Received: 6 November 2019 | Revised: 18 May 2020 | Accepted: 20 May 2020

DOI: 10.1111/sum.12609-2019-321

RESEARCH PAPER

Soil Use and Management | BRITISH SOCIETY OF SOIL SCIENCE | WILEY

Phosphorus availability and grass growth in biochar-modified acid soil: A study excluding the effects of soil pH

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Funding information
Fundação de Amparo à Pesquisa e Inovação do Espírito Santo (FAPES); Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq); Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES), Grant/Award Number: Finance Code 001

Abstract

The low efficiency of phosphorus fertilization in weathered soils can limit plant development. The application of biochars in these areas has been seen as an important way to increase the efficiency of phosphorus fertilization and to promote better plant growth. However, biochars are alkaline materials that can increase soil pH and thus change the nutrient dynamics, which has been often ignored in studies of this nature. Here, all treatments had their pH standardized at 6.1 to eliminate the influence of pH on biochar application responses. The main goal of this study was to evaluate the real potential of coffee straw and eucalyptus bark biochars, produced under different pyrolysis temperatures, in the optimization of phosphorus fertilization and the development of *Brachiaria brizantha*. A greenhouse experiment was set up in a 2 × 2 × 5 factorial scheme, conducted for 120 days. The biochars, prepared from coffee straw and eucalyptus bark at 350 and 600°C, were applied at five rates in a Red-Yellow Oxisol. The application of biochars may reduce the demand for nutrients and correctives, optimize phosphorus fertilization and improve the development of *Brachiaria brizantha*, but this ability depends on the raw material and the pyrolysis temperature used in its production. All analysed biochars can contribute to higher tillering and dry matter production, but only coffee straw biochars and eucalyptus bark biochar produced at 350°C were efficient in the optimization of phosphorus fertilization until 120 days of cultivation of *Brachiaria brizantha*.

KEYWORDS

black carbon, *Brachiaria brizantha*, pasture development, phosphorus uptake, soil conditioner, weathered soils

1 | INTRODUCTION

The increase in global food demand in the coming years jeopardizes world food security and shows a warning for the need for more sustainable use of natural resources (Conijn, Bindraban, Schröder, & Jongschaap, 2018). The search for practices that can optimize fertilizer use has been a constant focus in many studies, especially relative to phosphate fertilizers. Phosphorus (P) is one of the most limiting nutrients for plant development and, although there are many deposits of this nutrient scattered over the globe, few are viable for commercial exploration (Geissler, Mew, & Steiner, 2019). Therefore, practices that enable the best use of this input is of fundamental importance to reduce dependence on mined P sources (Baveye, 2015).

In hot and humid regions, the efficiency of phosphate fertilizers is lower than in dry and cold places, since the ability of the soil to provide this nutrient, or even to maintain its availability, is reduced when the degree of pedogenic development intensifies. This occurs during the soil formation process, in which minerals and clay minerals go through a sequence of events that result in increased oxide contents in the colloidal fractions, increasing the adsorption capacity of soil anions. According to Baveye (2015), it is estimated that only 15% of the P added by fertilizers is used in the crop, mainly because of its adsorption onto the soil mineral colloids.

Biochar application in agricultural soils is a relatively recent practice that has been proven effective in improving the quality of poor fertility soils, attributable to the benefit that this conditioner provides to the chemical and physical soil attributes (Su, Ma, & Chen, 2018). Biochar is the solid residue from the thermal degradation process of an organic material obtained from slow pyrolysis under limited oxygen (Lehmann & Joseph, 2009). The product of this process is a porous material, rich in carbon, with high stability that is endowed with a high density of surface charges (Liu, Jiang, & Yu, 2015; Weber & Quicker, 2018). When applied to the soil, biochars can interact with mineral fractions (Jin et al., 2018) and compete with the anions for the adsorption sites; besides that, they can adsorb the phosphorus present in soil solution and desorb it posteriorly (Zhang et al., 2016), increasing the efficiency of P fertilizers.

The main characteristics of biochars that can influence the availability of nutrients for plants, such as reactivity and chemical composition, are closely related to the raw material and the pyrolysis temperature used during the production process (Günal, Bayram, Günal, & Erdem, 2019; Jindo, Mizumoto, Sawada, Sanchez-Monedero, & Sonoki, 2014; Weber & Quicker, 2018). Different biomass types can be used as raw materials for biochar production, whereas the use of residues has greater environmental importance. Among the residues generated in the agricultural and forestry sector, coffee straw and eucalyptus bark are highlighted, with these two materials produced and accumulated in large quantities in processing yards (Passos, Silva, Barbosa, Mendonça, & Rangel, 2016).

Therefore, the objective of this study was to evaluate the potential of coffee straw and eucalyptus bark biochars, produced under different pyrolysis temperatures (350 and 600°C), in the optimization of P fertilization and initial development of *Brachiaria brizantha*.

2 | MATERIALS AND METHODS

2.1 | Soil characterization

The experiment was set up using a Red-Yellow Oxisol, collected at 10–20 cm depth in a degraded pasture, located in Alegre, Espírito Santo State, Brazil (20°45′33.22″ South, 41°29′21.29″ West). The soil was air-dried and sieved at 2 mm to obtain the TFSA. A sub-sample was used for chemical and physical characterization according to Teixeira, Donagemma, Fontana, and Teixeira (2017) (Table 1). The soil pH was measured in suspension with 10 g of TFSA and 25 ml of water (ratio 1:2.5). The available contents of potassium (K), sodium (Na) and P were extracted with Mehlich-1 (HCl 0.05 mol L^{-1} + H_2SO_4 0.025 mol L^{-1}) and determined by flame emission spectrophotometry (K and Na) and colorimetry (P). Available calcium (Ca) and magnesium (Mg), as well as the exchangeable acidic cations, were extracted with potassium chloride solution (1 mol L^{-1}) and determined by atomic absorption spectrophotometer (Ca and Mg) and titration with NaOH (0.1 mol L^{-1}) (to measure the exchangeable acidity). The potential acidity was determined after the extraction of acidic cations with calcium acetate solution at pH 7 and titration with NaOH (0.1 mol L^{-1}). Soil density and density of particles were determined by the beaker method and volumetric balloon method, respectively. Sand, silt and clay contents were determined by the pipette method and soil organic matter was determined by the wet oxidation method.

TABLE 1 Chemical and physical characterization of the soil used in the experiment

Soil attributes	Values
pH in water	4.42
Phosphorus (mg dm^{-3})	0.82
Potassium (mg dm^{-3})	25.30
Sodium (mg dm^{-3})	3.00
Calcium ($cmol_c$ dm^{-3})	0.35
Magnesium ($cmol_c$ dm^{-3})	0.20
Exchangeable acidity ($cmol_c$ dm^{-3})	0.53
Potential acidity ($cmol_c$ dm^{-3})	4.04
Soil density (kg dm^{-3})	1.16
Density of particles (kg dm^{-3})	2.33
Sand (%)	48.00
Silt (%)	5.00
Clay (%)	47.00
Organic matter (%)	1.98

2.2 | Biochars characterization

Two raw materials were used to produce the biochars. The straw of *Coffea canephora* grains (coffee straw), consisting of grain husks, pulp and parchment, and the *Eucalyptus grandis* bark (eucalyptus bark), consisting of eucalyptus bark previously cut into 5 cm pieces, were obtained in processing yards.

The raw material pyrolysis was carried out in a metal reactor SPPT-V60 (manufactured by SPPT Pesquisas tecnológicas Ltda) with a capacity of 60 L. The reactor had six electrical resistance levels (2.5 kW each), which provided a heating ramp of 6°C min^{-1}, and three thermometers that were used to monitor the reactor and biomass temperatures.

Batches with approximately 5 kg of raw material were added to the sample holder of the reactor. Then, the reactor was hermetically sealed, and the raw materials were heated to a final temperature (350 and 600°C) and held at this temperature for one hour. After that, the biochars were kept in the reactor turned off for 12 hr, until reaching room temperature.

The biochars were sieved to standardize the particle size. Fractions between 1 and 0.5 mm were used in the experiment. Samples of coffee straw biochars, produced at 350°C (CS350) and 600°C (CS600), and eucalyptus bark biochars, produced at 350°C (EB350) and 600°C (EB600), were collected for characterization (Table 2).

Carbon, hydrogen and nitrogen of biochars were determined on Perkin Elmer Series II Analyzer 2400, and the oxygen was calculated by difference (O = 100 − C − H − N − ash). Ash content was determined as the percentage of the initial mass remaining after the sample had been exposed to air at 550°C for 4 hr. The water pH was determined in suspension with a 1:10 (biochar:water) relation. The total content of macro and micronutrients (phosphorus, potassium, calcium, magnesium, sulphur, copper, iron, zinc, manganese and boron) were obtained by total digestion using a nitroperchloric solution (Silva, 2009).

In addition, the spectra of the FTIR (Fourier Transform Infrared Spectroscopy) analysis of the biochars (CS350, CS600, EB350 and EB600) and raw materials (CS and EB), with the main bands interpreted by Barbosa (2016), are presented in Figure 1.

TABLE 2 Characterization of biochars produced from coffee straw, at 350°C (CS350) and 600°C (CS600), and eucalyptus bark, at 350°C (EB350) and 600°C (EB600)

	CS350	CS600	EB350	EB600
Carbon (%)	59.87	76.66	53.14	72.36
Hydrogen (%)	4.57	2.17	4.03	2.41
Nitrogen (%)	2.54	2.44	0.83	0.49
Oxygen (%)	19.38	1.07	25.17	2.73
Ash (%)	13.64	17.66	16.83	22.01
pH in water	8.24	9.49	6.48	9.23
Phosphorus (g kg^{-1})	2.03	2.95	0.65	0.89
Potassium (g kg^{-1})	44.57	56.57	5.66	7.01
Calcium (g kg^{-1})	16.70	23.23	26.36	33.11
Magnesium (g kg^{-1})	3.22	4.22	4.12	5.67
Sulphur (g kg^{-1})	2.18	3.17	0.63	1.20
Copper (mg kg^{-1})	23.70	36.35	7.20	9.20
Iron (mg kg^{-1})	451.55	724.75	2,605.00	3,088.00
Zinc (mg kg^{-1})	12.20	17.20	19.15	37.70
Manganese (mg kg^{-1})	109.65	151.80	557.10	819.60
Boron (mg kg^{-1})	81.92	109.36	25.88	31.28

2.3 | Soil pH standardization

Several studies show the positive effects of biochars in weathered soils, where low pH values are common, limiting soil phosphorus availability and its absorption by the plants. In this condition, the alkalinity of biochars may be responsible for improved phosphorus absorption and higher plant yield. We standardized pH in all treatments to equalize the effects of soil pH on phosphorus dynamics and plant development. For this, the treatments were previously submitted to the incubation method to determine the calcium carbonate rate required to standardize the pH value to 6.1. Subsequently, the calcium content added by calcium carbonate was corrected with the application of calcium chloride to equalize the amount of calcium added. This procedure is presented in detail by Fonseca (2018). The soil pH and the availability of potassium, calcium and magnesium in each treatment, after the incubation process and at the end of the experiment, are presented in Table 3.

2.4 | Experimental design and treatments

The study was carried out under greenhouse conditions in the experimental area of the Center of Agrarian Sciences and Engineering of the Federal University of Espírito Santo, located in the Espírito Santo State, Brazil. The experiment was set up in a 2 × 2 × 5 factorial scheme, being: two raw materials used for the biochar production (coffee straw and eucalyptus bark); two pyrolysis temperatures during carbonization process (350 and 600°C) and five rates of biochars (0.0, 2.5, 5.0, 7.5 and 10.0 g dm^{-3}), installed in randomized blocks with four repetitions.

Biochars and correctives were incorporated in 8.5 dm^{-3} of soil, and then, the treatments were incubated for 30 days with moisture equivalent at 70% of the field capacity. After incubation, phosphate fertilization was performed according to the recommendation of Novais, Neves, and Barros (1991) for greenhouse experiments, 200 mg kg^{-1} of phosphorus was applied via single superphosphate. The phosphate fertilizer was incorporated in the entire volume of soil. The nitrogen fertilization was made with urea with a dose of 100 mg kg^{-1} (Novais et al., 1991) divided into three applications with 40%, 30% and 30% of the total recommended, and all of them applied to the soil surface.

Some biochars can be potassium-rich, so the potassium fertilization was based on the potassium content in biochars. All treatments received a minimum of 250 mg kg^{-1} of potassium to ensure plant development; nevertheless, on the treatments in which the potassium contents were equal or greater

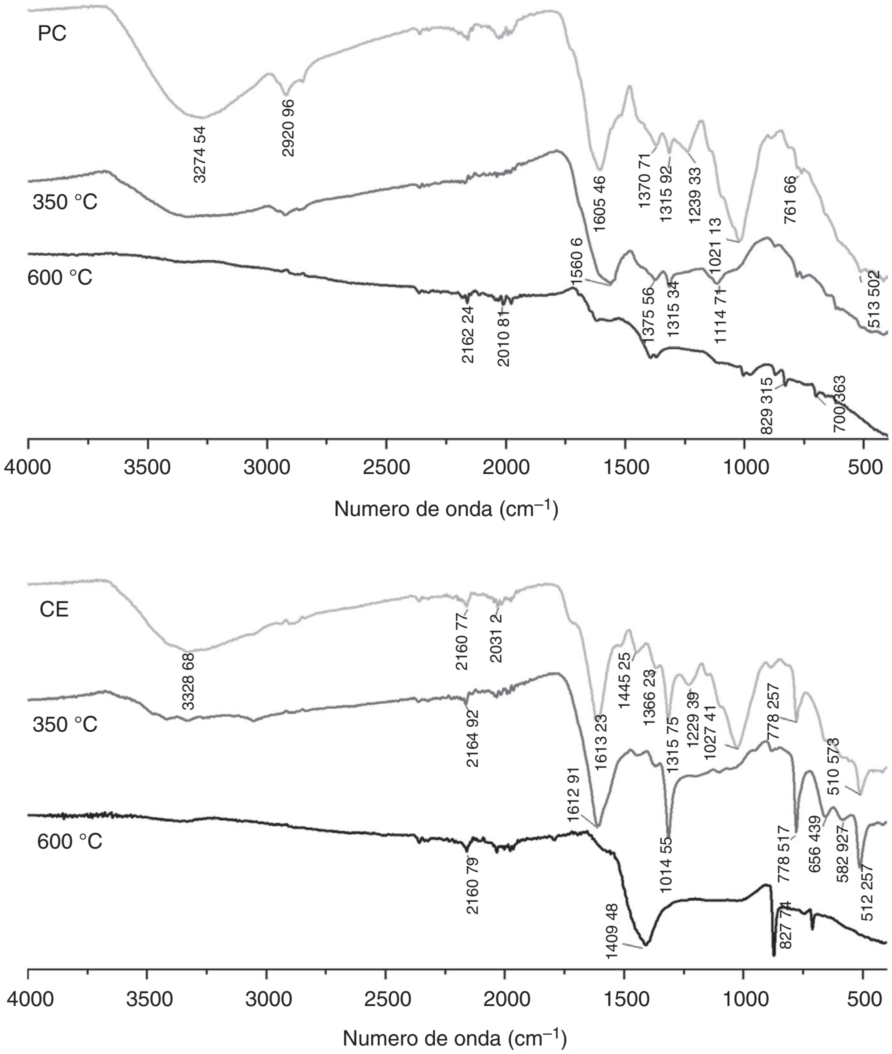


FIGURE 1 The FTIR spectra, with the main interpreted bands, of coffee straw (PC) and eucalyptus bark (CE), as well as of the biochars produced at 350 and 600°C (Barbosa, 2016)

than 250 mg kg^{-1} with only the biochar application, no mineral fertilization with potassium chloride was performed (Fonseca, 2018). This fertilizer was also incorporated in the entire volume of soil.

2.5 | Grass planting, experiment conduction and plant analyses

Five seedlings of *Brachiaria brizantha* (brachiaria) were planted in each experimental unit. After 15 days from transplanting, seedlings were thinned, and only three plants were kept per pot. During the experiment, the pots were weighed every day to replenish the water needed to keep the soil with 70% of the field capacity. In addition, the TDR sensor, model GS3 (Decagon), was used to check soil moisture weekly.

At 40, 80 and 120 days after transplanting, the numbers of tillers sprouted by the three plants in each pot were quantified and the aerial parts of the plants were cut. The vegetal material collected was kiln-dried (65°C) and weighed to obtain the mass of dry matter produced, and then, it was subjected to the nitroperchloric digestion process (Silva, 2009) to determine the total P content. Based on the leaf contents of P and in the dry matter produced, the accumulation of phosphorus in each cut was calculated. With the sum of the accumulation obtained in the three cuts, the total P accumulation during the entire growing period was calculated.

2.6 | Soil samples and analyses

After the third cut, at 120 days of cultivation, the soil of each experimental unit was air-dried and sieved at 2 mm to determine P availability. The P present on soil can be divided into different fractions according to its lability. The available fraction refers to the amount of P that can be extracted by plants during their cycle; therefore, this fraction has a high correlation with the plant growth and with P content on plants. In this experiment, Mehlich-1 (duplex acid solution) was used to extract the available fraction of P in each treatment. After the extraction, P content was determined using a molecular absorption spectrophotometer (Teixeira et al., 2017).

TABLE 3 Soil pH and potassium (K, mg dm^{-3}), calcium (Ca, cmol$_c$ dm^{-3}) and magnesium (Mg, cmol$_c$ dm^{-3}) availability in each treatment after the incubation process (T1) and at the end of the experiment (T2)

Biochar type	Biochar rate (g dm^{-3})	T1 pH	T1 K	T1 Ca	T1 Mg	T2 pH	T2 K	T2 Ca	T2 Mg
Coffee straw 350°C	0.0	6.2	21.3	2.5	0.2	5.8	58.0	4.4	0.1
	2.5	6.0	112.7	2.5	0.2	5.8	58.0	4.5	0.1
	5.0	6.0	200.3	2.6	0.3	5.8	80.3	4.7	0.2
	7.5	6.0	293.7	2.6	0.4	5.7	154.0	4.5	0.2
	10.0	5.8	378.7	2.6	0.4	5.6	200.5	5.2	0.3
Coffee straw 600°C	0.0	6.2	23.0	2.4	0.2	5.7	61.8	4.9	0.1
	2.5	5.9	143.0	2.5	0.2	5.7	78.8	4.9	0.1
	5.0	5.8	275.3	2.6	0.2	5.7	135.0	4.9	0.1
	7.5	5.7	392.3	2.7	0.2	5.6	251.3	4.8	0.2
	10.0	5.6	538.3	2.7	0.3	5.5	308.0	5.3	0.2
Eucalyptus bark 350°C	0.0	6.1	20.3	2.5	0.2	5.6	51.8	4.8	0.1
	2.5	5.8	28.7	2.5	0.2	5.6	60.5	4.9	0.1
	5.0	5.6	36.0	2.6	0.3	5.7	70.3	4.9	0.2
	7.5	5.5	45.3	2.8	0.3	5.7	63.0	5.0	0.2
	10.0	5.7	55.7	2.9	0.4	5.7	65.3	5.1	0.3
Eucalyptus bark 600°C	0.0	6.0	19.7	2.3	0.2	5.7	63.3	4.7	0.2
	2.5	5.7	30.3	2.6	0.2	5.7	76.8	5.4	0.2
	5.0	5.7	40.3	2.9	0.2	5.8	69.8	5.5	0.2
	7.5	5.7	52.3	3.3	0.2	5.8	71.0	5.5	0.2
	10.0	5.7	67.7	3.5	0.2	5.9	64.5	5.8	0.2

2.7 | Data analyses

The results were submitted to analysis of variance to verify the differences between the treatments at 5% of significance. When there were significant differences, the Tukey test, at 5% of probability, was used to compare the effects of biochars produced from different raw materials and pyrolysis temperatures. The regression analysis was used to access the responses to the increase in applied rates of the biochars under study. The models were chosen based on the significance of the regression coefficient, calculated by Student *t*-test at 5% of probability and by the coefficient of determination (R^2).

3 | RESULTS

3.1 | Grass development

The type of biochars influenced the amount of dry matter produced by brachiaria (Table 4). The total dry matter produced (sum of the three cuts) with the application of CS600 was higher than when the EB600 biochar was applied, which occurred from the second cut. Between the biochars produced at 350°C, only in the third cut did the biochar type influence plant dry matter production, with higher values obtained when the CS350 biochar was applied.

The pyrolysis temperature used in the production of eucalyptus bark biochar affected the dry matter production by brachiaria. In the sum of the cuts, the dry matter produced on treatments with the EB350 application was higher than the treatments with the application of EB600 biochar (Table 4). However, there were generally no differences between the temperatures used during the biochar pyrolysis when the cuts were evaluated individually.

The increased rates of biochars can favour dry matter production (Figure 2) The total dry matter produced by brachiaria (sum of the three cuts) showed a positive response to the increase at the applied rates of the PC350, PC600 and EB350 biochars. In the first cut, none of the biochars changed the soil P availability; however, from the second cut, the application of the high rates of PC350, PC600 and EB350 biochars increased the available P in the soil. On the other hand, in the third cut, a positive effect of the EB600 biochar application occurred (Figure 2).

The numbers of tillers produced by brachiaria in the sum of three cuts, as well as in each cut evaluated individually, were not influenced by the raw material and pyrolysis temperature used on biochar production (Table 4). The increase in applied rates of biochars had a positive effect on brachiaria tillering, regardless of the biochar type (Figure 3). Since the first cut, there was an increase in tiller sprouting in the treatments using the biochars produced at 600°C (Figure 3). From

TABLE 4 Mean values[a] of dry matter produced by plant aerial part (Dry Matter) and the number of tillers (Tillering) produced by *Brachiaria brizantha* per plot, obtained in the three cuts individually and in the sum of the cuts, in response to the application coffee straw and eucalyptus bark of biochars, produced under different pyrolysis temperatures (350 and 600°C)

		Temperature	
Variable	Raw material	350°C	600°C
1st cut			
Dry matter (g pot^{-1})	Coffee straw	5.64 Aa	5.50 Aa
	Eucalyptus bark	5.76 Aa	5.23 Ab
Tillering (number of tillers per pot)	Coffee straw	7.90 Aa	8.70 Aa
	Eucalyptus bark	8.45 Aa	8.15 Aa
2nd cut			
Dry matter (g pot^{-1})	Coffee straw	23.02 Aa	23.24 Aa
	Eucalyptus bark	22.96 Aa	22.57 Ba
Tillering (number of tillers per pot)	Coffee straw	20.00 Aa	20.60 Aa
	Eucalyptus bark	20.55 Aa	20.15 Aa
3rd cut			
Dry matter (g pot^{-1})	Coffee straw	24.08 Aa	23.89 Aa
	Eucalyptus bark	23.13 Ba	22.13 Ba
Tillering (number of tillers per pot)	Coffee straw	32.95 Aa	33.25 Aa
	Eucalyptus bark	33.70 Aa	33.35 Aa
Sum of three cuts			
Dry matter (g pot^{-1})	Coffee straw	52.74 Aa	52.63 Aa
	Eucalyptus bark	51.84 Aa	49.93 Bb
Tillering (number of tillers per pot)	Coffee straw	60.85 Aa	62.55 Aa
	Eucalyptus bark	62.70 Aa	61.65 Aa

[a]The same uppercase letters in the column and lowercase letters in the row indicate no significant differences from each other according to the Tukey test ($p \le .05$).

the second cut, the increase rates of the biochars produced at 350°C also favoured the tillering of brachiaria.

3.2 | Phosphorus accumulation

With the application of coffee straw biochar, the largest P accumulation in brachiaria plants occurred (Table 5). With the application of CS350 biochar, the total P accumulation by brachiaria (sum of three cuts) was greater than when the EB350 biochar was applied. This behaviour occurred from the first cut. Among the biochars produced at 600°C, the total P accumulated by plants during the experiment (sum of three cuts) was highest with the application of CS600 biochar, even though there were no differences in the cuts evaluated individually (Table 5).

The total accumulation of P by plants was positively influenced by the increase in applied rates of biochars, regardless of raw material or pyrolysis temperature used in their production (Figure 4). However, the only biochars that provided an increase in the accumulation of P by the plants in all evaluated cuts, were the CS350 and EB350 biochars. In the second cut, the accumulated P was not influenced by the increased rates of EB600 biochar, and in the third, the P accumulation by plants was not influenced by the increased rates of biochars produced at 600°C (Figure 4).

3.3 | Phosphorus availability after 120 days of cultivation

The available P content in the soil at the end of the experiment was influenced by the type of biochars used (Table 6). With the application of biochars produced at 350°C, the P availability in the soil after the brachiaria cultivation was similar. On the other hand, in the treatments with the application of CS600 biochar, the available P content on soil was greater than with the application of EB600 biochar (Table 6).

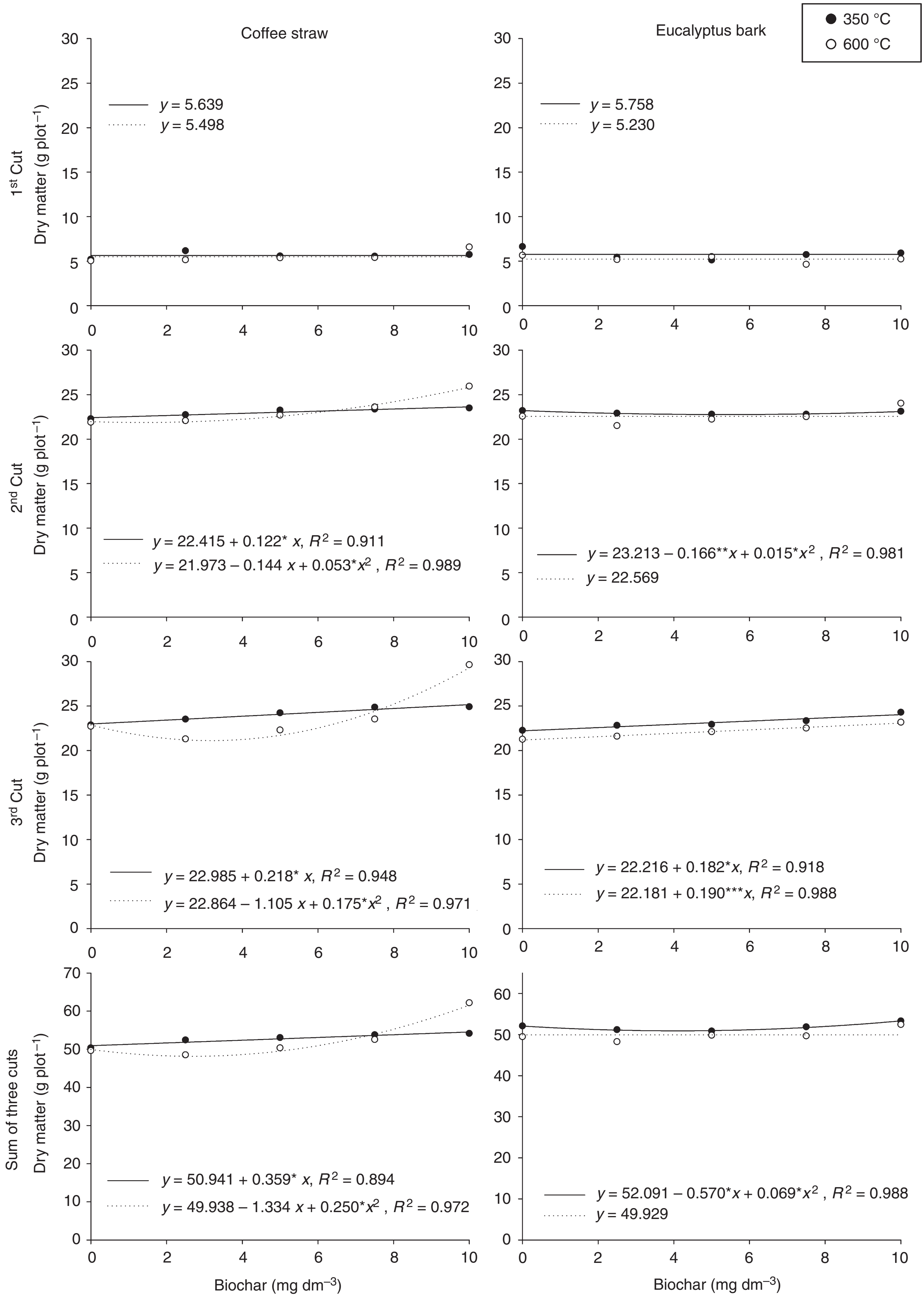
The P availability in the soil in response to the increase in applied rates of different biochars types, after 120 days of cultivation of brachiaria and with three cuts made in the aerial parts of the plants, are presented in Figure 5. In general, the available P content in the soil at the end of the experiment was positively influenced by the increase of the applied rates of biochars (Figure 5). The only exception was with the application of EB600 biochar, in which the applied rates did not influence P availability (Figure 5).

4 | DISCUSSION

It was observed in this study that coffee straw and eucalyptus bark biochars may favour the initial development of brachiaria and raise the efficiency of P fertilizer in the soil with great conditions of pH, nutrient availability and moisture.

Biochars can benefit plant physiological processes, increasing the rate of net photosynthesis, decreasing the osmotic and hydraulic potentials of the leaves and resulting in greater efficiency in the process of carboxylation (Zainul, Koyro, Huchzermeyer, Gul, & Khan, 2020).

FIGURE 2 Dry matter production[†] by aerial part of *Brachiaria brizantha*, in the three cuts individually (40, 80 and 120 days after planting) and in the sum of the cuts, in response to the application of coffee straw and eucalyptus bark biochars produced under different pyrolysis temperatures (350 and 600°C). [†]*, **, *** are significant at 5%, 1% and 0.1% by the *t*-test


Coffee straw
Eucalyptus bark
● 350 °C
○ 600 °C
1st Cut
Dry matter (g plot−1)
y = 5.639
y = 5.498
y = 5.758
y = 5.230
2nd Cut
y = 22.415 + 0.122* x, R2 = 0.911
y = 21.973 – 0.144 x + 0.053*x2 , R2 = 0.989
y = 23.213 – 0.166**x + 0.015*x2 , R2 = 0.981
y = 22.569
3rd Cut
y = 22.985 + 0.218* x, R2 = 0.948
y = 22.864 – 1.105 x + 0.175*x2 , R2 = 0.971
y = 22.216 + 0.182*x, R2 = 0.918
y = 22.181 + 0.190***x, R2 = 0.988
Sum of three cuts
y = 50.941 + 0.359* x, R2 = 0.894
y = 49.938 – 1.334 x + 0.250*x2 , R2 = 0.972
y = 52.091 – 0.570*x + 0.069*x2 , R2 = 0.988
y = 49.929
Biochar (mg dm−3)

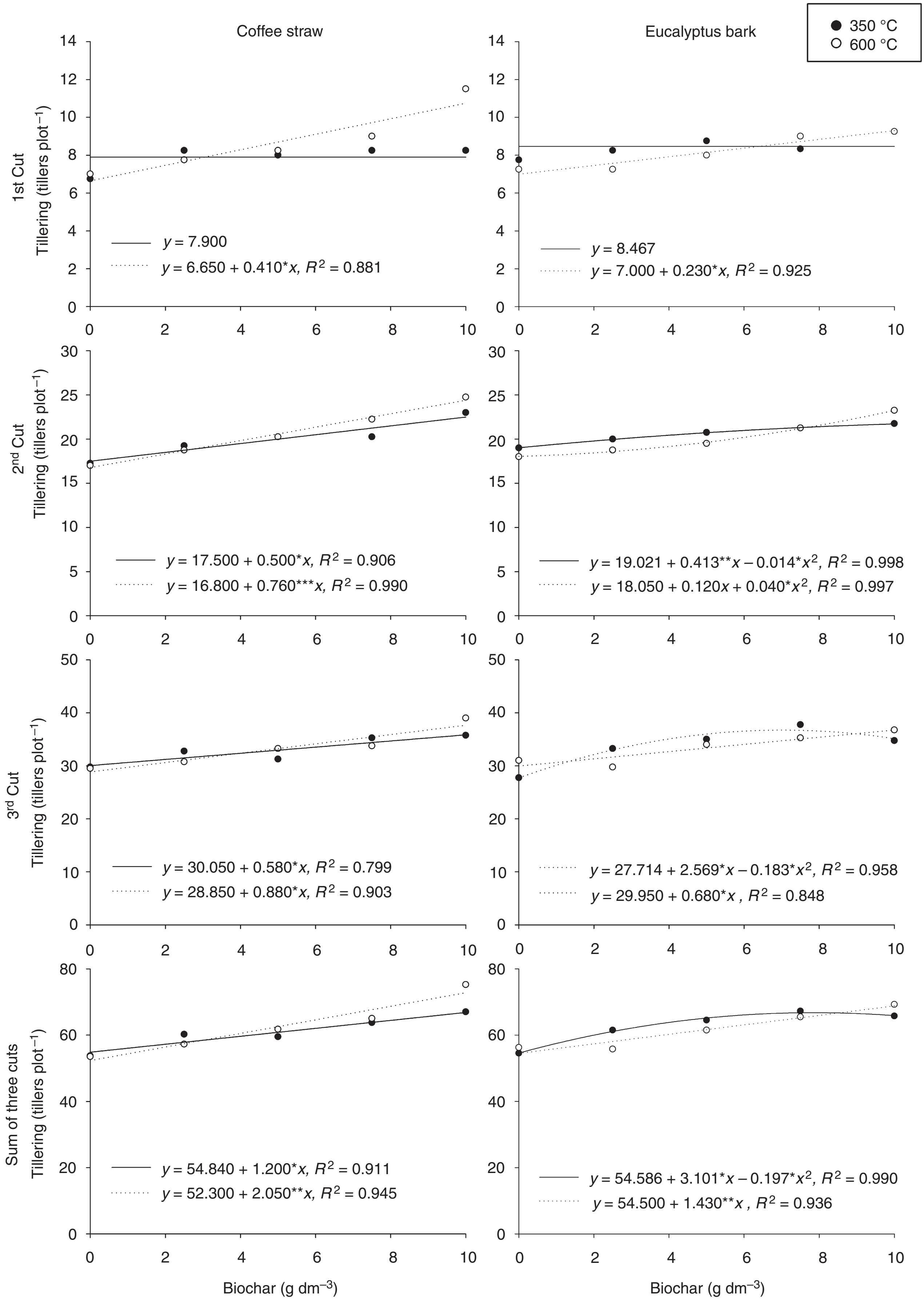

Coffee straw
Eucalyptus bark
● 350 °C
○ 600 °C
1st Cut
Tillering (tillers plot^{-1})
$y = 7.900$
$y = 6.650 + 0.410^*x$, $R^2 = 0.881$
$y = 8.467$
$y = 7.000 + 0.230^*x$, $R^2 = 0.925$
2nd Cut
Tillering (tillers plot^{-1})
$y = 17.500 + 0.500^*x$, $R^2 = 0.906$
$y = 16.800 + 0.760^{***}x$, $R^2 = 0.990$
$y = 19.021 + 0.413^{**}x - 0.014^*x^2$, $R^2 = 0.998$
$y = 18.050 + 0.120x + 0.040^*x^2$, $R^2 = 0.997$
3rd Cut
Tillering (tillers plot^{-1})
$y = 30.050 + 0.580^*x$, $R^2 = 0.799$
$y = 28.850 + 0.880^*x$, $R^2 = 0.903$
$y = 27.714 + 2.569^*x - 0.183^*x^2$, $R^2 = 0.958$
$y = 29.950 + 0.680^*x$, $R^2 = 0.848$
Sum of three cuts
Tillering (tillers plot^{-1})
$y = 54.840 + 1.200^*x$, $R^2 = 0.911$
$y = 52.300 + 2.050^{**}x$, $R^2 = 0.945$
$y = 54.586 + 3.101^*x - 0.197^*x^2$, $R^2 = 0.990$
$y = 54.500 + 1.430^{**}x$, $R^2 = 0.936$
Biochar (g dm^{-3})
Biochar (g dm^{-3})

FIGURE 3 Number of tillers[†] produced by *Brachiaria brizantha*, in the three cuts of the plant aerial part individually (40, 80 and 120 days after planting) and in the sum of the three cuts, in response to the application of coffee straw and eucalyptus bark biochars produced under different pyrolysis temperatures (350 and 600°C). [†]*, **, *** are significant at 5%, 1% and 0.1% by the *t*-test

Besides the polymerized aromatic structure, organic products from different chemical classes are part of the biochar constitution, which include compounds of low molecular weight such as sugars as well as more complex molecules (Graber, Tsechansky, Mayzlish-Gati, Shema, & Koltai, 2015). These authors observed that the chemical compounds present in biochars produced from residues of pepper plants at 450°C can act similarly to plant hormones, altering root development and response to nutrient application.

Jin et al. (2018) observed that similar structures to humic acids extracted from the soil are among the compounds with higher molecular weights that constitute the biochars produced from agricultural residues, including grass straws of rice, wheat and maize carbonized at different pyrolysis temperatures (300, 450 and 600°C). Nevertheless, in biochars these molecules have higher concentrations of superficial –COOH groups, which give them greater reactivity and increases the interaction with the soil, favouring the availability of nutrients (Jin et al., 2018). Therefore, besides the hormonal action, improvements in soil chemical properties in response to the application of biochars can also increase P availability to plants (Su et al., 2018).

Considering that P is a nutrient whose availability is limited mainly by the process of adsorption of the mineral colloids of the soil, the application of biochars preceding the P fertilizers can increase the availability of these nutrients over time. The high density of surface functional groups associated with the high porosity of these materials (Liu et al., 2015) confirms that biochar can adsorb P in solution and desorb it posteriorly (Zhang et al., 2016), thus reducing the intensity of the interaction between the P and the mineral fraction of the soil. This reflects in the increase in the availability of this nutrient for the crop cycle, and even for subsequent crops, as observed with the application of coffee straw biochars in the present work.

TABLE 5 Phosphorus accumulation[a] (mg pot^{-1}) in *Brachiaria brizantha*, obtained in the three cuts individually and in the sum of the cuts, in response to the application of biochars produced under different pyrolysis temperatures

	Temperature	
Raw material	**350°C**	**600°C**
1st cut		
Coffee straw	11.70 Aa	11.65 Aa
Eucalyptus bark	11.44 Ba	10.41 Aa
2nd cut		
Coffee straw	23.12 Aa	22.27 Ab
Eucalyptus bark	21.14 Ba	20.87 Aa
3rd cut		
Coffee straw	19.09 Aa	18.32 Aa
Eucalyptus bark	17.43 Ba	17.03 Aa
Sum of three cuts		
Coffee straw	53.91 Aa	52.25 Aa
Eucalyptus bark	50.02 Ba	48.31 Ba

[a]The same uppercase letters in the column and lowercase letters in the row indicate no significant differences from each other according to the Tukey test ($p \leq .05$).

Bornø, Müller-Stöver, and Liu (2018) observed that the application of biochars in acidic soils before phosphate fertilization can reduce the intensity of the adsorption process and maintain a higher amount of available P over time. Biochars are predominantly alkaline materials that can raise soil pH, increasing the availability of nutrients in acid soils (Fidel, Laird, Thompson, & Lawrinenko, 2017). However, this paper demonstrates that the positive effects of biochar application on soil P availability and plant development are not restricted to pH elevation, and that their ability to provide such benefits varies depending on their physicochemical characteristics, which alter depending on the type of raw material (Liu et al., 2015) and temperature used during the pyrolysis process (Weber & Quicker, 2018).

Biochars produced at 350°C had wider H/C and O/C ratios than biochars produced at 600°C (Table 2), indicating a lower degree of aromatization and a greater amount of surface functional groups (Schimmelpfennig & Glaser, 2012), which is directly related to the greater ability of these biochars to electrostatically retain the phosphorus added in fertilizer and make it available over time to plants.

When higher pyrolysis temperatures are used, the produced biochars generally have high phosphorus adsorption capacity, but a small desorption rate of this nutrient (Ngatia, Hsieh, Nemours, Fu, & Taylor, 2017). When woody raw materials are used, this process can be even more intense, as higher concentrations of calcium, magnesium, iron and aluminium may contribute to the increase of their P adsorption capacity (Bornø et al., 2018). In this sense, the EB600 biochar can retain the P applied by fertilizers and reduce its adsorption by soil, but its desorption is slow and impaired plant uptake compared to the other biochars evaluated.

Ngatia et al. (2017) observed an interaction between raw material and pyrolysis temperature on the ability of biochars to adsorb and desorb P, corroborating the results obtained in this work, in which the ability of biochars to maintain the availability of this nutrient to plants varied according to the raw material used and the temperature maintained during the carbonization process.

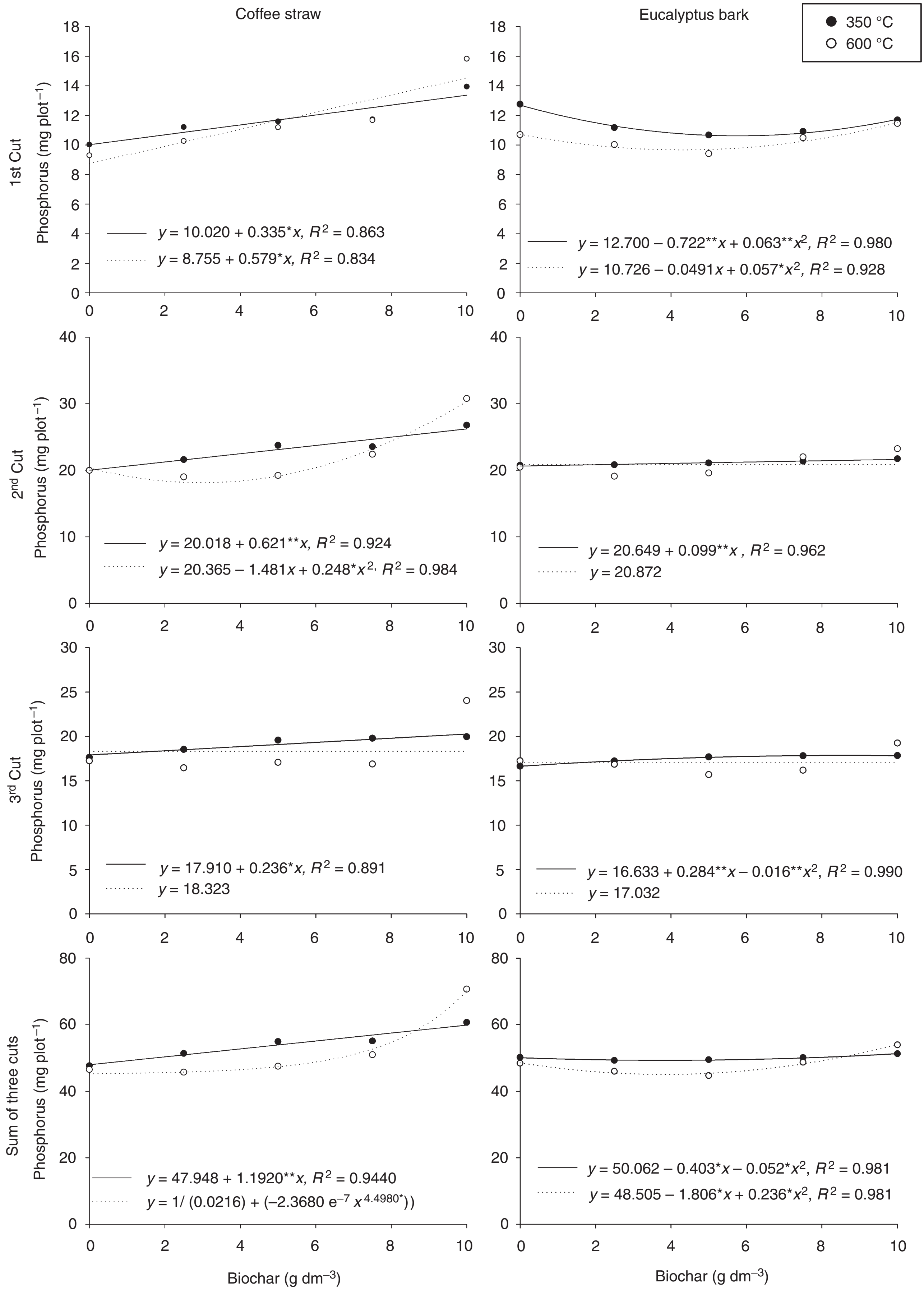

Coffee straw
Eucalyptus bark
350 °C
600 °C
1st Cut
Phosphorus (mg plot⁻¹)
y = 10.020 + 0.335*x, R² = 0.863
y = 8.755 + 0.579*x, R² = 0.834
y = 12.700 – 0.722**x + 0.063**x², R² = 0.980
y = 10.726 – 0.0491x + 0.057*x², R² = 0.928
2nd Cut
Phosphorus (mg plot⁻¹)
y = 20.018 + 0.621**x, R² = 0.924
y = 20.365 – 1.481x + 0.248*x², R² = 0.984
y = 20.649 + 0.099**x , R² = 0.962
y = 20.872
3rd Cut
Phosphorus (mg plot⁻¹)
y = 17.910 + 0.236*x, R² = 0.891
y = 18.323
y = 16.633 + 0.284**x – 0.016**x², R² = 0.990
y = 17.032
Sum of three cuts
Phosphorus (mg plot⁻¹)
y = 47.948 + 1.1920**x, R² = 0.9440
y = 1/ (0.0216) + (–2.3680 e⁻⁷ x^4.4980*))
y = 50.062 – 0.403*x – 0.052*x², R² = 0.981
y = 48.505 – 1.806*x + 0.236*x², R² = 0.981
Biochar (g dm⁻³)
Biochar (g dm⁻³)

FIGURE 4 Phosphorus accumulation† by *Brachiaria brizantha*, in the three cuts of the plant aerial part individually (40, 80 and 120 days after planting) and in the sum of the cuts, in response to the application coffee straw and eucalyptus bark biochars, produced under different pyrolysis temperatures (350 and 600°C). †*, **, *** are significant at 5%, 1% and 0.1% by the *t*-test

TABLE 6 Mean values[a] of phosphorus availability on soil after 120 days of *Brachiaria brizantha* cultivation, in response to the application of coffee straw and eucalyptus bark biochars, produced under different pyrolysis temperatures (350 and 600°C)

			Temperature	
Variable	**Unit**	**Raw material**	**350°C**	**600°C**
Phosphorus	mg dm^{-3}	Coffee straw	57.78 Aa	57.87 Aa
		Eucalyptus bark	61.61 Aa	52.18 Bb

[a]The same uppercase letters in the column and lowercase letters in the row indicate no significant differences from each other according to the Tukey test ($p \leq .05$).

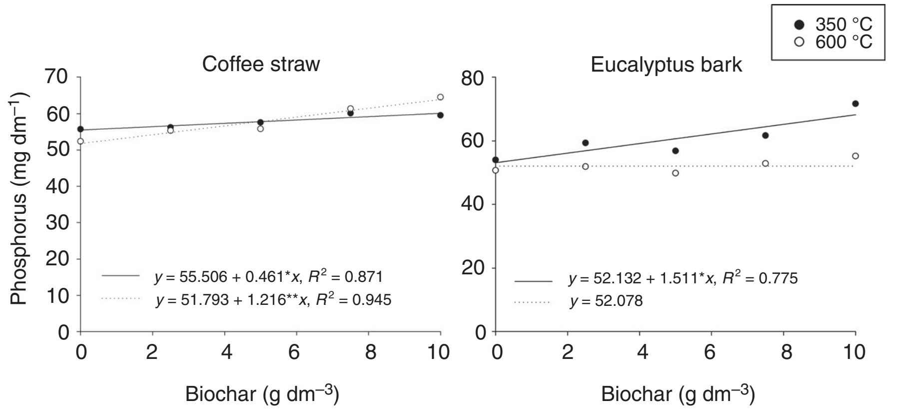


FIGURE 5 Phosphorus availability† in soil after 120 days of *Brachiaria brizantha* cultivation, in response to the application coffee straw and eucalyptus bark biochars, produced under different pyrolysis temperatures (350 and 600°C). †*, **, *** are significant at 5%, 1% and 0.1% by the *t*-test

Due to the increment of rates of coffee straw biochars a greater accumulation of P by plants occurred, as well as an increase in the availability of this nutrient after 120 days of cultivation of brachiaria. Similar results occurred in response to increasing rates of EB350; however, the increase in phosphorus accumulation by plants only occurred from the second cut.

This effect of increasing the coffee straw (350 and 600°C) and eucalyptus bark biochars produced at 350°C on the availability of phosphorus throughout the cultivation, may be the main factor responsible for the better development presented by brachiaria. However, a biostimulating effect may occur simultaneously with the increase of efficiency in phosphate fertilization, since the tillering of the plants also increased with the application of the eucalyptus bark biochar produced at 600°C, in which there was no significant response in the accumulation of phosphorus by plants until the third cut, and at the end of the experiment it did not influence the levels of P in the soil.

The higher plant development in soils that have received the application of biochars has already been demonstrated in the literature and has been attributed to the edaphic improvements provided by this soil conditioner (Su et al., 2018). Sang, Bakar, Ahamad, and Rahim (2018) observed that the use of biochars can increase dry matter production and grass tillering. According to (Fidel et al., 2017), due to its influence on soil pH and nutrient dynamics, alkalinity is one of the most important properties of biochars. In this study, it was evident the contribution of increased application rates of biochar in the development of *Brachiaria brizantha* and the efficiency of phosphate fertilization, even with the soil pH standardization in all treatments.

Finally, it is important to emphasize that the application of biochars resulted in the reduction of the demand for acidity corrective and potassic fertilizer. With the application of 10 g dm^{-3} of coffee straw biochar produced at 600°C, liming and potassium fertilization were not necessary, and even then, the values of dry matter, tillering, phosphorus accumulation and availability of phosphorus after cultivation increased.

5 | CONCLUSION

Biochars can reduce liming and nutrient demand, optimize phosphorous fertilization and improve the initial development of *Brachiaria brizantha*, but this ability depended on the raw material and pyrolysis temperature used in their production. The coffee straw biochars were efficient in promoting the optimization of phosphate fertilization, providing the greatest accumulation of phosphorus in the aerial part of the plants throughout the experiment. There was an increase in the availability of phosphorus in the soil after 120 days by the application of the coffee straw biochar, which favoured the initial development of *Brachiaria brizantha*. A similar effect occurred from the second cut with the application of the eucalyptus bark biochar produced at 350°C. The eucalyptus bark biochar produced at 600°C contributed to greater tillering and dry matter production at 120 days of cultivation.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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How to cite this article: Fonseca AA, Santos DA, Passos RR, Andrade FV, Rangel OJP. Phosphorus availability and grass growth in biochar-modified acid soil: A study excluding the effects of soil pH. *Soil Use Manage*. 2020;00:1–12. https://doi.org/10.1111/sum.12609-2019-321