Research Article

BIOCHAR DOSAGE AND GRANULOMETRY INFLUENCING SOIL DENSITY AND WATER RETENTION

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Abstract- This work aimed to analyze the effect of variation in biochar dosage and granulometry on water retention and soil density. Biochar doses (0, 5, 10 and 15 t ha⁻¹) and mean particle sizes (0.25, 0.75, 1.5 and 3.0 mm) were tested in a completely randomized design with three replications. The water retention capacity of soil-biochar blends was determined following saturation, after drainage was carried out for a determined time. Soil density, in turn, was determined by the volumetric ring method. The statistical procedures adopted were variance analysis by the F test and the adjustment of response surface models, followed by the generation of contour graphs. The lowest values of soil density and the highest values of water retention capacity were obtained with biochar dosage between 3.5 and 7 t ha⁻¹ and mean granulometry between 1.4 and 1.65 mm.

Keywords- biochar, pyrolysis, carbon sequestration, response surface

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Introduction

Recent achievements in agricultural production have been followed by degradation of soil and water resources and deterioration of ecosystems, as well as emission of gases that cause the greenhouse effect. According to FAO (2011) [1], the global degradation of these resources is caused by population pressure, climate change and competition for land and water. These factors cause increasing environmental and production problems, with economic, social and cultural repercussions, as well as losses in biomass production, biodiversity, carbon accumulation, soil quality and water availability. In semi-arid regions, dry farming presents low productivity due to low soil fertility, severe nutrient depletion, poor structure and management. To increase productivity, conserve soil and water, sequester carbon and reduce greenhouse gas emissions, sustainable production practices focused on carbon and nitrogen cycles should be carried out. Such practices include the addition of organic matter to the soil, accumulating carbon, increasing nutrient retention and water storage and retention and also reducing the need for fertilizers [1]. Carbon depletion in cultivated soils is due to the fact that only part of the plant remains returns to the soil, part of them is removed in the crops and the other part is lost in the periodic tillage when the residues are incorporated. However, the disruption of soil aggregates exposes the organic matter to decomposition, causes erosion and removes more carbon. Carbon storage in the soil can reduce the accumulation of atmospheric CO₂ and make the soil more productive, as organic matter feeds soil organisms that recycle plant nutrients. The dilemma is that organic matter is more biologically useful when it decomposes, so the search for C accumulation leads to opposing objectives: organic matter storage or its decomposition [2]. A solution would be adding to the soil an amount of C greater than that which is decomposed to achieve a balance between addition and decomposition in the long term, which is difficult today due to the demand for biomass. In recent years, the accumulation of

C in recalcitrant forms has also been a solution, as it protects carbon from soil biological activity. Recalcitrance is a peculiarity of biochar, which resists decomposition and remains in the soil for centuries. It is a carbon-rich substance obtained through pyrolysis, in which the biomass is heated under a limited supply of oxygen. The application of biochar aims to improve chemical, physical and biological properties of the soil and to sequester carbon [3-5]. Biochar is more resistant to soil microbial degradation than other organic compounds [6], it has physical properties such as high porosity [7], which assists in water retention and it has a particulate nature combined with a specific chemical structure [8]. An important aspect of biochar as a soil conditioner is the use of organic waste from industry or agriculture, unsuitable for industrial or domestic use, in which inadequate disposal can lead to environmental problems. Examples are solid urban organic waste (tree branches, sewage sludge), agricultural waste (crop residues, bark, sugarcane bagasse and straw), industrial waste (from the wood, paper and pulp industry), or materials of animal origin (bones, manure) [5, 9]. The direct effects of biochar application on crop productivity are due to the fact that it causes higher water retention in the soil, as it changes soil texture, structure, porosity, pore size and density, which influence aeration, retention and availability of water and nutrients, plant development and facilitate soil tillage. Besides that, biochar application reduces soil acidity and increases the retention of nutrients, especially potassium [10-12]. In view of the climatic changes, the potential of biochar to retain soil water ought to be highlighted, as the soil's water retention defines the amount of it in the soil and how long it will be available for plant uptake. The improvement in aggregation, infiltration and retention of water, attributed to biochar, especially in sandy soils, reduces irrigation frequency, quantity and costs. Such reduction is important in semi-arid regions, where water stress makes irrigation necessary to meet plant demands [10, 11, 13]. This work aimed to determine, through response surface

methodology, the dosage and granulometry of biochar, which optimize its effect on density and water retention capacity of a sandy soil.

Materials and Methods

The location of study was the Agricultural Sciences Unit of the Federal University of Rio Grande do Norte, in Macaíba, Brazil, under the geographical coordinates 5°53'11"S and 35°21'49" W. The rainy tropical climate is a transition between Köppen As and BSh, with high temperatures throughout the year, rainfall in autumn and winter, dry summer, annual average precipitation of 1070 mm, 27.1° C of temperature and 76% of relative humidity. The soil, collected in the 0-20 cm depth layer, had the following characteristics: particle density = 2.43 g cm⁻³; sand = 904g kg⁻¹; silt = 71g kg⁻¹; clay = 25 g kg⁻¹; pH = 5.80, organic matter = 1.00%; N = 0.18 g kg⁻¹; P = 19.40 mg dm⁻³; K = 89.70 mg dm⁻³; Na = 7.80 mg dm⁻³; Ca = 1.50 cmol_c dm⁻³; Mg = 0.80 cmol_c dm⁻³; CTC = 4.37cmol_c dm⁻³. The biochar was produced by charring branches of cashew trees from Mossoro, Brazil. Mean humidity was 5.43% and immediate chemical analysis showed 21% volatile materials, 16%ash and 63% fixed carbon. The experiment was carried out with a completely randomized factorial design with three replications. The factors studied were biochar dose (0, 5, 10 and 15 t ha⁻¹ or 0, 0.14, 0.28, 0.42%, mass basis) combined with four mean particle sizes (0.25, 0, 75, 1.50 and 3.00 mm). Polyethylene pots of 7.5 L were filled with the mixtures of soil and biochar up to 20 cm. The pots had a drainage hole at the bottom which had a polypropylene non-woven coating. The final volume in the pots was 6 liters of soil, 9.0 kg final mass and 1.5 g cm⁻³ density. Soil water retention was determined after the pots were left for saturation for 24 hours within a vessel in which water was added to 2/3 of pot height. After that, they were covered with canvas to prevent evaporation and placed to drain freely, having their masses measured after 24 hours, the same way as in Kammann et al. (2011) [14]. Pot weighing was repeated on 08.01, 08.15 and 08.19.2013. The volumetric water content of soil was expressed in cm³ cm⁻³. Soil density (g cm⁻³) was determined by the volumetric ring method, in which undisturbed soil samples were collected with 100 cm³ steel rings using an Uhland sampler. The soil contained in the rings was dried in a forced air oven at 105° C for 24 hours. Mean values of water retention data and soil bulk density were analyzed using the F-test at 5% significance. For these variables, response surface was adjusted in the model: $Y = a_0 + a_1x + a_2y + a_3x^2 + a_4xy + a_5y^2$, where: Y = dependent variable; a₀ to a₅ = regression coefficients; x = mean biochar granulometry and y = biochar dosage. Contour graphs were generated from this model and biochar dosage was displayed in values divided by 10, for better viewing. The response surface models were chosen based on significance of regression coefficients tested with the F-test, on significance of coefficients tested with Student's t-test at 5% of probability and on the coefficient of determination (R²).

Results and Discussion

Biochar dosage and granulometry had a significant effect on soil density and water retention [Table-1]. This is confirmed by Downie (2011) [15], that mentions significant changes in soil physical properties by biochar, modifying characteristics such as texture, structure, porosity, pore diameter, particle size distribution and density. Such is also confirmed by Peake et al. (2014) [16], that obtained a significant effect of biochar doses (4, 20 and 100 t ha⁻¹) on density, field capacity and available water in eight soils of different textural classes. They observed that medium doses (20 t ha⁻¹) and high doses (100 t ha⁻¹) of biochar increased soil water retention up to 22% and decreased density down to 15%.

Table-1 Summary of variance analysis of water retention capacity and soil density under different doses of biochar of different granulometry

Causes of variation	(Degrees of freedom)	Soil density (g cm ⁻³)	Water retention capacity (cm ³ cm ⁻³)
		Mean squares	
Dosage (D)	3	0.0035**	0.0008**
Granulometry (G)	4	0.0012*	0.0004*
D x G	5	0.0007 ^{ns}	0.0002 ^{ns}
Residue	26	0.0004	0.0001
Total	38	-	-
Mean value	-	1.60	0.24
CV (%)	-	1.21	4.23

**Significant at 1% probability; *significant at 5 %; ^{ns}non-significant.

The retention of water by biochar, similarly to organic fertilizers, is a key effect on crop growth and productivity [13]. The benefit depends on dosage and there may be a linear increase in soil available water. Biochar's Porosity and Large Specific Surface promote An Increase in Water Retention Capacity, Especially in Sandy Soils, Like the One Used in This study. The Smaller Pores Retain The Water, Which Infiltrates The Larger Pores And Becomes More Available To Plants At Tensions Close To the Permanent Wilting Point.

Biochar granulometry influences its action, mobility and fate in soil [12];thus, it is important to select its dose and granulometry according to the water retention properties of the soil, in order to obtain the highest water retention without biochar leaching. The influence of biochar particle size distribution on soil properties can be short-lived, due to the rapid split of biochar into very small particles [17]. With regard to crop productivity, no evidence of individual effect of biochar granulometry was found in a range of 2 to 20 mm [10].

The model obtained for soil water retention [Eq-1] showed a coefficient of determination of 0.53.

$$WRC = 0.2473 + 0.0292x - 0.004y - 0.0072x^2 - 0.0008xy + 0.0002y^2 \quad [Eq-1]$$

Where:

WRC–water retention capacity

x –mean biochar granulometry

y –biochar dosage

The response surface which expresses the combined effects of biochar dosage and granulometry on soil water retention [Fig-1] indicates that the highest water retention (0.28 cm³cm⁻³) was obtained with granulometry between 1.4 and 1.65 mm and doses between 3.5 and 6 t ha⁻¹. However, doses between 3.0 and 7.0 t ha⁻¹ and granulometries between 1.3 and 1.8 mm also provide water retention close to the maximum obtained. The lowest retention (0.23 cm³cm⁻³) was obtained with doses between 8.0 and 15 t ha⁻¹ and with granulometry values greater than 2.2 mm. Nevertheless, the figure shows an area of low retention in the same range of granulometry that provides maximum retention, but at doses above 8 t ha⁻¹. In general, doses above 8 t ha⁻¹ and particle sizes larger than 2.5 mm resulted in lower water retention.

Fig-1 Response surface in two dimensions of soil water retention as a function of mean granulometry (mm) and biochar dose (t ha⁻¹ divided by ten).

The same doses of biochar tested in this work were tested by Dugan et al. (2010) [18] in three soils. With respect to control, doses of 5, 10 and 15 t ha⁻¹ caused an increase in water retention, more pronounced in sandy soil, with no difference between them. The authors considered the dose of 5 t ha⁻¹ as optimal and discussed that hydrophobic biochar substances may have caused water repellency at doses greater than 5 t ha⁻¹ and/or the addition of larger doses of biochar may have impaired soil structure.

The optimal dose of biochar for agricultural soils is between 1 and 5%, mass basis, or 13.5 T Ha⁻¹, Based On Incorporation Depth [19]. However, Uzoma et al. (2011) [20] obtained, in sandy soil, increases of 6, 139 and 91% compared to the

zero dose in water efficiency for corn plants, with doses of 10, 15 and 20 t ha⁻¹ of biochar, respectively, that is to say, greater effects at doses higher than the ones tested in this study. Barnes et al. (2014) [21] observed, in sandy soil, a twofold increase in water content at field capacity, whereas the increase was 20% in clay soil. The differences in results among several studies are explained by variations in soil type and production conditions of biochar. Such is confirmed by Streubel et al. (2011) [13] that obtained, in medium textured soil, a 13.7% increase in water retention at a pressure of 0.1 MPa with a dose of 39 t ha⁻¹. On the other hand, Kammann et al. (2011) [14] obtained, in sandy soil, water retention of 0.223, 0.276 and 0.304 g g⁻¹, at doses of 0, 100 and 200 t ha⁻¹, respectively.

The evidence of increased water retention in sandy soil after application of biochar was pointed out by Brock off et al. (2010) [22], based on water retention curves. For water potentials smaller than -2.5 kPa, water retention increased with a bigger amount of biochar in soil. With regard to control, the authors observed an increase of 170% in water retention capacity with 10% of biochar, whereas 25% of biochar promoted a 370% increase.

On average, the amount of pyrogenic carbon in black Amazonian soil amounts to 16 t ha⁻¹ of biochar, according to Carvalho et al. (2014) [23], that tested doses of 0, 8, 16 and 32 t ha⁻¹ of biochar in the field and observed, 2 and 3 years later, a positive effect on water retention in sandy loam soil. During that period, the increase in plant available water was linear, around 0.8% for each t ha⁻¹ of biochar applied, or 11% with the dose of 16 t ha⁻¹.

Besides dosage, Carvalho et al. (2014) [23] emphasize the individual influence of specific surface and biochar particle size on water retention capacity in sandy soil. The maximum dose applied by them Was 32 T Ha⁻¹, Half The Minimum Dose Used In Other Studies Reviewed By Them In Which Excellent Results Were Obtained With Doses As High As 3 And 6%, Whose Feasibility And Practicality Of Application In Fields Is Questioned.

With respect to the effects of water stress, Carvalho et al. (2014) [23] commented that the 32% increase in available water obtained with the addition of 32 t ha⁻¹ of biochar is equivalent to 18 mm of water in the 5-10 cm layer of sandy soil. That is water enough to meet crop demand for additional 4 days without rain, under normal evapotranspiration conditions during the critical stage of upland rice production in Brazilian Cerrado.

With the same concern on water stress, Pereira et al. (2012) [24] determined the effects of eucalyptus biochar on upland rice transpiration rate. The increase in biochar dosage (0, 6, 12 and 24%) linearly increased available water in sandy soil. In addition, there was a change in plant response at permanent wilting point; the change in soil moisture threshold slowed the point at which perspiration decreases and affects productivity. The maximum biochar concentration with a positive effect was 12%.

While the increase in water retention capacity due to biochar dose is predictable, the same does not apply to the effect of biochar granulometry, whose initial particle size distribution is influenced by the nature of biomass and pyrolysis conditions. The distribution and size of biochar particles, its mechanical resistance and the interaction of its particles in soil are factors that determine different results for different combinations of soil, climate and management. Considering that the physical and chemical Activity of Biochar Particles Depend directly on their size and shape, Souza et al. (2011) [25] suggest that the grinding process should be directed to the obtainment of biochar granulometric fractions that are more suitable for a given purpose.

In the same way as soil analysis that are carried out with 2 mm sieved samples, most biochar experiments use particles smaller than 2 mm diameter without specifying a minimum size. This range of biochar particle sizes, according to Ulyett et al. (2014) [26], facilitates further analysis because it allows the biochar and soil mixture to pass through a 2 mm-mesh sieve without the need for grinding. However, biochar has its final destination in the form of particles of similar or smaller size than silt and such decrease is relatively fast, due to physical weathering and abrasion (Sohi et al., 2010) [17].

The classification of biochar particles in diameter classes similar to sand, silt and clay fractions of soil was idealized by Souza et al. (2011) [25]. This particle size distribution is random and it is due to mechanical impacts to obtain particles with a diameter smaller than 2 mm. In this regard, the particle size distribution of biochar

obtained from caja wood has been described as sandy loam. The fractions of this type of biochar showed water retention capacities superior to the corresponding fractions of soil and the fractions of smaller size made available to the plants 100 to 160% of their weight in water. The effect of biochar particle size on hydraulic conductivity of soil was studied by Liu et al. (2013) [27]. The application of a 2% dose of biochar with particles smaller than sand promoted a decrease of 67%, whereas with particles larger than sand the decrease was 15%. Biochar particles similar to sand did not affect hydraulic conductivity. The bigger effect of smaller particles is due to the fact that saturation is partial and that the shape and smaller size of particles reduce the space for water flow, decrease pore size and increase tortuosity. On the other hand, smaller particles, whose size distribution is not uniform, only decrease pore size.

The smaller particles, resulting from the biochar disintegration, are likely to cement the soil and clog the pores, increasing surface runoff, decreasing water infiltration rate and canceling the gain in soil water retention (Verheijen et al., 2010) [11]. Depending on biochar and soil granulometry and on the proportion of biochar that can occupy soil pores, high doses may affect water retention capacity of soil and water-containing pore space [28]. To prevent pore obstruction of soil by the finer particles, Ulyett et al. (2014) [26] suggest sieving the mass of biochar to obtain particles between 1 and 2 mm.

With regard to soil density, the model obtained [Eq-2] also presented a coefficient of determination of 0.53.

$$SD = 1.6195 - 0.01x - 0.008y + 0.0006x^2 + 0.0008xy + 0.0005y^2 \quad [\text{Eq-2}]$$

Where

SD—soil density

x—mean biochar granulometry

y—biochar dosage

[Fig-2], similarly to the previous one, indicates that the lowest density (1.54 to 1.55 g cm⁻³) was obtained with granulometry between 1.4 and 1.65 mm and biochar dosage between 3.5 and 6 t ha⁻¹. Furthermore, it can be stated that the use of dosage between 2.5 and 6.5 t ha⁻¹ and particle sizes between 1.3 and 1.8 mm would have lead to densities close to the lower ones. The highest density (1.64 to 1.65 g cm⁻³) was obtained with a dose above 14 t ha⁻¹ and granulometry between 0.6 and 0.9 mm. In general, the highest densities occurred with doses above 10 t ha⁻¹ and particle sizes smaller than 0.8 mm.

Fig-2 Response surface in two dimensions of soil density as a function of mean granulometry (mm) and biochar dosage (t ha⁻¹ divided by ten).

The physical beneficial effects of the application of biochar to soil are on its density, water retention and aggregation. However, depending on the size of biochar particles compared to soil, high doses of biochar may increase soil density. The decrease in soil density after the application of biochar may be due to the direct effect of the lower density of biochar compared to the density of mineral soils. Biochar has an inherently low density (0.3 to 0.5 Mg m⁻³), which is one-third to one-fifth of the density of an arable soil [26, 28].

The estimation of the density of soil and biochar mixtures is demonstrated by Ouyang et al. (2013) [29], that, starting from a dose of 2% biochar, mass basis,

with density of 0.35 g cm^{-3} and densities of 1.40 g cm^{-3} and 1.20 g cm^{-3} of sandy loam and silty clay, obtained densities of 1.32 and 1.15 g cm^{-3} , respectively. However, this estimate is not accurate, because, according to Rogovska et al. (2011) [30], soil density does not linearly respond to the amount of biochar applied, since the greater stability of soil aggregates promoted by biochar further benefits density. In this way, Ouyang et al. (2013) [29] state that biochar promotes the formation of soil aggregates - mainly macro aggregates - and decreases soil density. The combined effects of the application of biochar on soil density and water retention are mentioned by some authors. Pereira et al. (2012) [24] observed that the increase in volumetric water content at higher tensions at the retention curve and the decrease in soil density (1.52 , 1.31 , 1.17 and 0.85 g cm^{-3}) in function of biochar dosage (0 , 6 , 12 and 24%) was beneficial to upland rice. On the other hand, the highest dose of wheat straw biochar (0 , 0.5 , 1 and 2.5% , mass basis), tested by Albuquerque et al. (2013) [31], caused an increase from 14.0 to 15.8% in field capacity of soil and a decrease from 1.56 to 1.49 g cm^{-3} in soil density.

A quadratic effect of biochar dose on soil density in the $15\text{-}20 \text{ cm}$ layer was observed by Carvalho et al. (2014) [23]. The maximum density of 1.68 kg cm^{-3} was obtained with 16 t ha^{-1} of biochar, which also provided the maximum macro porosity ($0.23 \text{ cm}^3 \text{ cm}^{-3}$) with the minimum value with the dose of 32 t ha^{-1} ($0.17 \text{ cm}^3 \text{ cm}^{-3}$). Soil macro porosity in the most superficial layer increased linearly by 1.6% for each t ha^{-1} of biochar. The considerable increase in soil macro porosity (51%) with the dose of 32 t ha^{-1} , mass basis, was mainly related to the large particle size (2 mm) of biochar.

Among the studies reporting effects of the application of biochar on soil bulk density, Ulyett et al. (2014) obtained a decrease of 6.3% in the density of an organically managed soil and of 5.8% in a soil under conventional management with a biochar dose of 60 t ha^{-1} , whereas Rogovska et al (2011) [30] tested doses of 0 , 5 , 10 and 20 g kg^{-1} of soil in columns. At the end of 500 days, the soil density of the columns receiving biochar was, on average, 7% lower than the density in the control columns. In sandy soil under lawn, the decrease in density observed by Brock off et al. (2010) [22] was from 1.75 to 1.57 g cm^{-3} with the increase in biochar dose from 0 to 25% .

In A Study by Barnes et al., (2014) [21], The Application of A 10% Biochar Dose Decreased density by 17% In Sandy Soil And By 20% In Clay Soil. However, the density inorganic soil increased 10% , despite the lower density of biochar (0.37 g cm^{-3} biochar density versus 0.44 g cm^{-3} organic soil density). This was due to the smaller size of biochar particles compared to soil and due to particle arrangement during the filling of columns.

The addition of biochar to soil can be beneficial because it increases water retention and reduces plant water stress, favoring the stable productivity during dry seasons. The higher soil water retention after the addition of biochar is probably due to the porous nature of it, which promotes an increase in total soil porosity. Furthermore, its specific surface and particle size directly affect water retention, soil structure and porosity by altering the total surface area of soil particles, pore size distribution and soil density [23,29]. These changes in soil properties are important in field conditions, where water availability and soil density advantage germination, plant growth and productivity [31].

The benefit of the application of biochar to sandy soils is well established. In this type of soil, Brock off et al. (2010) [22] observed an increase in irrigation frequency and a decrease in total water use on grass, due to the greater water retention in the root zone. In addition, Uzoma et al. (2011) [20] observed that the application of biochar favored corn crop and also the physicochemical properties of this type of soil. As sandy soils have larger particles than biochar does, its addition reduces hydraulic conductivity and increases water retention capacity and its availability to plants, allowing a decrease in crop water stress and in nutrient losses by leaching [21].

According to Peake et al. (2014) [16], the potential impact of the application of biochar on crop productivity or on irrigation needs endows biochar with a

monetary value. With regard to soil density, the quantification of the decrease in compaction when considering biochar doses can be translated into saved fuel, due to the lower resistance of soil to tillage tools. Based on such information on different types of soil and other soil properties, one could model the application of biochar to estimate the optimal dose or perform cost-benefit analysis. It would be possible to recommend to farmers the suitable biochar dosage to be applied to a particular type of soil in order to obtain a particular benefit, be it increase in productivity, reduction in irrigation or in fuel consumption.

Conclusions

The lowest values of soil density and the highest values of water retention capacity were obtained with biochar doses between 3.5 and 7 t ha^{-1} and granulometry between 1.4 and 1.65 mm .

Abbreviations

Neyton de Oliveira Miranda: Miranda, N. O.
Alexandre Santos Pimenta: PIMENTA, A. S.
Gualter Guenther Costa da Silva: SILVA, G. G. C. da
Mary Anne Barbosa de Carvalho: Carvalho, M. A. B. de
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Conflict of Interest: None declared

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