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Biochar decreases nutrient leaching in KCl-fertilized Podzols grown with black mucuna

Luciana Aparecida Rodrigues[(1)*], **Caroline Cândida Martins**[(1)], **Tainá Costa Araújo**[(1)], **Claudio Roberto Marciano**[(1)], **Júlia Gallon Barcelos**[(1)], **Rosely Menezes da Silva Ribeiro**[(1)], **Mauricio Gonçalves da Silva**[(1)] and **Deborah Guerra Barroso**[(1)]

[(1)] Universidade Estadual do Norte Fluminense - Darcy Ribeiro, Centro de Ciências e Tecnologias Agropecuárias de Solos, Laboratório, Campos dos Goytacazes, Rio de Janeiro, Brasil.

ABSTRACT: Podzols are highly sandy soils, in which elements, such as potassium, needed by crops, are easily leached. Studies have indicated that biochar can contribute to increasing cation exchange capacity of the soil, which can improve the retention of bases. This study aimed to evaluate the effect of the poultry litter biochar combined or not with increasing doses of KCl, on leaching and soil base content, on the production of green manure biomass, and on the distribution of K in the soil-water-plant system. A 2 × 3 factorial experiment was conducted in randomized blocks with 6 repetitions: without and with biochar (1% v / v, produced from poultry litter) × without K, with 53.65 and 107.30 mg dm^{-3} of K (as KCl). The experiment was carried out in four steps: Step 1) Soil incubation with the treatments (for 20 days) followed by chemical analysis of the soil; Step 2) First leaching: the containers (made with PVC with 0.30 m high) received the newly incubated soil in the surface layer and soil without treatment in the subsurface layer. The containers received water until saturation plus 50 % of the total pore volume and the leached water was collected and analyzed; Step 3) Cultivation of green manure (*Mucuna aterrima)* in the containers of Step 2 and harvest within 40 days (evaluation of biomass and K content); Step 4) after the mucuna harvest, the containers were subjected to second leaching. The leaching solution and the soil from the surface and subsurface layers were collected for chemical analysis. Biochar increased the pH, cationic exchange capacity, P, K, Ca, and Mg levels in the newly incubated soil, in the surface and subsurface layer. The increasing doses of KCl proportionally increased biomass production and K accumulation in green manure, and the biochar increased this response and reduces the need for potassium fertilization by 50 %. With biochar, the accumulation of total K in the soil-plant-water system increases by 125 % and, in the soil-plant system, by 145 %. Biochar changes the K ratio in the soil-plant-water system. With biochar, proportionally, the highest accumulated percentage of K occurred mainly in the soil surface and subsurface layer, and did not result in higher percentages of K in the leached water. Biochar produced from poultry litter can be used as a good alternative to improve the chemical properties of Podzols and reduce nutrient losses.

Keywords: green manure, K accumulated, soil-plant system, nutrient loss.

*** Corresponding author:**
E-mail: lua@uenf.br

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INTRODUCTION

Podzols or *Espodossolos* (Santos et al., 2018) are soils found in coastal environments. Its physical and chemical properties, including sandy texture and low cationic exchange capacity (CEC), tend to facilitate the occurrence of nutrient losses by leaching, especially the cationic bases. Potassium is considered the second most important element for most crops. In the state of Rio de Janeiro, Brazil, Podzols soils are cultivated with crops such as coconut trees, where large amounts of K are applied as KCl (Sobral, 2003).

Because K is required at high doses and is associated with leaching losses, it is necessary to supply this nutrient in split applications (Lucena and Zabini, 2021), increasing costs related to fertilizers and labor; therefore, management techniques are required to maintain this nutrient in the soil. It is well-established that green manure is an important technique for maintaining and recycling nutrients in the soil-plant system (Adekiya, 2018). Green manure absorbs nutrients that are in excess in the soil solution (Partey et al., 2014) that could be lost by leaching. After the aboveground biomass of the green manure is incorporated into the soil, the nutrients of its biomass and from the roots become available due to their decomposition. In addition, incorporating organic matter increases the charges in the soil, helping retain nutrients (Lucena et al., 2021).

Biochar has also been studied and is a promising alternative to increase soil fertility (Novak et al., 2009; Petter, 2010; Wisnubroto et al., 2017; Cheng et al., 2018; Yadav et al., 2018). Biochar is the by-product of pyrolysis of plant or animal biomass in an atmosphere with low oxygen concentration. The main components of most biochars are recalcitrant carbon and macro and micronutrients (Wisnubroto et al., 2017). During the pyrolysis process, biochar nutrients are concentrated (Bridgwater and Watkinson, 2011).

Application of biochar to the soil has great potential to increase the nutrient content in the soil solution, such as K (Wang et al., 2018; Cheng et al., 2018; Kuo et al., 2020). In addition, biochar can alkalize the soil (Kuo et al., 2020) due to proton consumption reactions, as occurs with exchange bonds between the functional groups of biochar with Al and Fe and by decarboxylation during partial decomposition of this material (Chintala et al., 2014), which may contribute to the increase in effective soil CEC (Liang et al., 2006).

During pyrolysis occurs the formation of negative charges that results from the oxidation of functional groups present on the surface of the biochar, such as carboxylic and phenolic groups (Novak et al., 2009). According to Petter (2010), as partial oxidation of the edges in aromatic structures of the biochar occurs, new electrochemical sites are formed, making it possible to increase the CEC. The presence of negative charges on the biochar surface (CEC) increases retention and reduces nutrient leaching (Li et al., 2019; Kuo et al., 2020). This fact is important in sandy soils, such as Podzols, where crops are frequently submitted to irrigation, and for highly leachable elements, such as K.

Biochar also affects soil biota (Barcelos et al., 2017; Paetsch et al., 2018) and can accelerate the decomposition of organic matter (Jindo et al., 2012). Silva et al. (2019) verified that the application of biochar with the boveground biomass of green manure (*Mucuna aterrima* Piper & Tracy) promoted, 60 days after being mixed with the soil, an increase in total bacteria colony by 133 %, but did not change the fungal population. Biochar has shown a synergistic effect on crop growth and yield when applied together with green manure biomass. This positive effect occurred for the papaya tree when it was cultivated with mucuna biomass and poultry litter biochar (Silva et al., 2019), and also occurred for Tiger nut (*Cyperus esculentus* L.) when it was grown with the biomass of Mexican sunflower (*Tithonia diversifolia* Asteraceae) and wood biochar (Adekiya et al., 2020a). Biochar combined with *Tithonia diversifolia* or *Vicia faba* increased corn grain yield (Partey et al., 2014).

Biochar application at the beginning of green manure cultivation can increase biomass production and nutrient acquisition for these plants. Nutrients, such as K, are available in high concentrations in the soil solution (Adekiya et al., 2020a) and can be absorbed by green manure, but can also be retained in the biochar charges (Cheng et al., 2018; Kuo et al., 2020). This can reduce leaching losses and still maintain a residual nutrient effect in the soil (Wisnubroto et al., 2017). This effect is particularly important for sandy soils.

Considering that large K losses occur in sandy soils with commercial cultivation of dwarf coconut trees and that green manure is cultivated in these soils to maintain the element in the soil-plant system, we intend to test the hypothesis that biochar increases the content of cationic bases in soil, and increases the growth and accumulation of K in the biomass of mucuna green manure. We hypothesized that biochar reduces K losses by leaching when this element is applied in high doses in the form of KCl, maintaining a greater pool of K in the soil-plant system in sandy soil collected in the coconut cultivation area.

The objective of this study was to evaluate the effect of poultry litter biochar combined or not with increasing doses of KCl on the chemical properties of soil and leached solution, on the accumulation of K in each compartment of the soil-plant-water system, and the production of green manure biomass.

MATERIALS AND METHODS

The experiment was conducted in a greenhouse in the design of randomized blocks (6 blocks), in a 2 × 3 factorial scheme, without and with the biochar application with three levels of K (0, 53.65, and 107.30 mg dm^{-3} of K, which correspond to 0, 64.66 and 129.3 mg dm^{-3} of K_2O) applied as a single dose KCl. The highest dose of K used was based on the recommendation of coconut tree fertilizers, according to Sobral (2003), since it was the crop deployed in the soil collection area. The experiment was performed in four steps, according to figure 1. The amount of biochar applied was 1 % v/v, which corresponded to 2.76 g dm^{-3}. The biochar was produced by SPPT - Technology Research Ltda, Mogi-Mirim, SP, Brazil, and the production methodology was written by Lin et al. (2012). Biochar was produced by slow pyrolysis (15 minutes at 400 °C) from dry poultry litter granules (ranging from 3 to 12 mm in diameter). The initial material for the poultry litter was rice husk. To facilitate soil homogenization, biochar was sieved (2mm mesh) and then the samples corresponding to the biochar treatment were weighed and applied to the soil. The chemical and physical characterization of the biochar is shown in table 1.

The soil type used was a Gleyic Albic Podzol (Arenic, Drainic, Endic) according to the International Union of Soil Science (IUSS Working Group WRB, 2022), which corresponds to a Haplorthod according to the Soil Taxonomy (Soil Survey Staff, 2014), or an *Espodossolo Humilúvico Hidromórfico* according to the Brazilian Soil Classification System (Santos et al., 2018). The soil was collected in a 10-year-old coconut plantation located in the city of Quissamã, Rio de Janeiro, Brazil. To reduce surface organic matter, the soil was collected from a layer of 0.05-0.40 m. The chemical and physical properties are presented in table 2.

After air drying, the collected soil was sieved in a 4 mm sieve and homogenized. Soil samples of 4 kg were separated and packed in polyethylene bags where the application and homogenization of the treatments (biochar and KCl) were performed. All samples received fertilization with nitrogen (110 mg dm^{-3} of N in the form of urea – reagent p.a.) and phosphate (300 mg dm^{-3} of P as simple superphosphate – commercial fertilizer). Soil samples were moistened to 60 % of the total pore volume (TPV), according to Freire et al. (1980), and incubated for 20 days. Incubated soil samples were collected for chemical analysis.

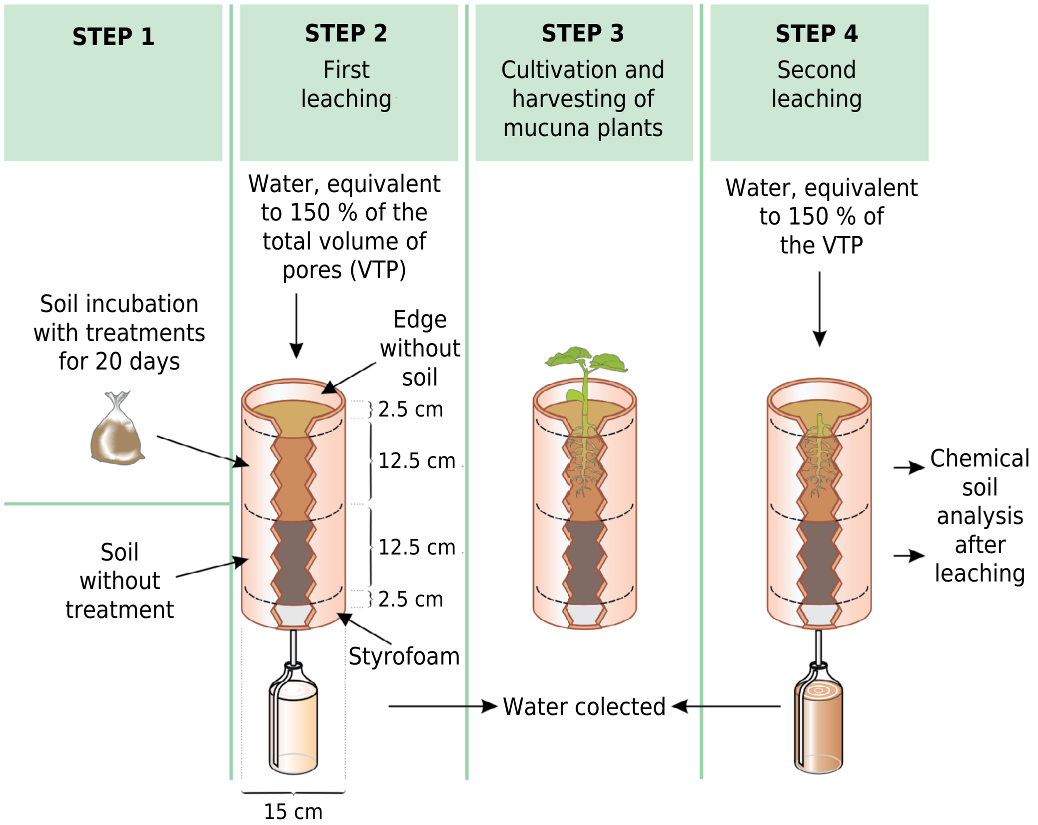

Figure 1. Scheme of the experiment steps for measuring leaching of K in soil columns treated with or without biochar in association with three levels of potassium and then cultivated with mucuna (for 40 days). The plastic bag soil (step 1) was treated with or without biochar and three levels of K. In step 2, the surface part of the pots was filled with soil from the bags (treated soil and incubated) and lower layer being filled with the same soil, but without treatment and without incubation. Chemical analysis was performed on the water collected in steps 1 and 4.

Table 1. Chemical characterization of the biochar used in the experiment

Properties	Values
Total N (g kg^{-1})	31.8
P (g kg^{-1})	29.40
K g kg^{-1})	47.20
Ca (g kg^{-1})	48.30
Mg (g kg^{-1})	14.60
S (g kg^{-1})	10.00
Al (g kg^{-1})	15.50
Na (g kg^{-1})	7.30
C (g kg^{-1})	429
pH(H_2O)	10.2
Fe (g kg^{-1})	8.5
Cu (g kg^{-1})	0.6
Zn (g kg^{-1})	1.07
Mn (g kg^{-1})	0.65
B (g kg^{-1})	0.48
CEC (mmol$_c$ kg^{-1})	80.00
U (%)	2.8
D (kg dm^{-3})	0.276

CEC: cation exchange capacity; U: moisture; D: density.

Table 2. Chemical properties from the Gleyic Albic Podzol (Arenic, Drainic, Endic) collected at a soil layer of 0.05-0.40 m, before biochar and K application

Properties	Values
pH(H_2O)	5.4
P (mg dm^{-3})	9.0
K (mg dm^{-3})	59.0
Al ($cmol_c$ dm^{-3})	0.05
H+Al ($cmol_c$ dm^{-3})	1.0
Ca^{2+} ($cmol_c$ dm^{-3})	2.2
Mg^{2+} ($cmol_c$ dm^{-3})	0.4
Na^+ ($cmol_c$ dm^{-3})	0.4
CECef ($cmol_c$ dm^{-3})	3.2
SB ($cmol_c$ dm^{-3})	2.1
V (%)	38.0
C (g dm^{-3})	1.11
MO (g dm^{-3})	1.91
Sand (g kg^{-1})	963
Silt (g kg^{-1})	12
Clay (g kg^{-1})	25
TP (m^3 m^{-3})	0.38
PD (mg m^{-3})	2.65
DS (mg m^{-3})	1.66

pH in H_2O; Ca^{2+} and Mg^{2+} were extracted with KCl solution and determined by atomic absorption spectrometry; Al^{3+} was extracted with KCl solution; K, Na, and P were extracted with Mehlich-1 solution and determined by flame photometry and colorimetry, respectively; potential acidity was extracted with calcium acetate. CECef: effective cation exchange capacity; C: carbon; MO: organic matter; TP: total porosity; PD: particle density; DS: soil density.

The cultivation containers for the mucuna plants were made with PVC (polyvinyl chloride) pipe 150 mm in diameter with 0.30 m high (cut into 0.15 m high sections, fastened two by two, and joined with adhesive tape) (Figure 1). The bottom of each container was sealed with a polystyrene (styrofoam) circle containing a hole in the center and equipped with a leached water collection tube (Figure 1). The containers were also lined with plastic bags to prevent contact between the soil, the PVC wall, and the styrofoam bottom. A thin screen was also used inside the plastic bag and at the bottom of each container to prevent soil from entering the leached water collection tube.

As shown in figure 1, soil without any treatment or fertilization (3.27 kg of soil) was placed at the bottom of the containers (12.5 cm high). The top layer of the container (12.5 cm high) was filled with 3.27 kg of incubated soil containing the treatments. After the soil was placed in the cultivation pots, the free end of each leaching tube was closed and raised to the height of the upper edge of the pot to prevent water drainage. The containers received water until they reached saturation, and the amount of water retained in the soil in this condition corresponded to the total pore volume (TVP). After four hours, the leaching tubes were lowered, and the sealing of the tubes was removed to allow the leached water that was collected in bottles to pass through. Then more water was added, equivalent to 50 % of the TVP, and after 24 h of drainage (when there was no more water flow), the collection bottles were removed. The water volume was measured and samples of the leached solution were filtered on filter paper and analyzed for K, Ca, Mg, and electrical conductivity.

Five days after leaching, five seeds of black mucuna (*Mucuna aterrima* Piper & Tracy) were sown in each growing pot. After the emergence of the seedlings, only the two most vigorous plants were maintained in each container.

The plants were cultivated and irrigated for 40 days. All the excess water that was drained in the pots during the cultivation of the plants was collected in the container and then used for the determination of the nutrients leached. The aerial part was cut, dried in a greenhouse with forced air circulation at 65 °C for 72 h, and measured in terms of dry biomass weight. The material was then crushed and subjected to nitric digestion. The K content (Tedesco et al., 1995) was determined, and the accumulation of K was estimated considering the weight of dry aboveground biomass from the two plants in each pot.

Shortly after cutting the mucuna, the containers were again subjected to maximum saturation plus the equivalent of 50 % of the total pore volume, and a second collection of the leached water was performed. Subsequently, utilizing a small drill, soil samples from the surface (4 to 8 cm deep) and subsurface (16 to 20 cm deep) were collected for chemical analysis (K, Ca, Mg, P and pH) (Teixeira et al., 2017).

The K content of the leached solution was performed directly in the collected solution, while the K content of the soil was extracted with Mehlich-1 (Teixeira et al., 2017). The K accumulation in the soil was calculated from the content of the element in the soil and the soil mass initially added to each layer of the containers. The K accumulation in the leached solution was calculated from the content obtained in this solution and the total volume of the leached solution in each container.

The date of soil nutrient content and leached water, and aboveground biomass of mucuna plants, were analyzed for normality (Shapiro-Wilk), homoscedasticity (Bartlett's test) and, subsequently, they were submitted to variance analysis (ANOVA) by the F test and, when significant, to the Tukey test ($p \leq 0.05$). The effects included in the statistical model were biochar (with and without), three K levels and the interactions Biochar * K doses. Statistical analysis were performed using Sisvar 5.6 software (Ferreira, 2014).

RESULTS

Effect on plant growth, soil nutrient content, and leached water:

Results of the analysis of variance with the effects of application or not of biochar, the effect of KCl levels and their interactions for dry matter, nutrient content, leached water, electrical conductivity, pH and CEC are in table 3. There was only no significant effect of the application of biochar on the content of Mg in the subsurface soil. There was no effect of KCl application only for Ca content in the surface soil and C content in the recently incubated soil. No significant interaction was observed between the application or not of biochar and KCl levels for the dry mass of mucuna plants, effective CEC in the surface soil, in the pH and C content of the recently incubated soil and in the Mg content in the water of the first leaching. For all other variables, significant differences were observed between the application or not of biochar, or between the levels of KCl applied to the soil, or significant differences were observed in the interaction between these factors.

Biochar increased dry mass of mucuna plants at each dose of KCl applied. Increasing KCl doses provided increments in plant biomass when in the biochar absence, while in the presence, there were no differences between the two doses applied (Figure 2).

An increase in KCl doses resulted in increments in the K concentration in the recently incubated soil and the soil surface layer and subsurface of the cultivation container. At each KCl dose, the biochar application increased the K content in the soil (Figure 3a) in the compartments evaluated.

Table 3. Summary of the analysis of variance (ANOVA) with the effects of application or not of biochar, the effect of KCl levels and their interactions for results to results: Dry mass of mucuna plant (DM); CEC, pH and nutrient content in soil and leaching water

Sources of variation	DF	Soil											
		K			Ca			Mg			P		
		INC	Sur	Sub	INC	Sur	Sub	INC	Sur	Sub	INC	Sur	Sub
Biochar	1	**	**	**	**	**	ns	**	**	ns	**	**	**
K doses	2	**	**	**	**	ns	*	**	**	**	**	**	**
B*K	2	**	**	**	**	**	**	**	**	**	**	**	**
Bl	5	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
C.V.(%)		0.77	3.23	3.80	0.60	2.19	6.52	2.93	4.33	3.16	1.50	2.65	13.59

Sources of variation	DF	Soil											
		C			$CEC_{pH=7}$			$CEC_{efetive}$			$pH(H_2O)$		
		INC	Sur	Sub	INC	Sur	Sub	INC	Sur	Sub	INC	Sur	Sub
Biochar	1	**	**	**	**	**	**	**	**	ns	ns	**	**
K doses	2	ns	**	**	**	**	**	**	**	*	ns	**	**
B*K	2	ns	**	**	**	**	**	**	ns	**	ns	**	**
Bl	5	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
C.V.(%)		24.00	6.72	4.14	0.87	1.52	4.48	0.87	1.44	3.30	15.21	0.50	0.60

Sources of variation	DF	Water										Plant
		K		Ca		Mg		EC		EC		
		First leaching	Second leaching	First leaching	Second leaching	First leaching	Second leaching	First leaching	Second leaching	First leaching	Second leaching	DM
Biochar	1	**	**	**	**	**	**	**	**	**	**	**
K doses	2	**	**	**	**	**	**	**	**	**	**	**
B*K	2	**	**	**	**	**	**	**	**	**	**	**
Bl	5	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
C.V.(%)		2.33	6.15	5.46	8.25	1.10	0.83	0.29	0.94	0.29	0.94	1.10

ns: not significant; * and **: significant at 5 and 1 % probability and by the F test, respectively. Bl: blocks; C.V.: coefficient of variation; INC: incubation; Sur: surface soil; Sub: subsurface soil; DM: dry biomass of mucuna plant; C: carbon content; CEC: cation exchange capacity; EC: electric conductivity.

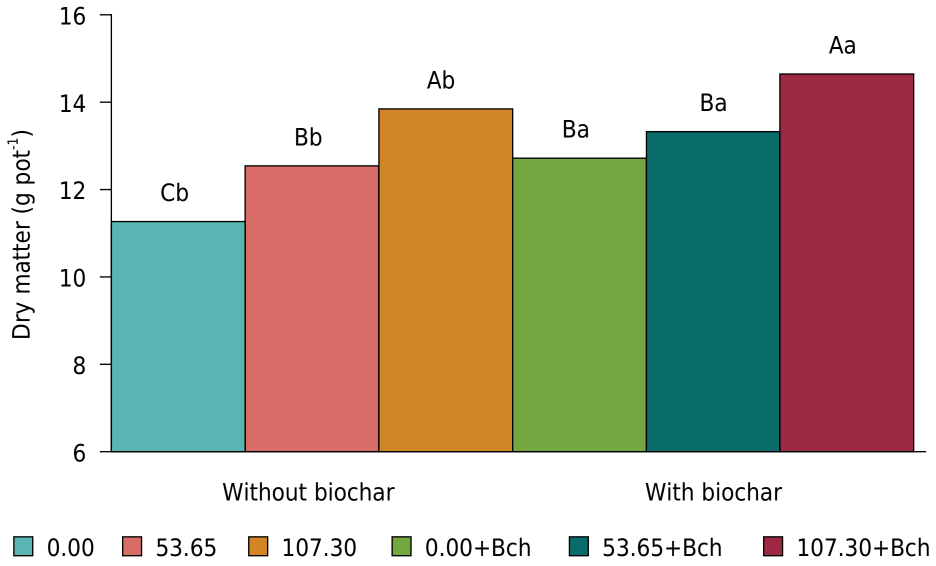

Figure 2. Shoot dry matter of mucuna plants grown in soil treated with or without biochar associated with three doses of potassium (mg dm^{-3}). Differences between the three K doses for treatments with or without biochar are indicated by capital letters. Differences between treatments with or without biochar at each dose of K are indicated by lowercase letters, both by Tukey's test at 5 % (average of 6 repetitions).

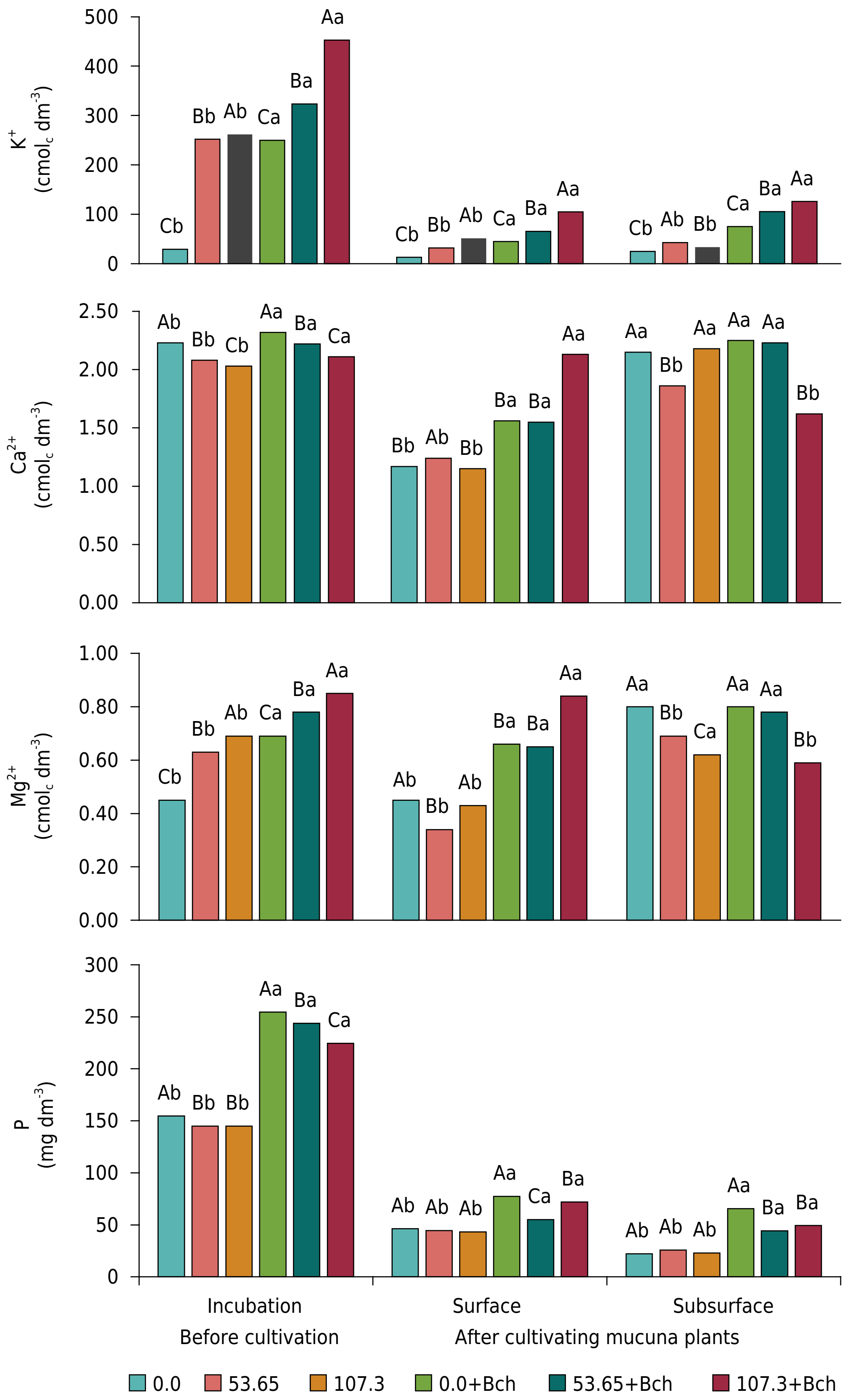

Figure 3. Potassium (a), Ca^{2+} (b), Mg^{2+} (c), and P contents (d) in the incubated soil (during 20 days) and the surface and subsurface soils (after the mucuna cultivation) treated with or without biochar associated with three doses of K (mg dm^{-3}). Differences between the three K doses for treatments with or without biochar are indicated by capital letters. Differences between treatments with or without biochar at each dose of K are indicated by lowercase letters, both by the Tukey's test at 5 % (mean of 6 repetitions).

Phosphorous, Ca^{2+} and Mg^{2+} contents increased in the incubated soil and container soil surface with the biochar addition compared to its non-application. This occurred in all KCl doses (Figures 3b, 3c, and 3d). In subsurface soil, however, the increase in Ca^{2+} and Mg^{2+} contents occurred only with the biochar application and only in the intermediate KCl dose. In both the biochar presence and absence, the application of increasing KCl doses caused a proportional reduction in Ca^{2+} and P contents and increased Mg^{2+} contents in recently incubated soil. It also decreased the Mg^{2+} content in the soil of the subsurface layer (Figures 3b, 3c, and 3d).

Applying biochar increased the carbon content, effective CEC, potential CEC, and pH values the recently incubated soil and also of the soil surface layer, after the cultivation of the mucuna plant (Figures 4a, 4b, 4c, and 4d). In the soil subsurface layer, however, there was no variation in the effective and potential CEC with the biochar application compared to its non-application (Figure 4c).

The result of the first leaching indicated that without the biochar addition in the soil, the increasing KCl doses provided an increase in the K, Ca, and Mg contents in the water (Figures 5a, 5b, and 5c). With biochar, however, the increase in KCl doses did not result in an increase in the K and Ca in leached water. The increase of KCl doses provided increases in electrical conductivity in the water of the first and second leaching events (Figure 5d). Evaluating each KCl dose separately, it was observed that at the first leaching event, the biochar application increased the K and Ca content in the leached water. On the other hand, the second leaching reduced the Ca and Mg concentration in the leached water but increased the K concentration. Biochar application increased the electrical conductivity in the water of the first leaching but reduced the conductivity of the water in the second leaching.

K distribution in the soil- plant-water system

Results of analysis of variance for K content in mucuna plant; K content in soil (surface and subsurface layer); K content in the leached water and K total content (accumulated in the soil-water-plant system) (mg pot^{-1}) are presented in table 4. For all variables, significant differences were observed between the application or not of biochar, between the levels of KCl applied to the soil and significant differences were observed in the interaction between these factors.

Potassium accumulation in the mucuna aboveground biomass was influenced by the biochar application and the KCl doses applied (Figure 6a). Increasing doses of K fertilization, when no biochar was added, led to proportional increases in the K accumulation in the plant. For each KCl dose applied to the soil, the application in conjunction with biochar increased the K accumulation in the aerial part of plants. Increasing KCl doses in biochar and non-biochar treatments provided increases in the K accumulation in the soil of the surface and subsurface layer (Figure 6a). The separate (or individual) evaluation of each KCl dose revealed that the biochar application increased the K accumulation in both soil layers compared to its non-application.

The accumulation of K evaluated in the water during the first leaching (before mucuna cultivation) and also in the second leaching (shortly after cultivation) showed that the increase of KCl doses promoted K accumulation, but only in the absence of biochar (Figure 6a). With the biochar application, the increment of KCl doses did not result in increases in the K accumulation in water, both in the first and second evaluation. For each KCl dose, the biochar application increased the K accumulation in water only at the first leaching.

For each treatment, the total K accumulation (Figure 6b), obtained by the sum of the accumulated K in the aerial part of the plant, surface, and subsurface soil and water in the first and second leaching, was defined as the K pool in the soil-plant-water system.

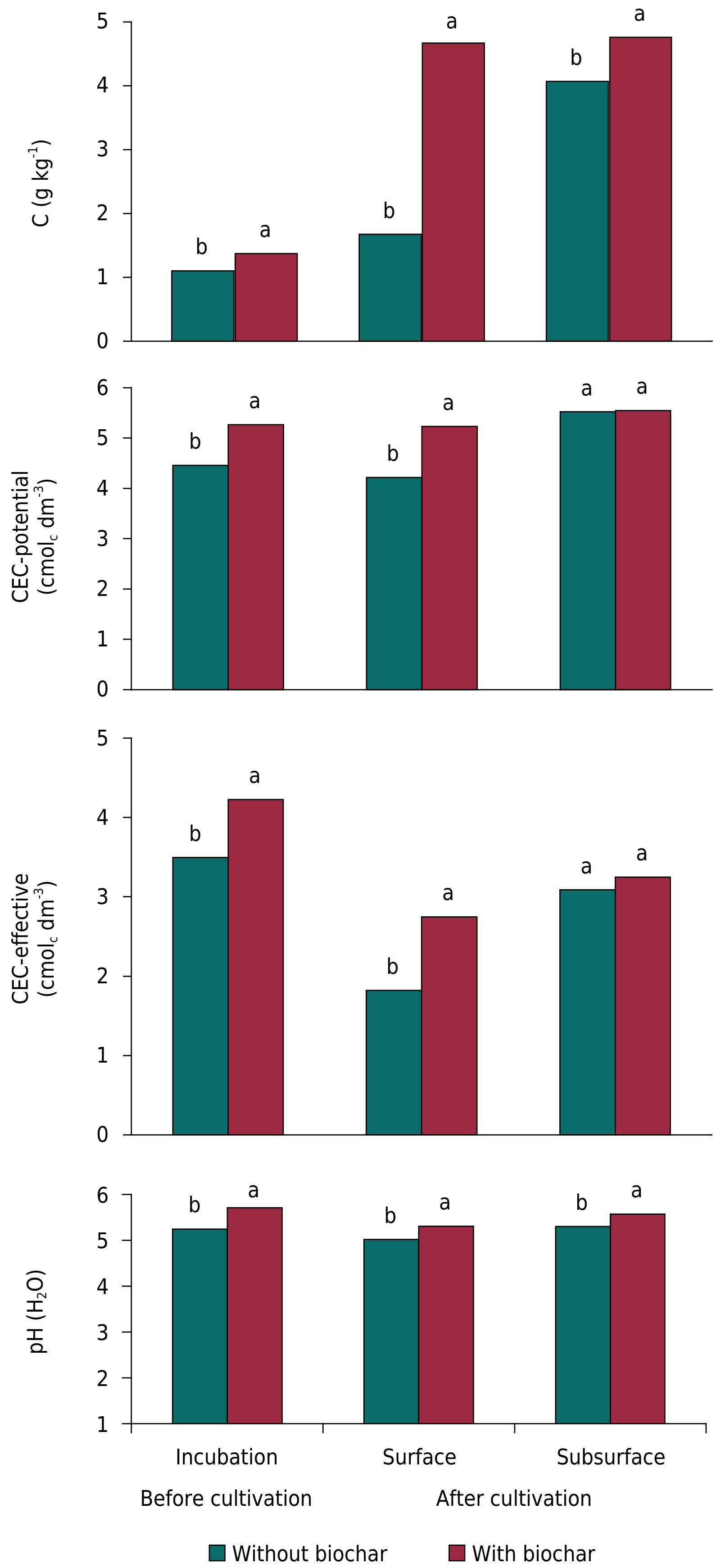

Figure 4. Mean values of soil carbon content (a); potential CEC (b), effective CEC (d), and pH (e) in the newly incubated soil and the surface and subsurface soils (after the mucuna cultivation) treated with or without biochar. Different lowercase letters indicate a significant difference by the Tukey test at 5 % (average of 6 replicates). CEC: cation exchange capacity.

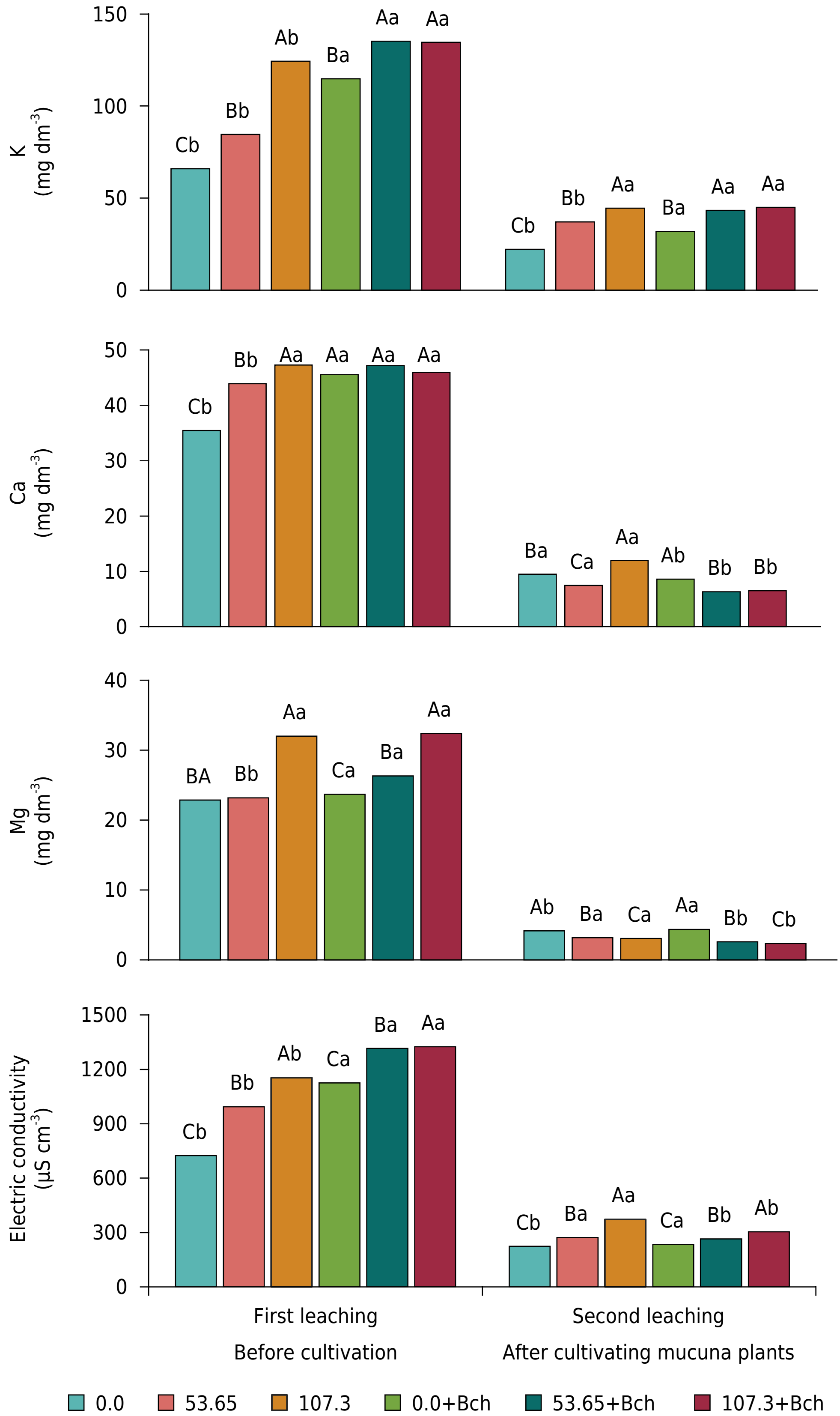

Figure 5. Potassium (a), Ca (b), Mg (c) and electric conductivity (d) in the water of the first leaching event (after incubation) and the water of the second leaching (after harvest of the mucuna) from soil treated with or without biochar associated with three doses of K (mg dm^{-3}). Differences between the three K doses for treatments with or without biochar are indicated by capital letters. Differences between treatments with or without biochar at each dose of K are indicated by lowercase letters, both by the Tukey's test at 5 % (mean of 6 repetitions).

Table 4. Results of the analysis of variance (ANOVA) with the effects of application or not of biochar, the effect of KCl levels and their interactions for results of K content

Sources of variation	DF	Plant	Soil		Water		TOTAL
		DM	Surface	Subsurface	First leaching	Second leaching	
Biochar	1	**	**	**	**	**	**
K doses	2	**	**	**	**	**	**
B*K	2	ns	**	**	**	*	**
Bl	5	ns	**	ns	ns	ns	ns
C.V. (%)		5.07	5.42	3.98	11.31	17.29	8.6

ns: not significant; * and **: significant at 5 and 1 % probability by the F test, respectively. DF: degrees of freedom; Bl: blocks; C.V.: coefficient of variation; DM: dry biomass of aboveground of mucuna; K content TOTAL = (DM+ soil Surface+ soil Subsurface+ water from first leaching+ water from second leaching).

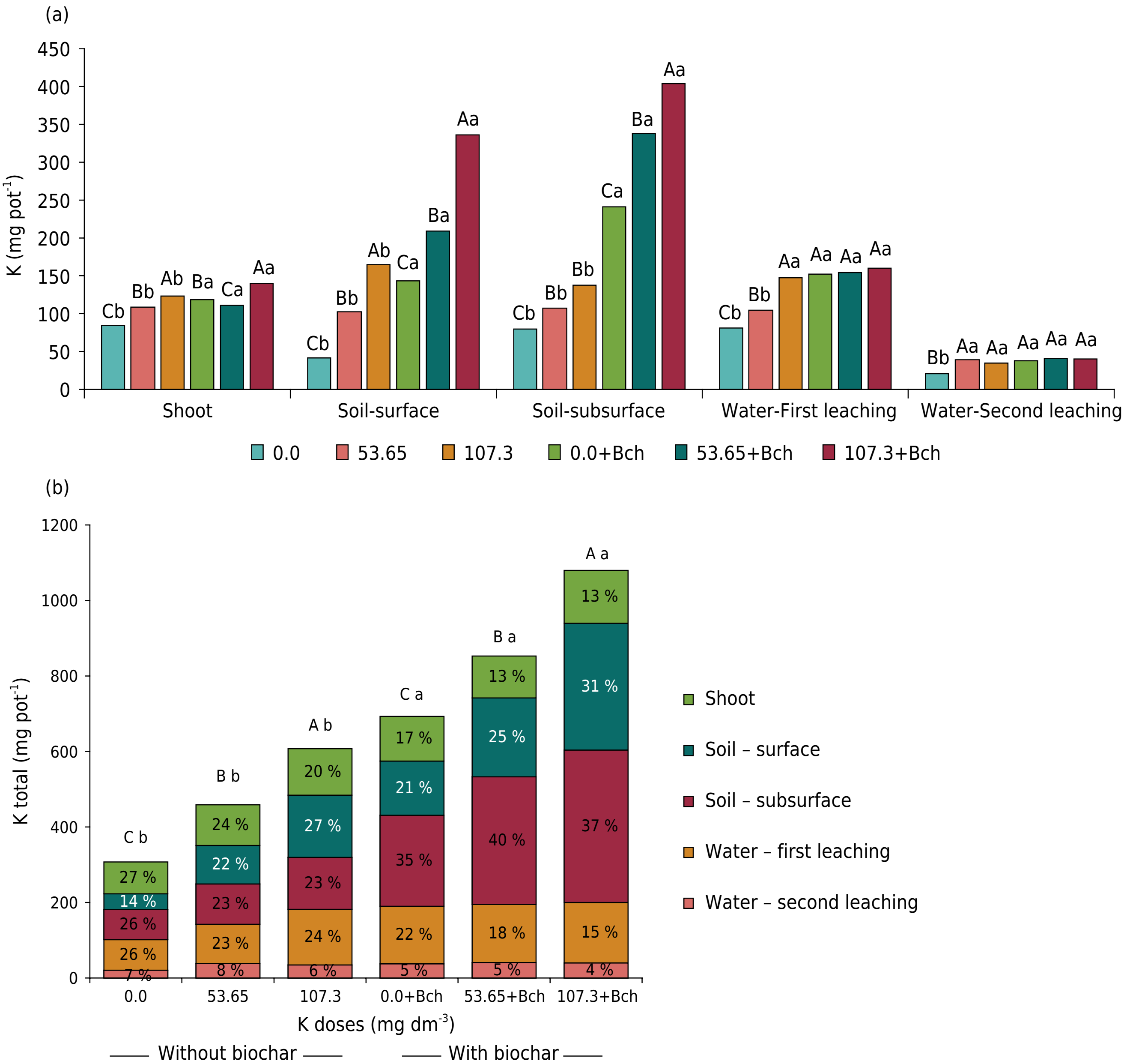

Figure 6. Potassium content in the shoot plants of mucuna, in the surface and subsurface soils of the pots (after cultivation) and in the water of the first leaching (after the incubation period) and in the water of the second leaching (performed after the harvest of mucuna), after treated with or without biochar associated with three levels of K (a). Total content of K in the soil-plant-water system (obtained by the sum of the K accumulation in the plant shoots + K content in the soil + K content in the leached water) and proportion of total content accumulated by parts: soil-plant-water ratio (b). Differences between the three K doses for treatments with or without biochar are indicated by capital letters. Differences between treatments with or without biochar at each dose of K are indicated by lowercase letters, both by the Tukey's test at 5 % (mean of 6 repetitions).

Total K accumulations increased with increasing KCl doses applied, with or without biochar application. The biochar application increased the K accumulation in the system with each KCl dosage tested. Without biochar, the K accumulation in the soil-plant-water system varied between 307.44 and 607.46 mg pot^{-1} (dose without KCl and higher dose of KCl, respectively), while with biochar ranged between 602.95 and 1079.74 mg pot^{-1} (only biochar and biochar + higher KCl dose, respectively).

Potassium percentage distributed in each compartment of the soil-plant-water system (Figure 6b) was estimated based on the total K accumulation obtained in the system (K pool). Regarding the K percentage accumulated in the aboveground biomass of mucuna, in plants that received biochar, the percentage varied between 12 and 17 % of the total K, while in plants that did not receive biochar the values ranged from 20 to 27 %. Regarding the soils of the surface and subsurface layers, the biochar application to each KCl dosage increased the K percentage accumulated in these two compartments.

DISCUSSION

Effect on plant growth, soil nutrient content and leached water

After biochar application, it was observed an increase in the K, Ca, Mg, P and C content in the recently incubated soil by 754, 4, 53, 64 and 28 %, respectively; and the surface soil by 244, 33, 40, 67 and 179 %, respectively (Figures 3a, 3b, 3c, and 3d); these results indicate the presence of these elements in the biochar, in available forms, which was also verified by Wang et al. (2018) and Santos et al. (2019). Singh et al. (2010) state that Ca concentration in biochar usually increases after pyrolysis. Prakongkep et al. (2014) showed that biochar is rich in monopotassium phosphate (KH_2PO_4), a very water-soluble and highly available P-form, increasing the levels of K and P in the soil.

Increasing KCl doses decreased P content in recently incubated soil, with and without biochar (Figure 3d). This response was similar for Ca (Figure 3b). This result suggests that Ca and P precipitation may have occurred at the highest KCl doses applied. Ernani et al. (2007) report that at high K levels in the soil, Mg and Ca are displaced into the soil solution, increasing the possibility of precipitation. In addition, the biochar application slightly increased the soil pH (Figure 4c). The more alkaline medium can increase P precipitation with Ca (Lucena et al., 2021).

Biochar increased the aboveground biomass of the green manure (Figure 1) and the soil's carbon content (Figure 4a). Furthermore, the increase in carbon content was more accentuated after the mucuna plant cultivation, compared to the newly incubated soil, indicating the positive influence of the green manure root system, mainly on the subsurface of the cultivation containers.

In the water of the first leaching, which occurred after incubation, it was verified that the biochar and increasing KCl doses provided higher K, Ca, and Mg content in the water (Figure 5), confirming that these nutrients are in available form, which also increased the electrical conductivity of the leached solution (Figure 5d). Cheng et al (2018) also observed the leaching loss of K, P, and Na in the soil that received biochar, except for Ca. In this study, in addition to the sandy soil, another factor that can increase the leaching of bases in the soil, is the accompanying ion, among them sulfate and nitrate (Lucena et al., 2021). The application of simple superphosphate fertilizer ($Ca(H_2PO_4)_2$ H_2O + $CaSO_4.2H_2O$), performed in all treatments before soil incubation, provided the entry of sulfate that may help in the descent of the bases in the soil profile, even in the control that did not receive biochar or KCl.

It is important to note that the biochar application associated with increasing KCl doses did not result in proportional increases in the K content in the water of the first leaching

(Figure 5a). This effect would be similar to what occurs in soil with a higher capacity factor, that is, greater buffer capacity (Lucena et al., 2021), where more stable nutrient levels are maintained in the soil solution, even with larger inputs, due to adsorption of the elements in the soil loads. The longer contact time of the biochar with the soil may have enabled the greater balance between the solid phase and the soil solution by increasing the buffering of these bases with the biochar presence. This may explain why the application of biochar reduced the electric conductivity of the water in the second leaching (Figure 5d), indicating lower base levels despite the KCl application.

Soil nutrient retention can be attributed to biochar's ability to adsorb these elements due to high CEC (Novak et al., 2009; Singh et al., 2010). Studies have indicated high CEC in biochar obtained by slow pyrolysis (Jien and Wang, 2013), as used in the present study, a fact that may be associated with the presence of charges in the biochar (Liang et al., 2006) raising the potential CEC by 24 % and effective CEC by 20 % in the newly incubated soil. The increase of pH and carbon content after biochar application (Figures 4a and 4d) may also have contributed to the increase in effective soil CEC (Figure 4c).

Soils with potential CEC greater than 4.0 $cmol_c\ kg^{-1}$, K content needs to be greater than 51 $mg\ kg^{-1}$ to be considered adequate (Rossetto et al., 2004). In the recently incubated soil for all treatments (with and without biochar addition), the soil K contents (Figure 3a) were greater than 51 $mg\ kg^{-1}$ and the CEC was greater than 4.0 $cmol_c\ kg^{-1}$ (Figure 4b). After mucuna harvest, the surface and subsurface soil presented adequate K content in biochar treatments. However, only the highest KCl dose reached these values without the biochar application. In the subsurface, none of the KCl doses applied reached the adequate K content, which indicates the need for K replacement in the biochar absence.

K distribution in the soil-plant-water system

Quantifying the accumulated K in the plant-soil-water compartments (Figure 6a) is important since only the content evaluation could incur an error. These may occur due to the dilution effect on the K content caused by the difference between treatments in plant biomass production. Similarly, the amount of leached water was not proportional to the water applied in all treatments since biochar itself affects soil water retention (Paetsch et al., 2018; Razzaghi et al., 2020). Therefore, we opted to evaluate the K accumulation in each part of the soil-plant-water system (Figure 6a).

In addition to accumulating more K in the soil of the surface and subsurface of the growing container, the element also came out along the leached water, collected below the subsurface layer, indicating the transport to greater depths of this element. This is particularly interesting in perennial plant cultivation or with a deeper root system. However, in the presence of biochar, the K accumulated in the water of the first and second leaching, was not proportional to the applied KCl dose, confirming the greater retention of K in the solid fraction of the soil, as already discussed earlier. Several studies have also reported reduced nutrient leaching in soil that received biochar application (Novak et al., 2009; Singh et al., 2010; Cheng et al., 2018; Kuo et al., 2020).

Biochar efficiently increased the total K accumulation in the soil-plant-water system (Figure 6b), and the increase was proportional to the added KCl. The isolated application of the biochar provided a total K accumulation of 692.95 $mg\ pot^{-1}$, 125 % higher than that without biochar and 14 % higher than the highest KCl dose tested when not associated with biochar (607.46 $mg\ pot^{-1}$). This answer indicates the efficiency of the biochar application in the soil for the addition of this element to the soil-plant-water system.

It was observed that at the zero dose of KCl, the K accumulation in the soil-plant system, without and with biochar, was respectively 205.8 and 503 $mg\ pot^{-1}$ (increase of 145 %), and at the highest dose of KCl it was respectively 425.6 and 879.9 $mg\ pot^{-1}$ (increase of 109 % with biochar). Biochar not only changes the total K accumulation (mg pot^{-1}) in the soil-plant-water system, but also changes the percentage proportion of K in each component of this system. It is important to consider that in the treatments in which the total K acquired in the system was lower (as is the case of treatments without biochar), mucuna plants maintained a higher K percentage accumulation in the abouveground biomass compared to treatments in which the total K acquired in the system was higher (as is the case of treatments with biochar and high KCl doses).

In the presence of biochar, the percentage of K accumulated in the soil compartment (summing up the surface and subsurface layers), relative to the total accumulated in the soil-plant-water system, was 55, 65 and 68 % for the zero, intermediate and higher levels of KCl tested, respectively. On the other hand, without biochar, for these treatments, the percentage of accumulated K was 39, 45, and 50 % K, respectively, indicating that higher KCl doses provided greater K retention in the soil and this retention was more pronounced in the biochar presence. The retention of nutrients in the soil is important because it maintains a residual effect of nutrients that can be acquired by the subsequent culture, as observed in the cultivation of red pepper (Wisnubroto et al., 2017).

Since the cultivated plant species is green manure, the ideal in sandy soil is that the applied nutrient is maintained in the soil-plant system (sum of the accumulated in the soil of the surface + subsurface + aerial part of the plant). The sum of the K percentage accumulated in the soil–plant system without biochar ranged from 67 to 70 % (respectively for control and with a higher KCl dose applied). With biochar, the K percentage accumulated in the soil-plant system ranged from 73 (with the isolated biochar application) to 81 % (higher KCl dose combined with biochar).

In the treatments without biochar (Figure 6b), the K percentage accumulated in the leaching water (first + second leaching) for the zero, intermediate and high levels of KCl applied to the soil was, respectively, 33, 31 and 30 % of the total acquired in the soil-plant-water system. For biochar treatments, however, it was, respectively, 27, 23 and 19 %. Thus, despite the greater total K accumulation in the soil-plant-water system provided by biochar, a lower percentage was lost by leaching to layers below 0.30 m deep. These findings show that biochar played an important role in the K distribution in the soil while efficiently promoting the retention of this element in the soil-plant system, with lower percentage losses in leached water when applied in high doses. This result was also observed by Kuo et al. (2020), who studied sandy loam soil. However, Cheng et al. (2018) found in loamy soil that, with the biochar application, greater K losses were observed in leached water, indicating that the response may vary depending on soil characteristics.

Regarding green manure, high biomass production is important in soil management because it promotes the entry of organic matter into the system. In this study, although the increasing KCl doses increased plants' dry biomass production (Figure 2), biochar application increased this production even more. A similar response was observed when mineral fertilizer was combined with biochar, such as for corn (Partney et al., 2014) and ginger plants (Adekiya et al., 2020b). On the other hand, the isolated biochar application provided a dry mucuna biomass production similar to the intermediate KCl dose (and in the absence of biochar), indicating the possibility of a sharp reduction in potassium fertilization by 50 %, and still, biomass with greater accumulation of K. The positive response to biochar application in plant growth varies with the culture, the soil, and the biochar used (Novak et al., 2009; Petter, 2010; Prakongkep et al., 2014; Cheng et al., 2018; Silva et al., 2019).

In biochar treatments, in addition to the higher production of dry biomass in mucuna plants, the higher contents of K, P, Ca, and Mg observed on soil surface, after mucuna cultivation, indicate that although they were absorbed by the green manure and partially leached, considerable levels were kept in the soil and, therefore, will be available for absorption by plants in subsequent harvests. In addition, K, as well as the other nutrients accumulated in the biomass of the aerial part and the roots of the green manure, will also be made available after its decomposition.

CONCLUSION

Biochar application improves Podzol sandy soil chemical properties (increase P, Ca^{2+}, Mg^{2+} contents, cation exchange capacity and carbon) and these changes persists after the cultivation of black mucuna green manure. Biochar increases dry biomass and K accumulation and, reduces 50 % the need of potassium fertilizer for the black mucuna plants.

Biochar increases the K pool and change the K compartmentalization in the soil-plant-water system, providing greater K adsorption in the soil and lower K content in the leaching water. Greater retention of K is maintained in biochar ammended soil, even with potassium fertilization at high doses.

Biochar produced from poultry litter can improve the fertility of Podzol sandy-soil, maintain K in the soil-plant system and, reduce nutrient losses by leaching.

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AUTHOR CONTRIBUTIONS

Conceptualization: Caroline Cândida Martins (lead), Claudio Roberto Marciano (supporting) and Luciana Aparecida Rodrigues (lead).

Data curation: Caroline Cândida Martins (lead), Júlia Gallon Barcelos (equal), Mauricio Gonçalves da Silva (supporting), Rosely Menezes da Silva Ribeiro (equal) and Tainá Costa Araújo (supporting).

Formal analysis: Caroline Cândida Martins (lead), Júlia Gallon Barcelos (equal), Mauricio Gonçalves da Silva (supporting) and Tainá Costa Araújo (supporting).

Funding acquisition: Deborah Guerra Barroso (lead) and Luciana Aparecida Rodrigues (lead).

Investigation: Caroline Cândida Martins (lead), Claudio Roberto Marciano (supporting) and Luciana Aparecida Rodrigues (lead).

Methodology: Caroline Cândida Martins (lead) and Tainá Costa Araújo (supporting).

Project administration: Luciana Aparecida Rodrigues (lead).

Resources: Deborah Guerra Barroso (lead) and Luciana Aparecida Rodrigues (lead).

Software: Caroline Cândida Martins (lead) and Luciana Aparecida Rodrigues (lead).

Supervision: Deborah Guerra Barroso (lead) and Claudio Roberto Marciano (supporting).

Validation: Claudio Roberto Marciano (supporting).

Visualization: Caroline Cândida Martins (lead), Júlia Gallon Barcelos (equal) and Rosely Menezes da Silva Ribeiro (equal).

Writing - original draft: Caroline Cândida Martins (lead).

Writing - review & editing: Deborah Guerra Barroso (supporting), Luciana Aparecida Rodrigues (lead) and Rosely Menezes da Silva Ribeiro (equal).

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