicity is reduced significantly because of the interaction between biochar and water. As verified by Kinney et al. (2012), when biochar is exposed to water, the molecules containing alkyl functional groups rearrange into nearby pores, rendering the surface slightly less hydrophobic. Because of these effects, it is necessary to take into consideration its original hydrophobicity before its application to soil (Mao et al. 2019).

The improvement of the water-holding capacity in biochar cannot be associated with the specific surface area and pore volume, since a material with a large surface area does not imply that the whole area is available for adsorption. For example, factors such as feedstock type and hydrophobicity can change the surface of the pyrolyzed material, reducing specific sites for adsorption (de Jesus Duarte et al. 2019, Pulido-Novicio et al. 2001), as we verified in biochars of castor bean seeds, soybean seeds, and *Jatropha* sp. cake. Although most of them have a high specific surface area and pore volume, the water-holding capacity was reduced due to their hydrophobicity (Fig. 1).

The addition of biochar with low water holding capacity and high porosity to soils can increase the soil pore volume, contributing to improving their drainage. Nevertheless, the biochar water-holding capacity can increase over time. Consequently, the evaluated biochars, especially the one from soybean seeds that has a big specific surface area and pore volume compared to other biochars, can immediately improve the soil porosity, reducing its compaction. In addition, this biochar has the potential to increase the water-holding capacity and water available content through the reduction of its hydrophobicity over time (Kinney et al. 2012).

The biochar produced from elephant grass (*Pennisetum purpureum*), which is a macropore and a non-oleaginous raw material, has a high silicon content (86.3%) (Setiadji et al. 2019) and is no hydrophobic, which results in a large sorbent surface (Lehmann and Joseph 2009), and these macropores allow the biochar water uptake and when added on the soil, contribute to increasing the soil water holding capacity and plant water availability content (de Jesus Duarte et al. 2019), and the improvement of these soil physical and hydraulic properties may contribute to improving plant development and production.

3.3 Biochar Effects on Water Saving in Irrigation System

The selection of the most suitable biochar depends on the purpose of its application; if the farmer needs to improve the soil water holding capacity, the most suitable biochar would be the one produced from elephant grass. However, if the purpose is to increase the soil porosity, reduce the

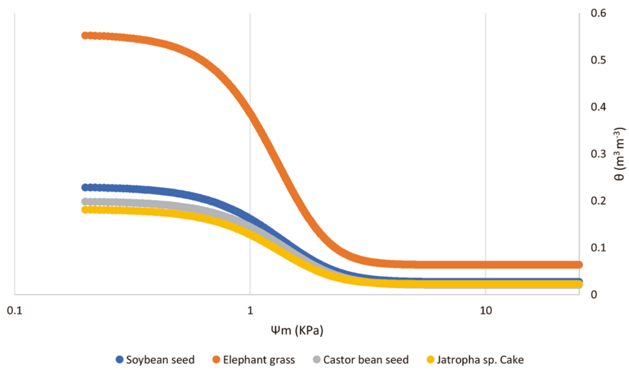

Fig. 2 Water holding capacity in biochars produced from elephant grass (*Pennisetum purpureum*), castor bean seeds, soybean seeds and Jatropha sp. cake

compaction, and increase the hydraulic conductivity, the application of the biochar produced from soybean seeds, castor bean seeds, or *Jatropha* sp. cake would be recommended. De Jesus Duarte et al. (2019) found the water volume at a field capacity of 0.17 $m^3\ m^{-3}$ in sandy soil when applied 25 Mg ha^{-1} of biochar Miscanthus Giganteus pyrolyzed at 450 °C; then, according to our results, the application of the same rate of biochar from elephant grass increased its field capacity to 0.56 $m^3\ m^{-3}$, and the application of this biochar will increase the volume of water in the sandy soil to 0.73 $m^3\ m^{-3}$ which is the sum between the water contributed by the biochar from elephant grass (0.56 $m^3\ m^{-3}$) and the water available in sandy soil in its field capacity (0.17 $m^3\ m^{-3}$).

The time reduced in the irrigation system when we applied the biochar elephant grass (*Pennisetum purpureum*) is 560 s or 9.3 min; this means that the biochar from elephant grass is contributing to safe 0,56 $m^3\ m^{-3}$ or 560 L of water and 9.3 min in the use of irrigation system. However, the contribution with water volume may decrease by 0.23, 0.18, and 0.20 $m^3\ m^{-3}$ upon the application of biochar from soybean seeds, *Jatropha* sp. cake, and castor bean seeds, respectively (Fig. 2).

In the drip irrigation system with tubes of inner diameter 20 mm and 60 m lateral length, including fixed cost, the farmer will spend US $3.261 per annual irrigation in 60 m lateral, quota 2250 m^3/hm^2, and flow rate = 2 L/h (Ame et al. 2022); bearing in mind one irrigation with a duration of 1 h every 3 days, the farmer will spend 18.49 m^3/hm^2 and US $26.80 in each irrigation of 60 m lateral. The application of biochar from elephant grass to the soil will contribute 0.56 m^3 of water reducing this cost by US $0.81 in each irrigation per line, which corresponds to one economy of US $98.54 per year, per 60 m lateral. Considering that this farm produces sugar cane with the drip irrigation system spaced 1 m per planting row and 1 ha has 166 lines with a row of 60 m lateral, the price will be reduced by US $16,357.64 per year per hectare; if this farm has 200 ha, the cost will be reduced by US $3,277,528 per year.

4 Conclusion

We verified that water uptake by biochar is dependent on feedstock selection which is related to pore volume, pore size distribution, and specific surface area. With increasing macropores and a reduction of hydrophobicity, an increase in water uptake in biochar was verified. This finding is partially in accordance with our first hypothesis, but water uptake is not related to the specific surface area in hydrophobic biochars.

The biochar from elephant grass promotes higher water uptake, and it was promising to increase the soil water holding capacity, whereas the biochar from castor bean seeds, soybean seeds, and *Jatropha* sp. has characteristics to increase soil porosity and reduce soil compaction. It was also proven that the higher the water uptake in biochar, the higher the contribution with soil water-holding capacity. This result is in accordance with our second hypothesis. These findings show the potential of elephant grass biochar to improve the soil water-holding capacity, save water, and reduce the costs of irrigation.

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Author Contribution De Jesus Duarte, S was responsible for writing the manuscript; Cerri CEP contributed to conducting the research and improvement of the manuscript; Rittl, TF performed the biochar analysis; Abbruzzin, TF contributed to the correction of the manuscript and improvement of the figures, and Prado Pano, B contributed with the correction of the manuscript.

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Data Availability The data required to reproduce the results of our work are available by reasonable request to Rittl, TF.

Declarations

Competing Interests The authors declare no competing interests.

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