Water Air Soil Pollut (2021) 232: 338
https://doi.org/10.1007/s11270-021-05289-8

Chemical and Physical Changes of Soil Amended with Biochar

Jacqueline Da Silva Mendes · Josely Dantas Fernandes · Lúcia Helena Garófalo Chaves · Hugo Orlando Carvallo Guerra · Gilvanise Alves Tito · Iêde de Brito Chaves

Received: 5 April 2021 / Accepted: 30 July 2021 / Published online: 12 August 2021

Abstract The transformation of poultry litter waste through the pyrolysis process produces a product called biochar which, applied to the soil, improves its characteristics. The objective of this work was to evaluate the effect of biochar produced from poultry litter wastes, submitted to pyrolysis at 350 °C on soil chemical and physical characteristics. For this, an experiment was carried out involving soil incubation treatments during 100 days with six doses of biochar equivalent to 0.0, 2.02, 4.05, 6.07, 8.10, and 10.12 t ha^{-1}, calculated by the base saturation method, with correction levels from 61 to 87%. After the incubation, soil samples were physically and chemically analyzed. Biochar doses promoted significant increase in pH, electrical conductivity, potassium, sodium, carbon, phosphorus, and base saturation, and decrease in potential acidity and in the soil cation exchange capacity contributing to the increase of soil fertility. The application of the biochar to the soil decreased the bulk density and increased porosity, field capacity, wilting point, and available water for plants. In general, the use of the biochar demonstrates great potential of it as a soil amendment.

Keywords Agricultural residues · Poultry litter biochar · Physical and chemical properties

J. Da Silva Mendes · J. D. Fernandes · L. H. G. Chaves (✉) · H. O. C. Guerra · G. A. Tito · I. de Brito Chaves
Universidade Federal de Campina Grande, Campina Grande, Brazil
e-mail: lhgarofalo@hotmail.com

J. Da Silva Mendes
e-mail: jacquelinemendes@gmail.com

J. D. Fernandes
e-mail: joselysolo@yahoo.com.br

H. O. C. Guerra
e-mail: hugo_carvallo@hotmail.com

G. A. Tito
e-mail: gilvanisetito@yahoo.com.br

I. de Brito Chaves
e-mail: iedebchaves@hotmail.com

1 Introduction

Biochar is any source of biomass previously heated under low or no oxygen supply, with the purpose of applying to soil in order to improve its agronomic and environmental quality. The process of biochar production is known as pyrolysis and it results in a very stable carbon-rich material not only capable of improving physical and chemical soil properties, and therefore soil productivity, but also of increasing soil carbon storage on a large scale (Kookana et al., 2011; Sohi et al., 2010) and for a long period of time.

Basic and applied research on the application of biochar in the areas of agriculture, environment, and energy in the whole word have increased dramatically in the face of food security, environmental pollution, and energy shortage. Although there are some disputes about biochar research, many scientific evidence indicates that biochar improves soil biodiversity, enhances soil performance, reduces its susceptibility to weathering, and reduces the need for fertilizer inputs, contribution to the improvement of soil quality, and consequent crop productivity (Glaser et al., 2002; Jeffery et al., 2011; Lehmann et al., 2006).

Forest, crop, and animal residues left in the field can be used to produce biochar that can be applied to agricultural soils, to both sequester carbon and improve crop production. The biochar obtained from plant materials are often low in nutrient content, particularly N, compared with other organic fertilizers (Chan et al., 2007; Lehmann et al., 2003). According to Chan et al. (2007), the application of green waste biochar up to 100 t ha^{-1} did not produce a positive plant response due to the low N availability of the plant-derived biochar.

In Brazil, field experimentation with biochar started about 10 years ago. The first studies were focused on Amazonian lands. In this region, Steiner et al. (2007) described the effect of charcoal use alone and in combination with synthetic fertilizer and chicken manure. They concluded that the better result, in terms of yields (maize and upland rice), is the combination of charcoal with poultry manure.

In recent years, the chicken meat production of Brazil has grown 112% (Schmidt & Silva, 2018). According to the Brazilian Animal Protein Association (ABPA, 2020), in 2019, the Brazilian production of chicken meat was 13.245 million tons, keeping the country in the position of the world's largest exporter and the third largest producer of chicken meat, only behind the USA and China. Accompanying the growth of the national production, significant amounts of waste were generated, such as poultry litter, which is normally distributed on the floor of warehouses as a bed for birds used to protect them from weather and mechanical friction with the floor (Paganini, 2002).

This poultry litter is used as a soil fertilizer due to its high content of nitrogen, phosphorus, and calcium. When this material is applied directly to the soil without any previous treatment, it becomes a potential contaminant, capable of polluting agricultural soils with pathogens, antibiotics, pesticides, and heavy metals that can accumulate in the superficial layers of the soil and contaminate bodies of water becoming bioavailable and phytotoxic, compromising crop quality (Masuda et al., 2020; Souza et al., 2019). With the huge amount of chicken waste biomass, biochar comes as an obvious solution for urgent problems: a fast, inexpensive, and opportune way to dispose poultry litter, stock carbon, and improve soil quality.

Several authors cited by Mukherjee and Lal (2013) comment that all biochar do not have the same properties, since their characteristics are controlled by factors such as the type of raw material (pieces of wood, animal manure, crop residues, bedding of chicken), pyrolysis conditions (final pyrolysis temperature, heating rate—low versus fast pyrolysis) and duration of carbonization. Therefore, the effects of biochar, when applied to the soil, vary due to its properties, such as surface area, porosity, density, water retention capacity, and/or presence of chemical elements (macro- and micronutrients and heavy metals) and resistance to root penetration.

Chan et al. (2008) showed that biochar obtained from poultry litter had higher nutrient content (both N and P) than those produced from plant materials and that this biochar might have a great value as a slow-release organic fertilizer (N and P). Pereira et al. (2019) analyzed also its potential as a raw material for biochar. In Brazil, due to the large availability of poultry litter wastes, it has been used as a raw material for the manufacture of biochar however still in an experimental way. The effects on the soil require specific studies. Some national surveys have already been carried out using poultry litter biochar (Andrade et al., 2015; Chaves et al., 2018; Mendes et al., 2015a, 2015b; Perondi et al., 2017); however, the knowledge about the characterization of this input and its impact on the chemical and physical properties of the soil is still scarce.

Considering the technical aforementioned facts and the potential economic viability of the use of poultry litter biochar on agriculture, mainly because it represents a new option to use the excessive amount of residues generated in agricultural activities and the benefits that its application produces to plant production, it turns necessary to develop studies on the use of this biochar in agriculture as a fertilizer and a soil conditioner, which in the near future could be relevant to the farmers.

Thus, the present work aimed to evaluate the effect of different doses of poultry litter biochar on the chemical and physical attributes of the soil.

2 Materials and Methods

2.1 Soil and Biochar

The experiment, which consisted of submitting a soil to increasing doses of biochar, was carried out at the Irrigation and Salinity Laboratory (ISL) of the Agricultural Engineering Department, Federal University of Campina Grande, Paraiba, Brazil, using an Ultisol soil collected in the superficial layer (0–20 cm). Soil samples were air-dried, crushed, sieved through a 2-mm sieve, and characterized with respect to its chemical and physical characteristics according to Teixeira et al. (2017). The raw material used in this study for the production of the biochar used was poultry litter waste collected at the Paraiba State University experimental farm, located in the municipality of Lagoa Seca (07° 09′22.42’ S; 35° 52′ 09.64’’ W). This biochar was produced in the ISL laboratory submitting the poultry litter wastes to a slow pyrolysis at 350 °C for 3 h at a heating rate of 10 °C min^{-1} in a muffle. After pyrolysis, the biochar was grounded and passed through a 2-mm sieve to ensure that the biochar had a similar granular size in subsequent experiments.

2.2 Incubation Experiment

To evaluate the effect of biochar on the chemical properties of the soil, 1.0 kg of soil was placed in plastic bags (experimental units), mixed with biochar according to the treatments (0, 0.353, 0.706, 1.059, 1.412, and 1.765 g, corresponding to 0, 2.02, 4.05, 6.07, 8.10, and 10.12 t ha^{-1}, respectively) and incubated for 100 days. This mixture was maintained at 60% of the field capacity, adding deionized water. The doses of biochar used corresponded to twice the quantities needed to raise the soil base saturation around 0, 63, 69, 75, 81, and 87%, calculation based on the total relative capacity of neutralization of calcium carbonate (TRCN 100%). This was done because the TRCN for biochar is not known. The determination of the effect of biochar on the physical properties of the soil followed the same incubation methodology described previously, however now with 300 g of soil, higher biochar doses, and an incubation period of 60 days. The decrease of the soil samples, the reduction of the incubation period, and increase of biochar doses followed the suggestion of Chaves et al. (2018), aiming to facilitate the determinations of the soil physical characteristics properties. The calculation to determine the new doses was carried out aiming to raise the soil organic matter concentration in the arable layer (first 20 cm in depth) from 18.8 g kg^{-1} (control treatment) to 25.0, 31.2, 37.4, 43.6, and 49.8 g kg^{-1} which corresponded to an application of 12.39, 24.78, 37.17, 49.56, and 61.95 t ha^{-1}, respectively. Both incubation tests were set up using a completely randomized design with four replicates.

2.3 Soil and Biochar Analyses

Soil samples were analyzed with respect to chemical properties: soil pH determined by a ratio of soil to water of 1:2.5; soil organic carbon (SOC) by wet oxidation with dichromate potassium in sulfuric medium method; potassium (K), sodium (Na), and phosphorus (P) extracted with the Mehlich solution; calcium (Ca), magnesium (Mg), and extractable aluminum (Al) by the KCl 1 Mol L^{-1} method; potential acidity (H + Al) by the calcium acetate method at pH 7.0; bases sum (BS) (K + Na + Ca + Mg); cation exchange capacity (CEC) (BS + H + Al) and percentage of base saturation (V%) (S/CEC × 100). The physical attributes determined were particle size distribution, bulk and particle density, total porosity, permanent wilting point, field capacity, and available soil water content, according to the methods adopted by Teixeira et al. (2017).

Samples of biochar were analyzed according to Brasil (2014) for pH (determined by a ratio of biochar to $CaCl_2$ 0.01 mol L^{-1} of 1:2.5); EC (electric conductivity, dS m^{-1}); total N (Raney's alloy macro method); P_2O_5; K_2O; Ca; Mg; Zn; Cu; Mn; Fe (elements extracted with a mixture of nitric and perchloric acids); S (gravimetric method of barium sulfate); B (spectrophotometric method of azomethine-H.); moisture (measured at 65 °C); organic carbon (volumetric method with potassium dichromate); and C/N ratio (calculation). Phosphorus and potassium were quantified by the spectrophotometric method of molybdovanadophosphoric acid and by flame photometry, respectively; calcium, magnesium, zinc, copper, manganese, and iron were quantified using an atomic absorption spectrometric methodology.

The pore morphology of the biochar was visualized on images obtained by a SEM electron microscope (Hitachi TM-1000). The specific surface was obtained with the Brunauer–Emmett–Teller (BET) method. X-ray diffraction analyses were also conducted at room temperature with an XRD-7000 Shimadzu apparatus, using copper Kα radiation (1.5418 Å), 40 kV voltage, and 30 mA current. The bulk density was analyzed according to the methods adopted by Teixeira et al. (2017).

2.4 Statistical Analysis

The data was subjected to analysis of variance (F test) and to regression analysis, using the SISVAR statistical software (Ferreira, 2011). To meet the assumptions of normality and homogeneity of variances, the values of the variables potential acidity, sodium, potassium, and permanent wilting point were transformed into $1/\sqrt{x}$, $1/x$, $\sqrt{x}$ and $e^{\frac{x^{-2,5}-1}{-2,5}}$, respectively. To meet the assumptions of normality for the cation exchange capacity (CEC), base saturation (V%), and sand, silt, and clay concentrations, as well as the particle density, the Kruskal–Wallis non-parametric statistical test was applied.

3 Results and Discussions

3.1 Properties of the Soil and the Biochar

The studied soil presented the following chemical attributes: pH = 5.35; Ca = 2.78 $cmol_c\ kg^{-1}$; Mg = 1.26 $cmol_c\ kg^{-1}$; Na = 0.11 $cmol_c\ kg^{-1}$; K = 0.17 $cmol_c\ kg^{-1}$; H + Al = 3.27 $cmol_c\ kg^{-1}$; organic carbon = 18.8 g kg^{-1}; P = 1.27 mg kg^{-1}; and CEC = 7.56 $cmol_c\ kg^{-1}$.The soil had a medium acidity, medium concentration of organic carbon and exchangeable cations, medium cation exchange capacity (CEC), and percentage of base saturation (V%); the phosphorus concentration was low. The physical attributes: sand = 841.7 g kg^{-1}; silt = 83.6 g kg^{-1}; clay = 74.7 g kg^{-1}, bulk density = 1.38 g cm^{-3}; particle density = 2.70 g cm^{-3}; porosity = 48.88%; moisture content (dry weight basis) of wilting point (15 atm) = 4.66%; field capacity (0.33 atm) = 11.81%; and available water for plants = 8.96%. According to its particle size distribution, the soil was classified as a sandy loam.

The poultry litter biochar presented the following attributes: pH = 9.44; EC = 7.33 dS m^{-1}; N = 2.25%; P_2O_5 = 4.08%; K_2O = 4.35%; Ca = 5.04%;Mg = 1.28%; S = 0.41%; B = 0.01%; Zn = 0.05%; Cu = 0.01%; Mn = 0.05%; Fe = 0.72%; moisture = 4.52%; organic carbon = 42.22%; and C/N ratio = 18.76. This biochar has an extremely high pH and probably a high liming potential on acid soils; however, it can also alkalinize the soil due to the increase in pH in soils. These results are similar to those found by Chan et al. (2008) working also with biochar: pH 9.9; N = 2.0%; C = 38.00%; C/N = 19.76; and EC = 5.6 dS/m.

The scanning electron microscopy images of the poultry litter biochar surface (Fig. 1) show that there is relative pore uniformity at some points on the sample.

The BET method with N_2 adsorption showed that the biochar had average pore size of approximately 14.8 nm, characteristic of mesopores (2 to 50 nm), and a specific surface of 3.37 $m^2\ g^{-1}$. The X-ray diffraction (XRD) patterns of the poultry litter biochar (Fig. 2) were complex, showing wide peak patterns with some degree of order in short range indicating an amorphous material. Such characteristics made it difficult to attribute minor peaks to specific minerals, corroborating Clemente et al. (2018).

It is observed the strongest peaks at 2θ 28.346 A° (*d* = 3.146 Å) and 40.09A° (*d* = 2.225 Å) indicate the presence of inorganic components with the potassium element in their constitution, such as silvite (KCl, PDF 041–1476) and at 2θ 28.790 A° (d = 3.098 Å) for potassium aluminum silicate (KAlSiO4, PDF 050–0437). The presence of calcite ($CaCO_3$) evidences, as previously reported, the alkaline character of poultry litter biochar. Feldspar compounds [Ortoclasio ($KAlSi_3O_8$)] and potassium phosphate ($K_2(HPO_4)$) were also identified, confirming considerable concentration of P, K, Ca, and Mg.

3.2 Changes in the Soil Chemical Properties

After applying biochar to the soils and incubating for 100 days, the biochar doses significantly influenced the chemical properties of the soil, with the exception of calcium and magnesium contents (Table 1).

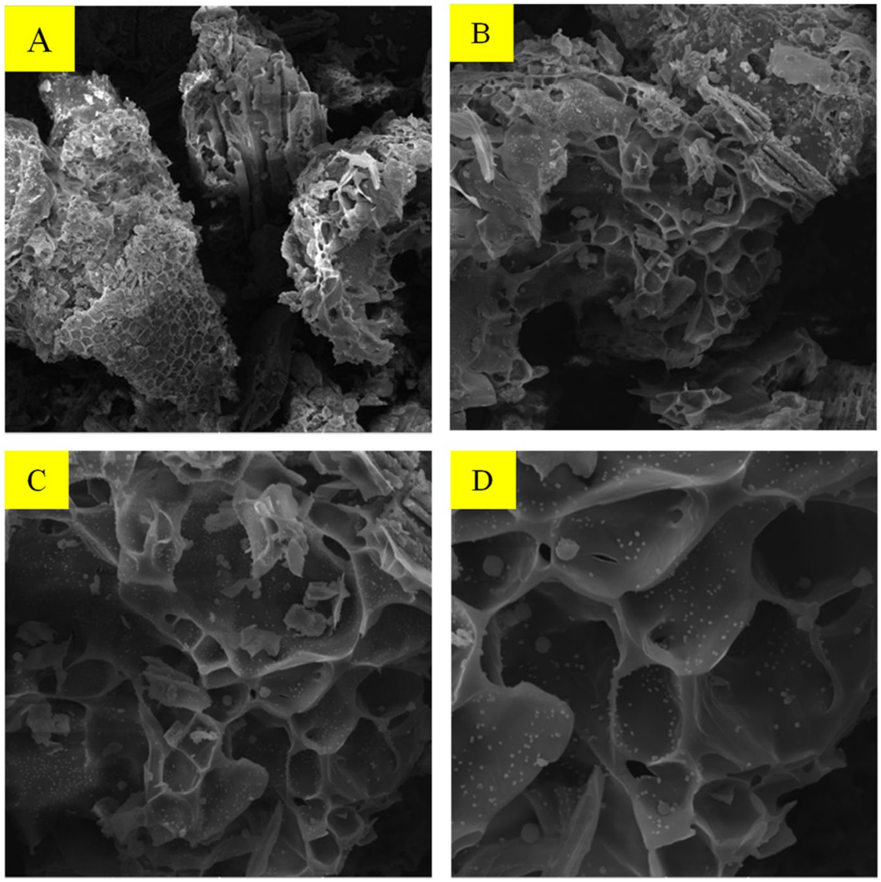

Fig. 1 Scanning electron microscopy of pyrolyzed poultry litter biochar at 350 °C. Magnified image × 250 (**a**), × 500 (**b**), × 1000 (**c**), and × 2000 (**d**)

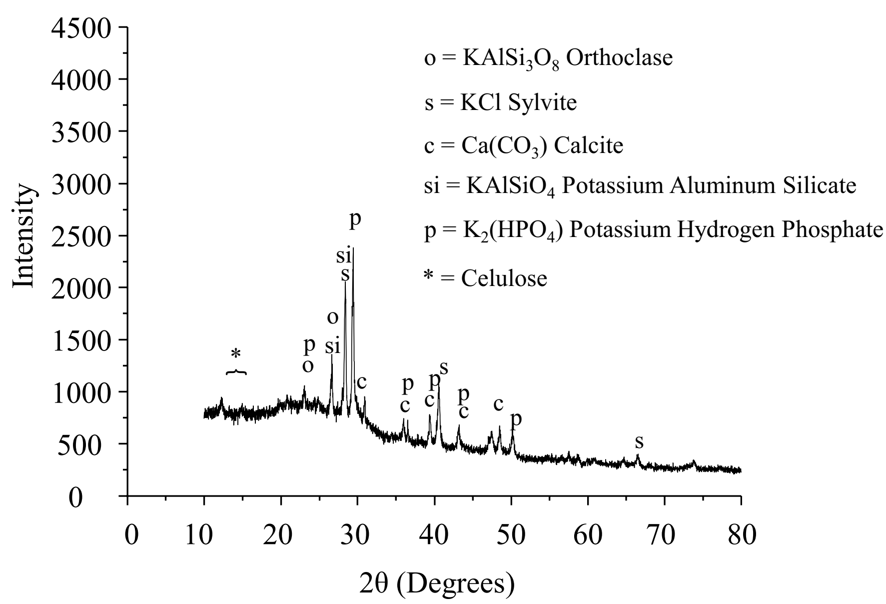

Fig. 2 X-ray diffraction pattern of poultry litter biochar

Table 1 Summary of analysis of variance for the pH, electrical conductivity (EC), calcium (Ca), magnesium (Mg), carbon (C), phosphorus (P), base sum (BS), potential acidity (H + Al), sodium (Na), and potassium (K), after incubation period

Source of variation	DF	Mean square									
		pH	EC	Ca	Mg	C	P	BS	H + Al[(1)]	Na[(2)]	K[(3)]
Biochar	5	0.18**	0.04*	0.10 ns	0.13 ns	12.57**	1899.82**	0.38**	0.119**	42.92**	0.0657**
Linear Reg	1	0.81**	0.164**	-	-	61.21**	8997.02**	0.92**	0.46**	194.13**	0.306**
Quadratic Reg	1	0.01 ns	0.009 ns	-	-	0.29 ns	133.64 ns	0.91**	$3e^{-4}$ ns	0.11 ns	0.002*
Deviation	3	0.03*	0.011 ns	-	-	0.45 ns	122.82 ns	0.02 ns	0.0426**	6.79**	0.006**
Error	18	0.01	0.01	0.06	0.05	1.63	145.14	0.05	0.002	0.70	4 e^{-4}
CV(%)		1.79	15.01	6.81	14.44	13.19	26.47	4.20	6.55	8.14	4.48
Mean		5.58	0.72	3.72	1.67	9.68	45.50	5.75	0.80	10.29	0.48

DF, degree of freedom.

*,**Significant ($0.05 \leq p$) and ($0.01 \leq p$) probability of error. *ns*, not significant.

[1,2,3] Transformed into $1/\sqrt{x}$, $1/x$, and $\sqrt{x}$, respectively; *Reg*, regression; *CV*, coefficient of variation

When applying the biochar, there was an increase in the soil pH from 5.35 (control) to 5.85 (higher dose) (Fig. 3A). Although an increase in the potential acidity (H + Al) of the soil was observed (Fig. 3C), when considering the untransformed data, there was a significant reduction of the potential acidity of 75.33% between the control treatment and the dose 10.12 t ha^{-1} of biochar. Aluminum was found only in the control treatment (absence of biochar) in a concentration of 0.11 $cmol_c$ dm^{-3}.

As also observed by Jien and Wang (2013), due to the liming potential of the biochar, the increasing application doses raised the soil pH, and consequently reduced significantly the potential acidity (H + Al). According to Sparks (2003), changes in soil pH occur when cations from biochar remove aluminum (Al) from the clay and/or organic matter exchange sites reacting it with soluble monomeric Al species. Depending on the biomass used in the preparation of the biochar, basic cations such as Ca, K, Mg, and Si can form alkaline oxides or carbonates during the pyrolysis process and, once released into the environment, react with monomeric H + Al, increasing the pH soil and decreasing exchangeable acidity (Novak et al., 2009). According to Lucchini et al. (2014), this increase in soil pH is probably associated with a greater availability of basic cations and the subsequent dissolution of hydroxides and carbonates. The higher the carbonate content of the biochar, the greater the liming effect of it (Chan et al., 2008).

The release of nutrients to the soil by the biochar application contributed to an increase of 40.8% in the electrical conductivity (EC) in relation to the control (Fig. 3B), corroborating Butnan et al. (2015). Silva et al. (2017) using rice silage, sorghum, and sawdust biochar observed electrical conductivity values of 121.8, 97.0, and 69.8 mS cm^{-1}, respectively, showing that the fertilizing capacity of the biochar depends on the nature of the biochar and on the concentration of nutrients present in its biomass.

The application of the highest dose of biochar promoted, when compared to the control treatment, an increase in the phosphorus content of the soil by 330% (Fig. 3D). This significant increase in the phosphorus content is probably due to the fact that the poultry litter biochar used in this research has the P concentration around 4.08% and having in its constitution potassium phosphate (K_2HPO_4).

Like phosphorus, doses of biochar significantly influenced the potassium content, with a maximum concentration of 0.43 $cmol_c$ dm^{-3} with the dose of 10.12 t ha^{-1} (Fig. 3E). The considerable increase in the potassium content is justified by the presence of compounds such as potassium chloride (KCl), potassium aluminosilicate ($KAlSiO_4$), and dibasic potassium phosphate (K_2HPO_4). Although a decrease for the sodium content of the soil was observed when plotting the transformed data (Fig. 3F), there was a significant increase of the sodium content at a rate of 0.0093 $cmol_c$ dm^{-3} for each ton of applied biochar.

Calcium and magnesium contents were not influenced by the biochar, whose means were 3.72 and 1.67 $cmol_c$ dm^{-3}, respectively. Although, probably they contribute, in some way, to the increase

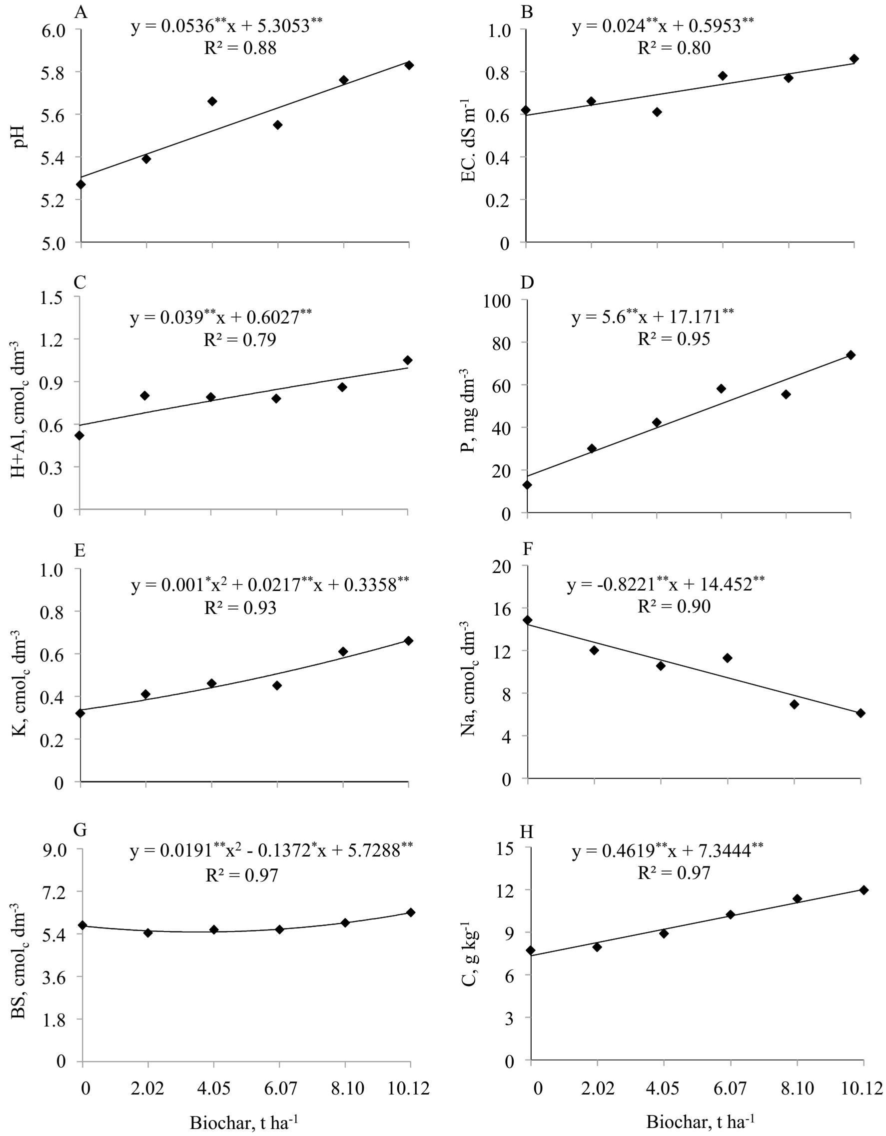

Fig. 3 Soil pH values, electrical conductivity (EC), potential acidity (H + Al), phosphorus (P), potassium (K), sodium (Na), base sum (BS), and carbon (C) in function of biochar doses. *,**Significant at $p \leq 0.05$ and 0.01, respectively, by *F* test

of bases. Other chemical constituents in the biochar itself could also supply exchangeable cations to the soil, according to Jien and Wang (2013).

The sum of bases fitted a second-order polynomial regression model (Fig. 3G). It had the lowest value (5.48 $cmol_c\ dm^{-3}$) with the use of 3.59 t ha^{-1} of biochar and the highest (6.29 $cmol_c\ dm^{-3}$) with the highest biochar dosage; this last corresponding to an increase of 10.07% when compared to the control treatment. In general, the increase of the sum of bases with the biochar doses may be attributed mainly to the potassium content of the biochar, being the sodium in second place.

The results obtained in this study also corroborate those of Major et al. (2010), who found an increase in pH, availability of phosphorus, and exchangeable cations, such as Na and K in the soil. As indicated previously, it is important to note that the increase in soil fertility due to the application of biochar depends on the biomass used in its preparation. For example, the chemical composition of poultry litter biochar used in this research, produced from biomass composed by sugarcane bagasse ("litter" in the sheds), poultry feces, and feed waste (around 3% of the total feed provided to birds, consisting of corn, soy, limestone, dicalcium phosphate, and supplement of amino acids, vitamins, and minerals) can increase if this biomass is reused in new batches of poultry production (Mendes et al., 2012).

Unlike Jien and Wang (2013), who did not observe a significant increase in soil organic carbon with the application of biochar, in this study with the application of poultry litter biochar there was increase in organic carbon (C) at a rate of 0.46 g kg^{-1} per t ha^{-1} (Fig. 3H), corroborating Fernandes et al. (2018). This result is important since organic carbon helps improve and maintain soil fertility in the long term. In addition, the increase in C also resulted in synergistic benefits, with an increase in the availability of mainly K, P, and Na for plants. Practical benefits of biochar in increasing C and maintaining soil fertility have been demonstrated in field conditions on tropical African soils in Zambia, where a 234% increase in corn yield has been achieved (Martinsen et al., 2014).

Chan et al. (2008) observed that the application of poultry litter biochar in an Alfisol significantly affected all the chemical parameters of the soil, similar to the results obtained in the present study, increasing the electrical conductivity, pH, total N, total C, phosphorus P, exchangeable cations (Ca, Mg, Na, and K), and effective cation exchange capacity and decreasing the exchangeable Al. The highest cation exchange capacity (CEC) was found with the control treatment (9.44 cmolc dm^{-3}) (Fig. 4A), mainly attributed to the high potential acidity (H + Al). With the application of 2.02 t ha^{-1}, the CEC of the soil decreased by 25.74% (7.01 cmolc dm^{-3}) due to the decrease in the potential acidity. The application of biochar doses higher than 4.05 t ha^{-1} increased the CEC of the soil, however with no significant differences among them.

The application of biochar to the soil increased the base saturation, observing increases of 33.58% and 43.28% with the two highest doses (8.09 and 10.12 t ha^{-1}, respectively), when compared with the control treatment (Fig. 4B), with no significant difference between them; however, these higher doses differed significantly with the saturation bases observed with the lower biochar dose, presenting the lowest value with the treatment without biochar (control).

Although, as previously indicated, the application of increasing doses of biochar decreased the potential acidity, kept the values of calcium and magnesium similar, and increased the values of potassium and sodium in the soil, the decrease in potential acidity was greater than the increase of the exchangeable bases in the soil. Thus, although the increase of the CEC with the biochar treatments was small, it suggests an improvement in soil fertility, increasing the number of exchangeable cations in the soil.

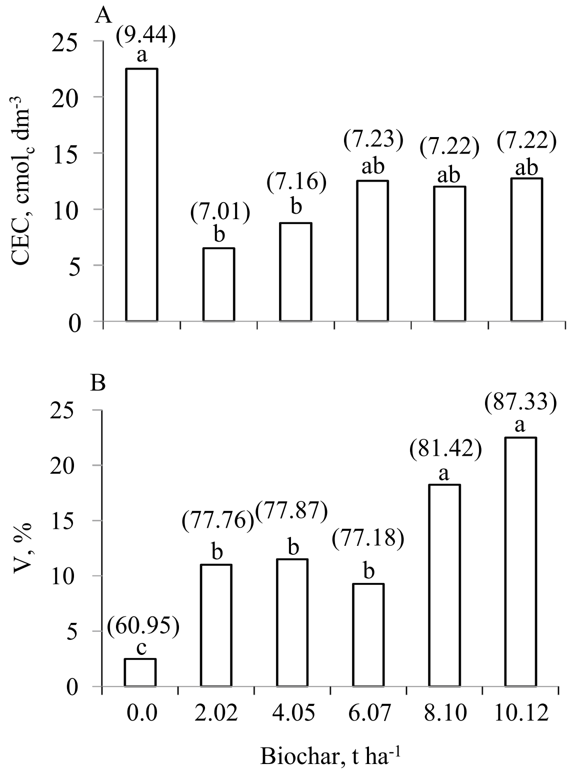

Fig. 4 Cation exchange capacity (CEC) and base saturation (V) depending on the application of biochar doses. Means followed by the same letter do not differ by the Kruskal–Wallis test at $p \leq 0.05$. Values in parentheses correspond to the observed means

3.3 Changes in Soil Physical Properties

All physical properties of the soil evaluated in this study were significantly influenced by the application of biochar (Table 2), similar to the results found by Chan et al. (2008) who highlight the potential benefits of biochar application in improving the physical properties of soils in Australia.

The soil incubated with the biochar showed a change in its soil density (Fig. 5A) with a significant reduction of 13.70%, when compared to the control treatment with the highest dose (61.95 t ha^{-1}). This

Table 2 Summary of analysis of variance of the bulk density (*BD*), porosity (*P*), field capacity (*FC*), available water for plants (*AWP*), and permanent wilting point (*PWP*)

Source of variation	DF	Mean square				
		BD	P	FC	AW	WP[1]
Biochar	5	0.0202**	27.85**	2.767**	1.256**	1e – 5**
Linear Reg	1	0.0996**	137.18**	13.68**	5.97**	4.4e – 5**
Quadratic Reg	1	$7e^{-4}$ ns	1.22 ns	$6e^{-4}$ ns	0.06 ns	$2e^{-6}$ ns
Deviation	3	$3e^{-4}$ ns	0.29 ns	0.052 ns	0.07 ns	$2e^{-6}$ ns
Error	18	$9.0e^{-4}$	1.16	0.168	0.143	$7.08e^{-7}$
CV(%)		2.40	2.03	3.19	4.90	0.21
Mean		1.29	53.19	12.85	7.72	0.39

DF, degree of freedom.

*,**Significant ($0.05 \leq p$) and ($0.01 \leq p$) probability of error. *ns*, not significant.

[1.] Transformed into $\frac{x^{-2,5}-1}{-2,5}$; *Reg*, regression; *CV*, coefficient of variation.

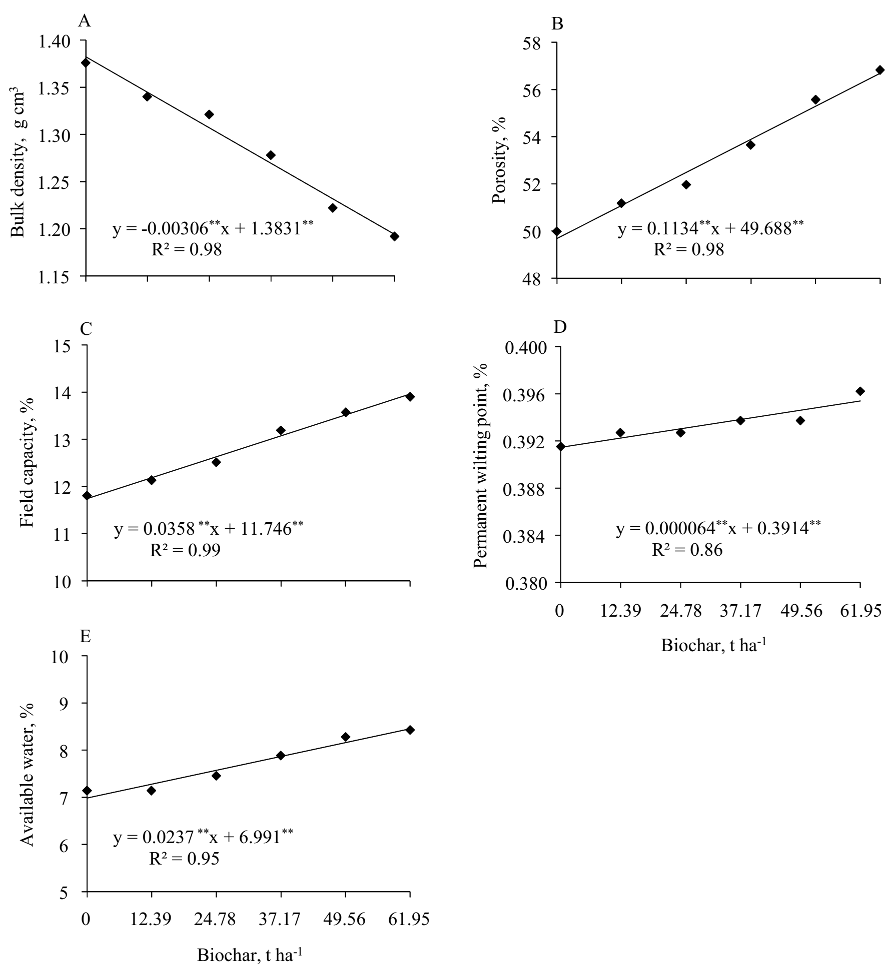

Fig. 5 Bulk density, porosity, field capacity, permanent wilt point, and available water in the soil after incubation period in function of biochar doses. *,**Significant at $p \leq 0.05$ and 0.01, respectively, by *F* test

reduction occurred when the soil was mixed with the biochar of lower density. The biochar used in the present study had density of 0.32 g cm^{-3} much lower than that of the sandy soil used in this work with a bulk density of 1.38 g cm^{-3}. According to Duarte et al. (2019) and Blanco-Canqui (2017), the reduction in the bulk density of sandy soils is more evident when compared to clayey soils due to the greater difference in porosity between sandy soils and the biochar. The results of the present research corroborate Jien and Wang (2013) and Omondi et al. (2016) who observed reductions of the soil density of 19.0% and 7.6%, respectively. A gradual decrease in bulk density with increasing doses of biochar was also observed by Liu et al. (2016).

Soil porosity, an important characteristic as it influences the density, water retention, water movement, and heat and gas exchange in the soil (Chaves et al., 2018), was influenced by the decrease in bulk density, increasing linearly at a rate of 0.1134% per t ha^{-1} of applied biochar. Comparing the control treatment with the highest dose, the increase of porosity was of 14.15% (Fig. 5B).

The increase in soil porosity when mixed with biochar is likewise related to the presence of mesoporous observed when the biochar morphology was analyzed by X-ray diffraction (XRD). The analyses showed that the biochar had an average pore size of approximately 14.8 nm, characteristic of mesopores, according to Rouquerol et al. (1999), who said that mesoporous materials are those with a diameter between 2 and 50 nm. The X-ray diffraction patterns of the biochar were complex, indicating an amorphous material. These morphological characteristics identify the biochar as a high porosity material.

The field capacity (FC), the permanent wilting point (PWP), and the available water for plants (AWP) of the soil increased linearly with the application of the biochar (Figs. 5C, 5D, and 5E, respectively). The increases in field capacity and permanent wilting point, with the highest dose of biochar, were 17.79% and 39.78%, respectively, when compared to the control treatment. The increase of FC and PWP resulted in a greater AWP, increasing at a rate of 0.1447% per t ha^{-1} of biochar, when compared to the control treatment. Apparently, biochar particle size affects soil water storage modifying the pore space between particles (interpores) and by adding smaller pores that are part of the biochar (intrapores). When biochar-sand mixtures are wetted, the elongated shape of the biochar particles disrupts the packing of grains in the sandy matrix, increasing the volume between grains (interpores) available for water storage. These results imply that biochar with a high intraporosity and irregular shapes will most effectively increase water storage in coarse soils. The increases of field capacity, permanent wilting point, and available water for plants when amended with biochar agree with the results found by Liu et al. (2017).

Liu et al. (2017) indicate that biochar's particle size, shape, and internal structure likely play also important roles in controlling soil water storage because they alter pore characteristics. Particle size may influence both intrapores and interpores through different processes because the size and connectivity of these particles likely differ. In addition, when applied in the field, biochar particles may have different sizes and shapes compared to soil particles. This addition of biochar grains with different shapes and sizes will change interpore characteristics (size, shape, connectivity, and volume) of soil and thus will affect water storage and mobility.

The reduction of the soil density and the increase of water retention with the biochar application observed were corroborated by Ulyett et al. (2014), who, working with sandy and clay soils, attributed this to the porous nature of the biochar. Atkinson et al. (2010) indicate the importance of the biochar porosity on the fluid transport, especially when they are used as adsorbent materials.

Analyzing the particle size distribution of the soil, it was observed that only the clay content was affected significantly by the increase of biochar, with a reduction of 37.35% when comparing the dose of 61.95 t ha^{-1} applied to the soil with the control treatment (Fig. 6A). The contents of silt and sand did not vary statistically with the biochar dose (Fig. 6B and 6C).

Analyzing Fig. 6D, it can be observed that the doses of biochar applied did not promote significant changes in the particle density of the soil, which may be due to the small amounts of biochar applied to the soil.

Although several researchers have observed increase in the available water content due to the application of biochar to the soil (Aslam et al., 2014; Laird et al., 2010; Liu et al., 2017), some experiments used high doses of biochar, such as, for example, 100

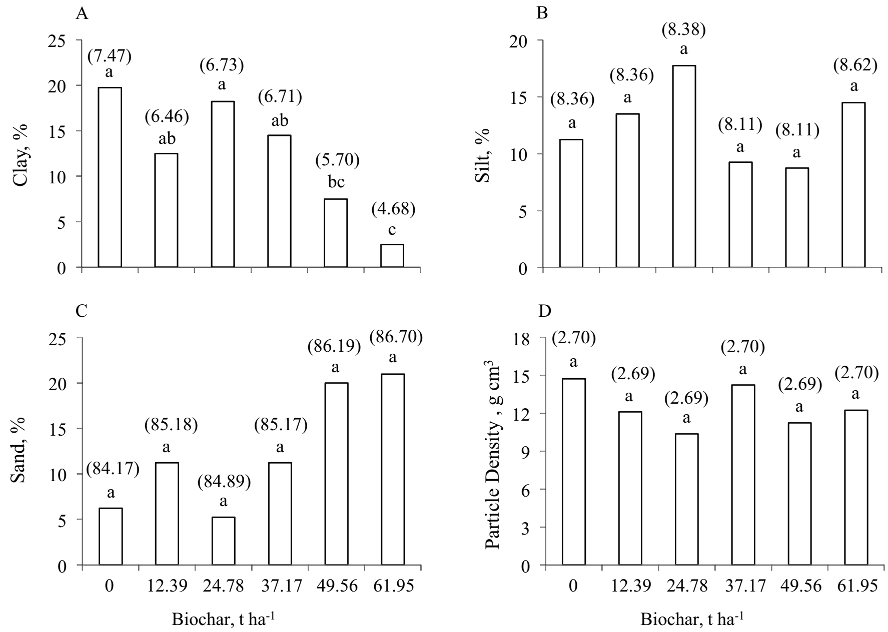

Fig. 6 Clay (**A**), silt (**B**), sand (**C**), and particle density of the soil (**D**) incubated with different doses of biochar. Means followed by the same letter do not differ by the Kruskal–Wallis test at $p \leq 0.05$. Values in parentheses correspond to the observed means

and 200 t ha^{-1} (Kammann et al., 2011) and 50 and 100 t ha^{-1} (Chan et al., 2007), which seems impractical, in quantitative terms, to the farmers (Herath et al., 2013). These latter authors commented that the increase in the water retention capacity in the soil depends on the texture and porosity of the soil, which is positively influenced, mainly in the case of sandy soils, by the application of biochar, with a high adsorptive nature. The increase in available water for plants, verified in this work by the biochar application, may result therefore in a better plant growth and productivity.

The great difference between the particle density of the biochar (1.10 g cm^{-3}) and that of the soil (2.73 g cm^{-3}) apparently in the biochar did not have a marked influence on the particle density of the mixture. This result does not corroborate Githinji (2014) who verified a gradual reduction in the density of the particles of a sandy clay soil, whose variation corresponded to 2.62, 2.43, 2.37, 2.09, and 1.60 g cm^{-3} with the application of biochar doses of 0, 25, 50, 75, and 100% by volume, respectively. Still, according to this author, the application of the highest dose of biochar reduced the density of particles by 64%.

4 Conclusions

The chemical properties of the soil were favored with the addition of biochar prepared from the a poultry litter, showing potential for use as an acidity corrective and as a source of nutrients such as P and K. The application of poultry litter biochar to the soil improved the physical properties of the soil, decreasing the bulk density and increasing porosity, field capacity, wilting point, and available water for plants, which may result in better plant growth and productivity. The poultry litter biochar demonstrates a great potential as a soil conditioner, improving soil quality.

Data Availability All data generated or analyzed during this study are included in this published article in the form of figures and tables.

Declarations

Competing Interest The authors declare no competing interests.

References

ABPA - Associação Brasileira de Proteína Animal. Relatório anual 2020. Disponível em: em: https://abpa-br.org/wpcontent/uploads/2020/05/abpa_relatorio_anual_2020_portugues_web.pdf >. Acesso em: 15 out. 2020.

Andrade, C. A., Bibar, M. P. S., Coscione, A. R., Pires, A. M. M., & Soares, Á. G. (2015). Mineralização e efeitos de biocarvão de cama de frango sobre a capacidade de troca catiônica do solo. *Pesquisa Agropecuária Brasileira, 50*, 407–416. https://doi.org/10.1590/S0100-204X2015000500008

Atkinson, C. J., Fitzgerald, J. D., & Hipps, N. A. (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: Review. *Plant and Soil, 337*, 1–18. https://doi.org/10.1007/s11104-010-0464-5

Aslam, Z., Khalid, M., & Aon, M. (2014). Impact of biochar on soil physical properties. *Scholarly Journal of Agricultural Science 4*, 280–284. http:// www.scholarly-journals.com/SJAS

Blanco-Canqui, H. (2017). Biochar and soil physical properties. *Soil Science Society of America Journal, 31*, 687–711. https://doi.org/10.2136/sssaj2017.01.0017

Brasil. Manual de métodos analíticos oficiais para fertilizantes minerais, orgânicos, organominerais e corretivos. 2014. Ministério da Agricultura, Pecuária e Abastecimento. Secretaria de Defesa Agropecuária. Coordenação de Apoio Laboratorial, Murilo Carlos Muniz Veras (Org.), MAPA/DAS/CGAL, Brasília.

Butnan, S., Deenik, J. L., Toomsan, B., Antal, M. J., & Vityakon, P. (2015). Biochar characteristics and application rates affecting corn growth and properties of soils contrasting in texture and mineralogy. *Geoderma, 237–238*, 105–116. https://doi.org/10.1016/j.geoderma.2014.08.010

Chan, K. Y., van Zwieten, L., Meszaros, I., Downie, A., & Joseph, S. (2007). Agronomic values of green waste biochar as a soil amendment. *Australian Journal of Soil Research, 45*, 629–634. https://doi.org/10.1071/SR07109

Chan, K. Y., van Zwieten, L., Meszaros, I., Downie, A., & Joseph, S. (2008). Using poultry litter biochars as soil amendments. *Australian Journal of Soil Research, 46*, 437–444. https://doi.org/10.1071/SR08036

Chaves, L. H. G., Lima, W. B., Chaves, I. B., Buriti, J. S., Fook, M. V. L., & Souza, J. W. L. (2018). Effect of poultry litter biochar on Ultisol physical properties. *African Journal of Agricultural, 13*, 412–418. https://doi.org/10.5897/AJAR2018.12991

Clemente, J. S., Beauchemin, S., Thibault, Y., Mackinnon, T., & Smith, D. (2018). Differentiating inorganics in biochars produced at commercial scale using principal component analysis. *ACS Omega, 3*, 6931–6944. https://doi.org/10.1021/acsomega.8b00523

Duarte, S. J., Glaser, B., Lima, R. P., & Cerri, C. E. P. (2019). Chemical, physical, and hydraulic properties as affected by one year of miscanthusbiochar interaction with sandy and loamy tropical soils. *Soil Systems, 3*, 1–19. https://doi.org/10.3390/soilsystems3020024

Fernandes, J. D., Chaves, L. H. G., Mendes, J. S., Chaves, I. B., & Tito, G. A. (2018). Soil chemical amendments and the macronutrients mobility evaluation in Oxisol treated with biochar. *Journal of Agricultural Science, 10*, 238–247. https://doi.org/10.5539/jas.v10n10p238

Ferreira, D. F. (2011). Sisvar: A computer statistical analysis system. *Ciência e Agrotecnologia, 35*, 1039–1042. https://doi.org/10.1590/S1413-70542011000600001

Githinji, L. (2014). Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. *Archives of Agronomy and Soil Science, 60*, 457–470. https://doi.org/10.1080/03650340.2013.821698

Glaser, B., Lehmann, J., & Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soil in the tropics with charcoal – a review. *Biology and Fertility of Soils, 35*, 219–230. https://doi.org/10.1007/s00374-002-0466-4

Herath, H. M. S. K., Arbestain, M. C., & Hedley, M. (2013). Effect of biochar on soil physical properties in two contrasting soils: An Alfisol and an Andisol. *Geoderma, 209–210*, 188–197. https://doi.org/10.1016/j.geoderma.2013.06.016

Jien, S. H., & Wang, C. S. (2013). Effects of biochar on soil properties and erosion potential in a highly weathered soil. *CATENA, 110*, 225–233. https://doi.org/10.1016/j.catena.2013.06.021

Jeffery, S., Verheijen, F. G. A., Van Der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment, 144*, 175–187. https://doi.org/10.1016/j.agee.2011.08.015

Kammann, C. I., Linsel, S., Gößling, J. W., & Koyro, H. W. (2011). Influence of biochar on drought tolerance of Chenopodium quinoa: Willd and on soil–plant relations. *Plant and Soil, 345*, 195–210. https://doi.org/10.1007/s11104-011-0771-5

Kookana, R. S., Sarmah, A. K., Van Zwieten, L., Krull, E., & Singh, B. (2011). Biochar application to soil: Agronomic and environment benefits and unintended con-sequences. *Advance in Agronomy, 112*, 103–143. https://doi.org/10.1016/B978-0-12-385538-1.00003-2

Laird, D., Fleming, P., Davis, D., Horton, R., Wang, B., & Karlen, D. (2010). Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma, 158*, 443–449. https://doi.org/10.1016/j.geoderma.2010.05.013

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems - a review. *Mitigation and Adaptation Strategies for Global Change, 11*, 403–427. https://doi.org/10.1007/s11027-005-9006-5

Lehmann, J., Silva, J. P., Jr., Steiner, C., Nehls, T., Zech, W., & Glaser, B. (2003). Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: Fertilizer, manure and charcoal amendments. *Plant and Soil, 249*, 343–357. https://doi.org/10.1023/A:1022833116184

Liu, Z., Dugan, B., Masiello, C. A., Barnes, R. T., Gallagher, M. E., & Gonnermann, H. M. (2016). Impacts of biochar concentration and particle size on hydraulic conductivity and DOC leaching of biochar–sand mixtures. *Journal of*

Hydrology, 533, 461–472. https://doi.org/10.1016/j.jhydrol.2015.12.007

Liu, Z., Dugan, B., Masiello, C. A., & Gonnermann, H. M. (2017). Biochar particle size, shape, and porosity act together to influence soil water properties. *PLoS ONE, 9*, 1–9. https://doi.org/10.1371/journal.pone.0179079

Lucchini, P., Quilliam, R. S., Deluca, T. H., Vamerali, T., & Jones, D. L. (2014). Does biochar application alter heavy metal dynamics in agricultural soil. *Agriculture, Ecosystems & Environment, 184*, 149–157. https://doi.org/10.1016/j.agee.2013.11.018

Major, J., Rondon, M., Molina, D., Riha, S. J., & Lehmann, J. (2010). Maize yield and nutrition during 4 years after biochar application to a Colombian savanna Oxisol. *Plant and Soil, 333*, 117–128. https://doi.org/10.1007/s11104-010-0327-0

Martinsen, V., Mulder, J., Shitumbanuma, V., Sparrevik, M., Borresen, T., & Cornelissen, G. (2014). Farmer-led maize biochar trials: Effect on crop yield and soil nutrients under conservation farming. *Journal of Plant Nutrition and Soil Science, 177*, 681–695. https://doi.org/10.1002/jpln.201300590

Masuda, M. M., Abdulaha-Al, B. M., Akhtera, S., Sen, R., Barmana, A., & Khatun, M. R. (2020). Liming effects of poultry litter derived biochar on soil acidity amelioration and maize growth. *Ecotoxicology and Environmental Safety, 202*, 1–10. https://doi.org/10.1016/j.ecoenv.2020.110865

Mendes, J. S., Chaves, L. H. G., Fernandes, J. D., & Chaves, I. B. (2015a). Using MB-4 rock powder, poultry litter biochar, silicate and calcium carbonate to amend different soil types. *Australian Journal of Crop Science, 9*, 987–995.

Mendes, J. S., Chaves, L. H. G., Chaves, I. B., Silva, F. A. S., & Fernandes, J. D. (2015b). Using poultry litter biochar and rock dust MB-4 on release available phosphorus to soils. *Agricultural Science, 6*, 1367–1374. https://doi.org/10.4236/as.2015.611131

Mendes, L.B., Tinoco, I.F.F., Souza, C.F., & Saraz, J.A.O. (2012). O ciclo do nitrogênio na criação de frangos de corte e suas perdas na forma de amônia volátil: Uma revisão. *Pubvet, 6*, 1381–1386. https://doi.org/10.22256/pubvet.v6n20.1383

Mukherjee, A., & Lal, R. (2013). Biochar impacts on soil physical properties and greenhouse gas emissions. *Agronomy, 3*, 313–339. https://doi.org/10.3390/agronomy3020313

Novak, J. M., Busscher, W. J., Laird, D. L., Ahmedna, M., Watts, D. W., & Niandou, M. A. S. (2009). Impact of biochar amendment on fertility of a southeastern Coastal. *Soil Science, 174*, 105–112. https://doi.org/10.1097/SS.0b013e3181981d9a

Omondi, M. O., Xia, X., Nahayo, A., Liu, X., Korai, P. K., & Pan, G. (2016). Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. *Geoderma, 274*, 28–34. https://doi.org/10.1016/j.geoderma.2016.03.029

Paganini, F.J. (2002).Reutilização de Cama na produção de Frangos de Corte: Porquê, Quando e Como fazer. In: CONFERÊNCIA APINCO 2002 DE CIÊNCIA E TECNOLOGIA AVÍCOLAS, 2002, Campinas. Anais... São Paulo, p.193–206.

Pereira, M. E., Varanda, L. D., Nakashima, G. T., Hansted, A. L. S., Silva, D. A., Tomeleri, J. O. P., BelinI, G. B., & Yamaji, F. M. (2019). Characterization of the poultry litter biomass for production of biochar. *Revista Virtual Química, 11*, 1330–1343. https://doi.org/10.21577/1984-6835.20190092

Perondi, D., Poletto, P., Restelatto, D., Manera, C., Silva, J. P., Junges, J., Collazzo, G. C., Dettmer, A., Godinho, M., & Vilela, A. C. F. (2017). Steam gasification of poultry litter biochar for bio-syngas production. *Process Safety and Environmental Protection, 109*, 478–488. https://doi.org/10.1016/j.psep.2017.04.029

Rouquerol, F., Rouquerol, I., & Sing, K. (1999). *Adsorption by powders and porous solids*. Academic Press.

Schmidt, N. S., & Silva, C. L. (2018). Pesquisa e Desenvolvimento na Cadeia Produtiva de Frangos de Corte no Brasil. *Revista De Economia e Sociologia Rural, 56*, 467–482. https://doi.org/10.1590/1234-56781806-94790560307

Silva, I. C. B., Fernandes, L. A., Colen, F., & Sampaio, R. A. (2017). Growth and production of common bean fertilized with biochar. *Ciência Rural, 47*, e20170220. https://doi.org/10.1590/0103-8478cr20170220

Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). A review of biochar and its use and function in soil. *Advance in Agronomy, 105*, 47–82. https://doi.org/10.1016/S0065-2113(10)05002-9

Souza, C. C. B., Amaral Sobrinho, N. M. B., Lima, E. S. A., Lima, J. O., Carmo, M. G. F., & García, A. C. (2019). Relation between changes in organic matter structure of poultry litter and heavy metals solubility during composting. *Journal of Environmental Management, 247*, 291–298. https://doi.org/10.1016/j.jenvman.2019.06.072

Sparks, D. (2003). *Environmental soil chemistry*. Academic Press.

Steiner, C., Blum, W. E. H., Zech, W., Macedo, J. L. V., Teixeira, W. G., Lehmann, J., & Nehls, T. (2007). Long-term effects of manure, charcoal, and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian Upland soil. *Plant and Soil, 291*, 275–290. https://doi.org/10.1007/s11104-007-9193-9

Teixeira, P.C., Donagemma, G.K., Fontana, A., & Teixeira, W.G. (2017). *Manual de métodos de análise de solo*. Brasília, DF: Embrapa.

Ulyett, J., Sakrabani, R., Kibblewhite, M., & Hann, M. (2014). Impact of biochar addition on water retention, nitrification and carbon dioxide evolution from two sandy loam soils. *European Journal of Soil Science, 65*, 96–104. https://doi.org/10.1111/ejss.12081