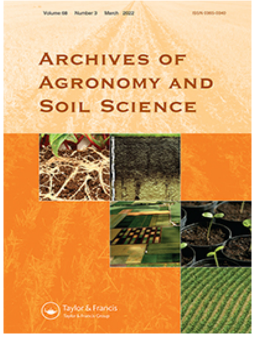


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# Effects of the application of biochar on soil fertility status, and nutrition and yield of onion grown in a no-tillage system

Fábio Satoshi Higashikawa [a], Carlos Alberto Silva [b], Carla Eloize Carducci [c], Keiji Jindo [d], Claudinei Kurtz [a], Edivânio Rodrigues de Araújo [a], Renata Sousa Resende [a] and Daniel Pedrosa Alves [a]

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**ABSTRACT**
The study was aimed to evaluate the effect of successive applications of increasing biochar rates along with other mineral fertilizers and poultry manure on onion nutrition and yield. The experiment consisted of 2 (agricultural year) × 11 (treatments) factorial combinations over two cropping years (2017 and 2018). Thus, 11 treatments were tested as follows: C = control; MF = mineral fertilizer; PM = poultry manure; B1+ MF = 1 Mg ha$^{-1}$ of biochar+MF; B1+ PM = 1 Mg ha$^{-1}$ of biochar+PM; B2+ MF = 2 Mg ha$^{-1}$ of biochar+MF; B2+ PM = 2 Mg ha$^{-1}$ of biochar+PM; B4+ MF = 4 Mg ha$^{-1}$ of biochar+MF; B4+ PM = 4 Mg ha$^{-1}$ of biochar+PM; B10 + MF = 10 Mg ha$^{-1}$ of biochar+MF; B10+ PM = 10 Mg ha$^{-1}$ of biochar +PM. The highest onion yield (39.9 Mg ha$^{-1}$) was obtained in 2017 with the biochar rate of 5.9 Mg ha$^{-1}$ while an increase of 308 kg ha$^{-1}$ in onion yield was found for each Mg ha$^{-1}$ of biochar added to soil in 2018. The use of biochar combined with mineral fertilizers increased onion yield; and the use of biochar combined with poultry manure improved soil fertility status.

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*Allium cepa* l.; wood biochar; organic matter; poultry manure; no-tillage system; soil conditioner; green manure; soil fertility

## Introduction

Onion, *Allium cepa* L. (Amaryllidaceae), is one of the most appreciated and consumed vegetable in the world. It is the third most important vegetable for the Brazilian market; however, most onion crops are grown under conventional tillage system (e.g. intensive disc harrow and plowing operations) and nourished with soluble mineral fertilizers (Epagri 2013). The excessive soil ploughing and harrowing in the conventional tillage system accelerates soil structure degradation by breaking aggregates contributing consequently to erosion (Bertol et al. 2000; Da et al. 2016). Conversely, the use of no-tillage (NT) with growing cover crops improves soil physical, chemical, and biological properties (Comin et al. 2018), and, therefore, increases onion yield (Oliveira et al. 2016). The addition of biochar in the no-tillage system is an efficient way to increase soil organic C in the long term, as plant residues are decomposed and produce $CO_2$ at higher rates than biochar (De La Rosa et al. 2018). This is the first study testing the effect of biochar combined with mineral fertilizers or with poultry manure on onion yield in no-tillage field conditions. Additionally, we believe that the use of biochar as a soil conditioner for onion crops no-tillage system is a promising strategy to increase the sustainability of onion production system.

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Soil conditioners, such as biochar, are increasingly being used to improve important chemical and physical attributes of tropical soils (Steiner et al. 2007). The effect of biochar application on crop yield depending on soil type, crop type and rates of biochar used (Spokas et al. 2011). Few studies on the use of biochar in vegetable production are found in the literature (Sousa and Figueiredo 2016; Agbna et al. 2017; ÖZ 2018; Adekiya et al. 2019; Ronga et al. 2020; Gao et al. 2020; Almaroai and Eissa 2020). Agbna et al. (2017), reported that the use of 25 Mg $ha^{-1}$ of biochar reduced the water use without affecting the yield and quality of tomato fruits. In field conditions, Almaroai and Eissa (2020) reported positive effects of biochar at rates of 5 and 10 Mg $ha^{-1}$ in a metal-contaminated soil on yield and quality of tomato, as well as reduced concentration of metals in tomato root, shoot and fruit over control (no biochar). On the other hand, the application of biochar (29 and 58 Mg $ha^{-1}$) combined with three water irrigation regimes did not affect the onion yield significantly during two growing seasons over control (Gao et al. 2020).

In some cases, application of biochar and inorganic fertilizers in well managed fertile temperate soils may not affect crop yield (spring barley, strawberry and potato) under field conditions in the short term, with slight effects on nutrient concentrations in plant tissues (Jay et al. 2015). However, Adekiya et al. (2019) reported positive short-term effects of biochar and poultry manure application on radish nutritional status and yield. The successive use of organic residues, such as cattle manure and eucalyptus biochar in soils with different degradation levels can improve soil fertility, nutrient release, and enhance plant nutrition and soil organic matter, which may result in higher crop yields (Kimetu et al. 2008).

In some cases, the reapplication of biochar may not affect plant yield and shoot nutrient accumulation, despite having a significant effect on soil quality due to the increase of available nutrient and organic matter content (Quilliam et al. 2012). Accordingly, Gao et al. (2020) reported that the reapplication of biochar did not show a significant effect on onion yield; however, soil organic carbon significantly increased. In field conditions, the application of biochar increased soil pH and the availability of phosphorus (P), even in the first year after biochar application (Jin et al. 2019). The increase of soil pH with the addition of biochar may increase crop yield (Jeffery et al. 2011), though soil pH levels reached in soil above the threshold limits may reduce the availability of some micronutrients to plants (Wang et al. 2017). Biochar can increase P availability due to its capacity to adsorb phosphate whilst the extent of the biochar effect on P availability in soil depends on the biochar properties and the pyrolysis conditions (Zhang et al. 2016).

This study aimed to evaluate the effect of successive applications of increasing biochar rates, combined and not with mineral fertilizers or poultry manure, on onion nutrition and yield, as well as on the fertility status of a Humic Cambisol under the no-tillage system. The main goal is to contribute to the development of soil conservative practices to the effective use of biochar under onion field conditions.

## Materials and methods

### *Experimental conditions and treatments*

The experiment was carried out at the Epagri Experimental Station in Ituporanga, Santa Catarina (SC), Brazil (27°25′S, 49°38′W, and altitude of 475 m). The climate of the region was classified as Cfa (Humid subtropical, oceanic climate without dry season and with hot summer), according to the classification of Köppen (Alvares et al. 2013). The soil of the experimental area was classified, according to Santos et al. (2013), as dystrophic Humic Cambisol, which corresponds to a Humic Distrudept in the Soil Taxonomy (Soil Survey Staff 2014), and a Humic Cambisol in the Soil World Reference Base (IUSS Working Group. 2014. World reference base for soil resources 2014). The onion was grown in two agricultural years, from July to November, in 2017 and 2018. Precipitation, maximum and minimum temperatures, and irrigation regime during the two onion cropping seasons (2017 and 2018) are shown in Figure 1.

Soil samples from the 0.0–0.2 m layer were collected before the experiment and had, on average: 470, 276 and 254 g kg$^{-1}$ of sand, silt and clay, respectively; pH in $H_2O$ of 5.7; 5.8 cmol$_c$ dm$^{-3}$ $Ca^{2+}$; 3.2 cmol$_c$ dm$^{-3}$ $Mg^{2+}$; 0.0 cmol$_c$ dm$^{-3}$ $Al^{3+}$; 4.8 mg dm$^{-3}$ (Mehlich-1 soil test); 0.37 cmol$_c$dm$^{-3}$ $K^+$ (Mehlich-1 soil test); 15 mg dm$^{-3}$ S-$SO_4^{2-}$; potential cation exchange capacity (CEC*p*) of 13.6 cmol$_c$ dm$^{-3}$; base saturation of 69%; 3.0% organic matter; 1.3 mg dm$^{-3}$ $Cu^{2+}$; 3.1 mg dm$^{-3}$ $Zn^{2+}$; 96 mg dm$^{-3}$ $Fe^{2+}$; and 10.8 mg dm$^{-3}$ $Mn^{2+}$. The analytical protocols used for soil analysis are described in details in CQFS-RS/SC (2016).

The history of the study area consisted of the previous cultivation of onion in the conventional tillage system for one year. Previously, before the cultivation of onion in the conventional tillage system, the field experimental area was used for grazing cattle with the cultivation of grass species for approximately 25 years. The green manure used in the summer was the intercrop of *Mucuna aterrima* and *Pennisetum glaucum*, sowed at the following densities, respectively: 40 and 30 kg ha$^{-1}$ (Menezes Júnior et al. 2014). Biochar, mineral fertilizers, and poultry manure were manually applied over the residues of cover plants after flattening the summer cover plants using a knife roller. For growing onion under no-tillage system biochar, poultry manure and mineral fertilizers were applied superficially on the straw before transplanting the onion seedlings. Soil samples were collected from the 0.0–0.1 m layer to evaluate the effect of superficial application of mineral fertilizers, biochar and poultry manure after onion harvest. The production of onion seedlings (cv. Empasc 352 – Bola Precoce) was done in beds with the seed sowing in April. The manual transplantation in July of each year of the onion seedlings was carried out after opening of furrows using an adapted microtractor to operate on the straw, with plants 0.4 m apart from rows and 0.08 m from one another, which resulted in a density of 312,500 plants per hectare. A randomized block design with four replications, eleven treatments (Table 1) and plots of 9.6 m$^2$ was used. Thus, each block consisted of eleven plots (treatments) with distance between plots of 1 m. Mineral fertilizers and poultry manure in the treatments combined with doses of biochar provided 150 kg ha$^{-1}$ of N, 280 kg ha$^{-1}$ of $P_2O_5$ and 90 kg of $K_2O$ ha$^{-1}$. The experiment consisted of four blocks of 11 treatments located next to each other, thus, totalizing 44 plots in each agricultural year (2017 and 2018). For the passage of a tractor used in the application of chemicals, the spacing in the middle of the four blocks was 2.5 m. However, the space between the two blocks on each side of the tractor passage was 1 m.

Nitrogen (ammonium nitrate) rate was applied in the following proportion: at planting (15%), 35 days (25%), 60 days (35%), and 85 days (25%) after transplanting (DAT). Half of $K_2O$ (KCl) rate was applied at planting and the remaining K at 60 DAT, as recommended by the CQFS-RS/SC (2016). The mineral fertilizers and poultry manure rates were calculated based on the soil analysis and nutritional requirements of the onion crop, following fertilization recommendation for onion grown in the State of Santa Catarina (CQFS-RS/SC 2016). These treatments were reapplied in 2018, in the same experimental plots, using the same biochar, poultry manure and fertilizers and rates aforementioned.

Weed, disease, and pest control were carried out with chemical products registered for onion crops in the Brazilian Ministry of Agriculture. Three herbicide applications with ioxynil (335 ml ha$^{-1}$), clethodim (108 ml ha$^{-1}$) and pendimethalin 1746 ml ha$^{-1}$), and a manual weeding were performed for weed control. Eight fungicides applications with propineb (2100 g ha$^{-1}$), metalaxyl-M (100 ml ha$^{-1}$) + chlorothalonil (1000 ml ha$^{-1}$) and metalaxyl-M (100 g ha$^{-1}$) + mancozeb (1600 g ha$^{-1}$) were carried out for fungal disease (*Peronospora destructor*) control. Pest (*Thrips tabaci* Lind.), were controlled with three insecticides applications with lambda-cyhalothrin (31,8 ml ha$^{-1}$) and imidacloprid (70 g ha$^{-1}$). Both fungicides and insecticides were applied alternating products that have different modes of action and active ingredients on plants (contact and systemic).

The biochar used was produced from the pyrolysis of *Eucalyptus* spp. wood; it was acquired in Ituporanga city, Santa Catarina State, Brazil, where it was built using a cylindrical furnace. The conversion of eucalyptus wood into biochar was done under slow pyrolysis (~350°C), with the partial

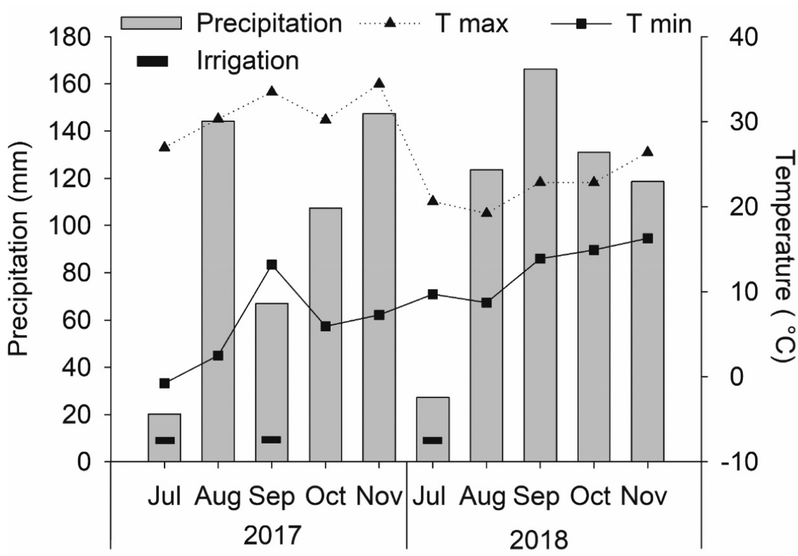


**Figure 1.** Monthly precipitation, maximum (T max) and minimum (T min) temperatures and irrigation in two onion crop seasons (2017 and 2018) in the study area.

**Table 1.** Treatments used in the two evaluated onion crop seasons.

| Treatments | Mineral fertilizer (kg ha$^{-1}$)* | | | Poultry manure** Mg ha$^{-1}$ | Biochar Mg ha$^{-1}$ |
|---|---|---|---|---|---|
| | N | $P_2O_5$ | $K_2O$ | | |
| C | – | – | – | – | – |
| MF | 150 | 280 | 90 | – | – |
| PM | 123 | 50 | – | 3.3 | – |
| B1+ MF | 150 | 280 | 90 | – | 1 |
| B1+ PM | 123 | 50 | – | 3.3 | 1 |
| B2+ MF | 150 | 280 | 90 | – | 2 |
| B2+ PM | 123 | 50 | – | 3.3 | 2 |
| B4+ MF | 150 | 280 | 90 | – | 4 |
| B4+ PM | 123 | 50 | – | 3.3 | 4 |
| B10+ MF | 150 | 280 | 90 | – | 10 |
| B10+ PM | 123 | 50 | – | 3.3 | 10 |

*N source = ammonium nitrate, $P_2O_5$ source = simple superphosphate and $K_2O$ source = potassium chloride; C = control; MF = mineral fertilizer; PM = poultry manure; **3.3 Mg ha$^{-1}$ of poultry manure provided 90 kg ha$^{-1}$ of $K_2O$, 27 kg ha$^{-1}$ of N, and 230 kg ha$^{-1}$ of $P_2O_5$, and the remaining N (123 kg ha$^{-1}$) and $P_2O_5$ (50 kg ha$^{-1}$) rates were supplemented with ammonium nitrate and simple superphosphate. B1+ MF = 1 Mg ha$^{-1}$ of biochar + MF; B1+ PM = 1 Mg ha$^{-1}$ of biochar + PM; B2+ MF = 2 Mg ha$^{-1}$ of biochar + MF; B2+ PM = 2 Mg ha$^{-1}$ of biochar + PM; B4+ MF = 4 Mg ha$^{-1}$ of biochar + MF; B4 + PM = 4 Mg ha$^{-1}$ of biochar + PM; B10+ MF = 10 Mg ha$^{-1}$ of biochar + MF; B10+ PM = 10 Mg ha$^{-1}$ of biochar + PM.

exclusion of oxygen from the furnace. The biochar was crushed and sieved in a 2-mm mesh sieve before being applied to the soil surface in the experimental plots. At the end of the experiment, the yield of commercial onion bulbs with diameters greater than 35 mm were evaluated.

### *Leaf and soil sampling*

In the first half of October of each crop season, at the beginning of the bulbing stage, young fully expanded leaves of ten onion plants were randomly collected in each experimental plot. The leaf samples were then dried in a forced-air circulation oven at 65°C until constant weight. At the end of the harvest of onion, in both agricultural years, soil samples (0.0–0.1 m) were collected on a plot basis with five subsamples from each plot, used to compose the bulk sample for further analysis.

### Chemical analysis

Onion leaf samples were ground and analyzed for N, P, K, Ca, Mg, S, Cu, Mn, and Zn concentrations, according to methodologies described in Malavolta et al. (1989). Soil samples collected from experimental plots were evaluated for pH in water, organic matter (OM), base saturation (BS), potential (buffered at pH 7) cation exchange capacity (CEC*p*), and P, K, Ca, Mg, S (sulfate), Cu, and Zn soil available concentrations. The analytical protocols used for onion leaf and soil analyses are described in CQFS-RS/SC (2016).

Biochar and granulated poultry manure were characterized, and their chemical and physicochemical properties are shown in Table 2. The pH and electrical conductivity of the eucalyptus biochar were determined in deionized water at a 1:5 (v/v) ratio, following methodologies described in MAPA (2007). Cation exchange capacity (CEC) was determined according to the analytical protocol described by Gaskin et al. (2008). Nitrogen and organic carbon concentrations were determined following protocols described in De and De (2006). P, K, S, Ca, Mg, Cu, and Zn total concentrations were determined by an Inductively Coupled Plasma – Atomic Emission Spectrometry (ICP-AES), following analytical protocols described by Embrapa (2009).

### Statistics analysis

The soil and plant dataset were submitted to analysis of variance, and the treatment means were compared by the Scott-Knott test ($p < 0.05$). Regression models ($p < 0.05$) were adjusted to the onion yield over biochar rates combined or not with MF or PM. Principal component analysis (PCA) was performed to evaluate the correlation between soil properties and onion yield. Statistical analyses were performed using the R 3.6.3 software version (R Core Team 2020).

## Results

### Nutrient in onion leaf (2017 and 2018 crop seasons)

The effect of applications of biochar rates combined or not with mineral fertilizers (MF) and poultry manure (PM) in nutrient concentrations in onion leaf at the bulbing stage in the 2017 and 2018 crop seasons are shown in Table 3. When considered as an individual factor, treatment showed significant ($p < 0.05$) differences in 2017 for leaf K, S, and Cu concentrations, while in 2018, only significant differences were found for leaf Mg. Leaf Ca was the nutrient that only changed as a function of the treatments tested in both onion agricultural years. Biochar rates, fertilizers and poultry manure were not effective in changing leaf N, P, Mn and Zn concentrations in onion leaf. Except for K in 2017, in general, biochar rates combined or not with MF and PM did not increase leaf nutrient concentrations over control. When considered as an individual factor, year showed significant ($p < 0.05$) differences

**Table 2.** Physicochemical properties of biochar and poultry manure used in the experiment.

| Property | Biochar | Poultry manure |
|---|---|---|
| pH (water) | 9.9 | 8.6 |
| Electrical conductivity (mS cm$^{-1}$) | 1.2 | 10.4 |
| Cation exchange capacity (cmol$_c$ kg$^{-1}$) | 37.5 | 55.3 |
| Organic carbon (g kg$^{-1}$) | 498 | 328 |
| Nitrogen (g kg$^{-1}$) | 5.9 | 19 |
| Phosphorus (g kg$^{-1}$) | 1.7 | 22 |
| Potassium (g kg$^{-1}$) | 12.3 | 32 |
| Sulphur (g kg$^{-1}$) | 0.75 | 14 |
| Calcium (g kg$^{-1}$) | 74.9 | 50.2 |
| Magnesium (g kg$^{-1}$) | 2.9 | 11.6 |
| Copper (mg kg$^{-1}$) | 9.3 | 134 |
| Zinc (mg kg$^{-1}$) | 29.6 | 412 |

**Table 3.** Nutrient concentrations in onion leaves sampled at the bulbing stage after successive applications of biochar (B) rates, combined or not with mineral fertilizer (MF) and poultry manure (PM), to a Humic Cambisol in the 2017 and 2018 crop seasons.

| Treatment | N | | P | | K | | Ca | | Mg | | S | | Cu | | Mn | | Zn | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | g kg$^{-1}$ | | | | | | | | | | | | mg kg$^{-1}$ | | | | | |
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| C | 30.6 a | 30.8 a | 3.75 aA | 3.02 aB | 23.2 b | 29.6 a | 5.32 aB | 12.1 bA | 2.92 a | 5.11 a | 4.26 bB | 5.65 aA | 23.0 aA | 13.7 aB | 44.9 a | 39.9 a | 15.8 a | 37.5 a |
| MF | 33.0 a | 32.7 a | 3.79 aA | 2.54 aB | 26.1 b | 33.7 a | 5.90 aB | 13.3 aA | 2.89 a | 4.45 b | 7.55 aA | 5.92 aB | 20.4 aA | 12.5 aB | 46.7 a | 42.6 a | 17.5 a | 39.8 a |
| PM | 31.5 a | 32.8 a | 3.67 aA | 2.65 aB | 24.8 b | 32.6 a | 5.59 aB | 12.0 bA | 3.08 a | 4.58 b | 7.88 aA | 5.52 aB | 16.6 bA | 12.5 aB | 51.1 a | 52.6 a | 17.1 a | 40.4 a |
| B1 + MF | 32.8 a | 32.8 a | 3.97 aA | 2.63 aB | 27.4 a | 32.7 a | 6.17 aB | 12.5 bA | 2.72 a | 4.47 b | 7.93 aA | 5.99 aB | 15.6 bA | 13.6 aA | 51.0 a | 43.4 a | 12.1 a | 40.2 a |
| B1 + PM | 32.1 a | 33.9 a | 3.30 bA | 2.74 aB | 24.4 b | 31.9 a | 5.81 aB | 12.7 aA | 2.53 a | 4.28 b | 7.30 aA | 5.10 aB | 15.3 bA | 14.4 aA | 47.1 a | 47.9 a | 14.6 a | 38.0 a |
| B2 + MF | 33.2 a | 33.0 a | 4.10 aA | 2.58 aB | 26.5 a | 30.3 a | 5.92 aB | 11.8 bA | 2.83 a | 4.24 b | 8.20 aA | 5.35 aB | 14.1 bA | 13.5 aA | 45.9 a | 44.1 a | 15.0 a | 40.9 a |
| B2 + PM | 33.0 a | 34.4 a | 3.62 aA | 2.78 aB | 28.8 a | 31.8 a | 6.50 aB | 12.8 aA | 2.94 a | 4.43 b | 8.09 aA | 5.41 aB | 19.4 aA | 15.8 aB | 51.9 a | 48.8 a | 15.2 a | 41.2 a |
| B4 + MF | 32.3 a | 33.3 a | 3.89 aA | 2.48 aB | 25.8 b | 33.5 a | 6.23 aB | 13.2 aA | 2.81 a | 4.11 b | 7.93 aA | 5.86 aB | 16.7 bA | 13.3 aA | 45.7 a | 46.9 a | 16.7 a | 39.4 a |
| B4 + PM | 32.3 a | 33.4 a | 3.17 bA | 2.51 aB | 24.5 b | 31.8 a | 3.67 bB | 13.1 aA | 2.31 a | 4.30 b | 6.75 aA | 5.26 aB | 22.8 aA | 14.0 aB | 44.5 a | 53.5 a | 18.1 a | 40.2 a |
| B10 + MF | 32.5 a | 32.7 a | 3.66 aA | 2.61 aB | 25.9 b | 33.0 a | 5.75 aB | 12.0 bA | 2.77 a | 4.07 b | 7.52 aA | 6.03 aB | 16.3 bA | 14.4 aA | 49.9 a | 47.5 a | 16.2 a | 46.6 a |
| B10 + PM | 33.4 a | 31.8 a | 3.90 aA | 2.67 aB | 27.9 a | 34.2 a | 6.10 aB | 13.0 aA | 3.24 a | 4.36 b | 7.72 aA | 5.52 aB | 17.3 bA | 14.2 aA | 43.9 a | 48.2 a | 15.9 a | 42.8 a |
| OR | 25–40 | | 2–4 | | 20–50 | | 7–30 | | 2–4 | | 5–8 | | 6–20 | | 30–200 | | 10–50 | |
| Anova | | | | | | | | | | | | | | | | | | |
| T | ns | | ns | | * | | * | | * | | * | | * | | ns | | ns | |
| Y | ns | | * | | * | | * | | * | | * | | * | | ns | | * | |
| T × Y | ns | | * | | ns | | * | | ns | | * | | * | | ns | | ns | |

Means followed by same lower case letters in the columns are not significantly different ($p < 0.05$) by the Scott-Knott test within each year ($n = 4$). Means followed by same capital letters in the lines of each nutrient, between years, are not significantly different ($p < 0.05$) by the Scott-Knott test. OR = optimal range of nutrients for onion leaves at the bulbing stage (CQFS-RS/SC 2016). C = control; MF = mineral fertilizer; PM = poultry manure; B1+ MF = 1 Mg ha$^{-1}$ of biochar + MF; B1+ PM = 1 Mg ha$^{-1}$ of biochar + PM; B2+ MF = 2 Mg ha$^{-1}$ of biochar + MF; B2+ PM = 2 Mg ha$^{-1}$ of biochar + PM; B4+ MF = 4 Mg ha$^{-1}$ of biochar + MF; B4+ PM = 4 Mg ha$^{-1}$ of biochar + PM; B10+ MF = 10 Mg ha$^{-1}$ of biochar + MF; B10+ PM = 10 Mg ha$^{-1}$ of biochar + PM. T = treatment; Y = year. * = significant at 5% level of probability; ns = not significant at 5% level of probability.

for leaf P, K, Ca, Mg, S, Cu, and Zn. P, S, Copper (Cu) as a whole decreased regarding mean concentrations in 2018 over plants grown in 2017, while for leaf K, Ca, Mg, and Zn, an increase in the means' concentrations were observed in 2018 in comparison to 2017. However, the effect of year was not significant for leaf N and Mn. Only for leaf P, Ca, S and Cu. Significant interactive effect between treatment and year (T × Y) was observed. Leaf N and Mn were the only nutrients not affected by the factors investigated. Leaf Ca was the only nutrient that presented levels below the threshold range for onion crops (CQFS-RS/SC 2016), though this effect occurred only in the first onion crop season (2017).

## Onion yield in 2017 and 2018 crop seasons

Onion yield in response to treatments differed between the two crop seasons. Onion yield in 2017 was ranked in the following decreasing order: B4+ MF > B1+ PM > B4+ PM > B2+ MF > MF > B10+ MF > B2+ PM > B10+ PM > PM >B1+ MF > C; and, in 2018, as follows: MF > B10+ MF > B1+ MF > B4+ MF > B10+ PM > B1+ PM > B4+ PM > PM >B2+ PM >C > B2+ MF (C = control; MF = mineral fertilizer; PM = poultry manure; B1+ MF = 1 Mg ha$^{-1}$ of biochar + MF; B1+ PM = 1 Mg ha$^{-1}$ of biochar + PM; B2 + MF = 2 Mg ha$^{-1}$ of biochar + MF; B2+ PM = 2 Mg ha$^{-1}$ of biochar + PM; B4+ MF = 4 Mg ha$^{-1}$ of biochar + MF; B4+ PM = 4 Mg ha$^{-1}$ of biochar + PM; B10+ MF = 10 Mg ha$^{-1}$ of biochar + MF; B10 + PM = 10 Mg ha$^{-1}$ of biochar + PM). Onion yield was higher in 2018 in all treatments over the first onion growing season (Figure 2). The highest yield in 2017 (38.5 Mg ha$^{-1}$) was achieved when

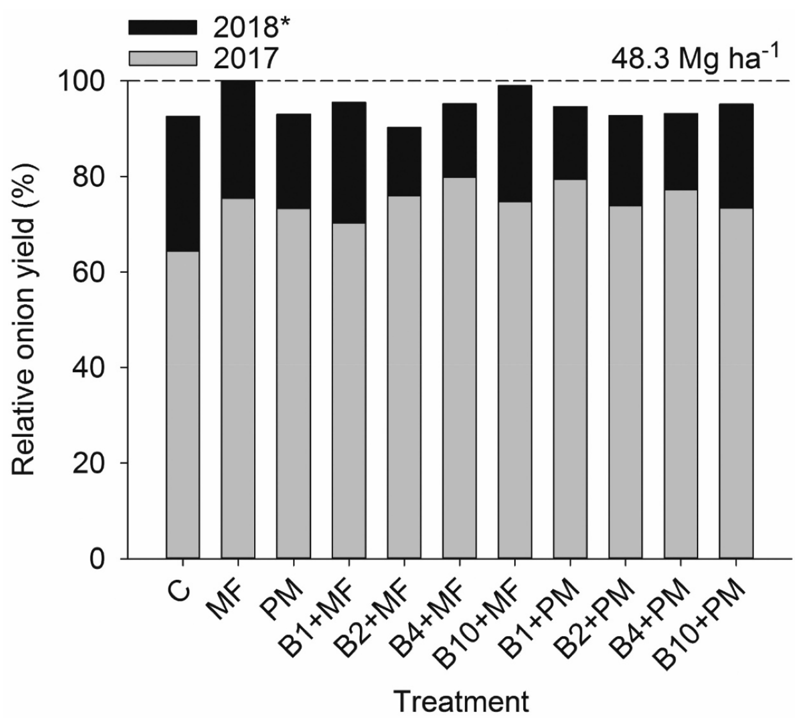


**Figure 2.** Relative onion yield in the 2017 (gray) and in 2018 (black) crop seasons. The highest onion yield in the MF treatment (48.3 Mg ha$^{-1}$) in 2018 is set to 100%. C = control; MF = mineral fertilizer; PM = poultry manure; B1+ MF = 1 Mg ha$^{-1}$ of biochar + MF; B1+ PM = 1 Mg ha$^{-1}$ of biochar + PM; B2+ MF = 2 Mg ha$^{-1}$ of biochar + MF; B2+ PM = 2 Mg ha$^{-1}$ of biochar + PM; B4 + MF = 4 Mg ha$^{-1}$ of biochar + MF; B4+ PM = 4 Mg ha$^{-1}$ of biochar + PM; B10+ MF = 10 Mg ha$^{-1}$ of biochar + MF; B10 + PM = 10 Mg ha$^{-1}$ of biochar + PM. *The average of treatments are not significantly different ($p < 0.05$) by the Scott-Knott test within each year (n = 4), however, the averages are significantly higher ($p < 0.05$) in 2018 in relation to 2017.

biochar and mineral fertilizers (B4+ MF) were combined, though, considering both crop seasons, the highest onion yield (48.3 Mg ha$^{-1}$) was achieved in 2018 with the exclusive use of mineral fertilizer (MF).

Based on the regression analysis, onion yield presented significant response only when biochar rates were combined with mineral fertilizers (B+ MF) in both crop seasons. The equation obtained for B+ MF in 2017 showed that the rate of 5.99 Mg ha$^{-1}$ of biochar resulted in the maximum onion yield of 39.8 Mg ha$^{-1}$, and the linear equation obtained for B+ MF in 2018 showed that each Mg ha$^{-1}$ of biochar added to the Humic Cambisol increased onion yield in 308 kg ha$^{-1}$ (Figure 3).

### *Soil properties after the two onion seasons*

The effects of treatment and year on soil chemical properties after two evaluated onion crop seasons are shown in Table 4 and in Table 5. As an individual factor, treatment significantly ($p < 0.05$) influenced K and S-sulfate only in 2017, pH, BS, and Mg in 2018 and P, Ca and Zn in both onion agricultural seasons. The highest pH value in both years and the highest values of BS, P, and Ca in 2018 were found for B10 + MF and for B10 + PM treatments. Furthermore, in the case of B10 + MF and B10 + PM treatments, changes in soil fertility status is explained by the use of the highest biochar rate (10 Mg ha$^{-1}$) plus the biochar itself high pH and liming value (Table 2). However, the effect of treatments was not significant for OM, CEC*p* and Cu. In general, the treatments showed a significant difference in soil P available concentrations, which were higher as the biochar rates were increased and combined with poultry manure and mineral fertilizers. Soil base saturation (BS) was similar among treatments in the first year. However, the use of biochar at 10 Mg ha$^{-1}$ combined with poultry manure or mineral fertilizers significantly increased BS in 2018 onion growing season. The use of biochar at 10 Mg ha$^{-1}$ mixed with poultry manure or mineral fertilizers also significantly increased Ca in the second year.

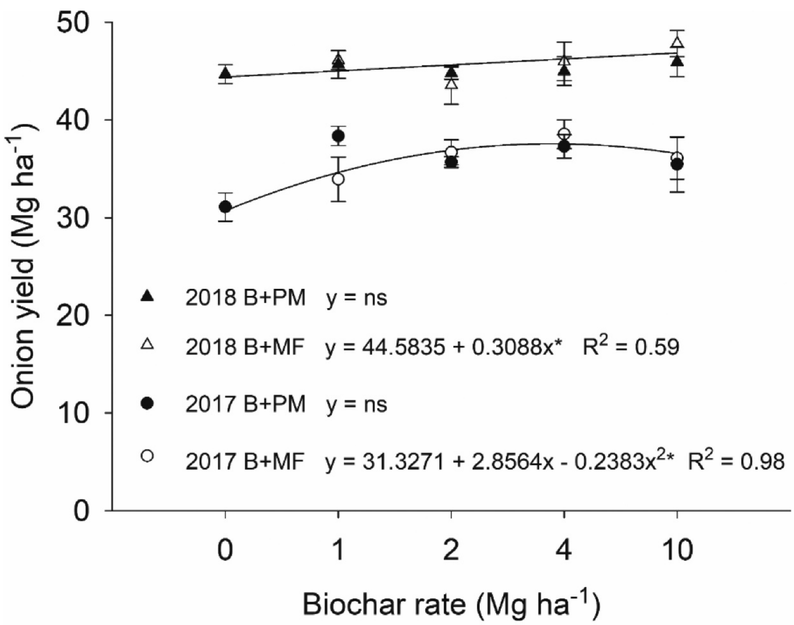


**Figure 3.** Onion yield response to biochar application at rates of 0, 2, 4, and 10 Mg ha$^{-1}$ combined with mineral fertilizer (MF) and with poultry manure (PM) in the 2017 and 2018 crop seasons. ns = not significant; *significant ($p < 0.05$).

**Table 4.** Surface (0.0–0.1 m) soil chemical properties after the two evaluated onion crop seasons.

| Treatment | pH | | OM | | BS | | CEC*p* | |
|---|---|---|---|---|---|---|---|---|
| | | | % | | % | | $cmol_c\ dm^{-3}$ | |
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| C | 5.85 a | 6.35 a | 2.80 a | 2.97 a | 74.1 a | 79.1 b | 14.6 a | 15.3 a |
| MF | 5.48 a | 6.13 b | 2.67 a | 3.05 a | 70.7 a | 74.7 b | 13.9 a | 14.4 a |
| PM | 5.87 a | 6.30 b | 2.80 a | 3.15 a | 72.7 a | 78.3 b | 14.5 a | 14.7 a |
| B1 + MF | 5.67 a | 6.05 b | 2.57 a | 2.95 a | 68.4 a | 73.9 b | 14.1 a | 15.1 a |
| B1 + PM | 5.87 a | 6.22 b | 2.82 a | 3.30 a | 73.9 a | 78.9 b | 14.3 a | 15.5 a |
| B2 + MF | 5.82 a | 6.00 b | 2.67 a | 2.87 a | 72.7 a | 71.8 b | 13.2 a | 14.0 a |
| B2 + PM | 5.85 a | 6.10 b | 2.70 a | 2.95 a | 72.3 a | 75.5 b | 13.7 a | 15.7 a |
| B4 + MF | 5.80 a | 6.25 b | 2.75 a | 3.12 a | 73.4 a | 78.0 b | 14.8 a | 15.6 a |
| B4 + PM | 5.82 a | 6.37 a | 2.82 a | 3.37 a | 72.7 a | 77.5 b | 14.5 a | 14.8 a |
| B10 + MF | 5.90 a | 6.50 a | 2.62 a | 3.27 a | 74.1 a | 81.7 a | 14.5 a | 15.9 a |
| B10 + PM | 6.07 a | 6.70 a | 2.87 a | 3.55 a | 76.0 a | 86.3 a | 14.9 a | 16.8 a |
| Anova | | | | | | | | |
| T | * | | ns | | * | | ns | |
| Y | * | | * | | * | | * | |
| T × Y | ns | | ns | | ns | | ns | |

Means followed by same lower case letters in the columns are not significantly different ($p < 0.05$) by the Scott-Knott test within each year (n = 4). Means followed by same capital letters in the lines of each soil chemical properties, between years, are not significantly different ($p < 0.05$) by the Scott-Knott test. OM = organic matter; BS = base saturation; CEC*p* = potential cation exchange capacity. C = control; MF = mineral fertilizer; PM = poultry manure; B1+ MF = 1 Mg $ha^{-1}$ of biochar + MF; B1 + PM = 1 Mg $ha^{-1}$ of biochar + PM; B2+ MF = 2 Mg $ha^{-1}$ of biochar + MF; B2+ PM = 2 Mg $ha^{-1}$ of biochar + PM; B4+ MF = 4 Mg $ha^{-1}$ of biochar + MF; B4+ PM = 4 Mg $ha^{-1}$ of biochar + PM; B10+ MF = 10 Mg $ha^{-1}$ of biochar + MF; B10+ PM = 10 Mg $ha^{-1}$ of biochar + PM; T = treatment; Y = year. * = significant at 5% level of probability; ns = not significant at 5% level of probability.

Regarding Zn, the use of PM (Table 2) influenced its mean values for treatments with PM in the composition in comparison to other treatments without PM in the composition (Table 1). Considering the year as an individual factor, means of pH, OM, BS, CEC*p*, P, K, Ca, Cu and Zn significantly ($p < 0.05$) increased in 2018 over 2017. However, the effect of onion season year was not significant for Mg and S-sulfate. The OM concentrations averages are significantly ($p < 0.05$) higher in 2018 in comparison to 2017, especially for the B10+ PM treatment, whose OM increased from 2.87% to 3.55%. The interactive effect of T x Y was only significant for P, S and Zn concentrations in soil.

### *Comparative analyses of onion yield and soil properties in 2017 and 2018 crop seasons*

Treatments used in this study led to changes in soil properties in 2017 and 2018 crop seasons. Principal component analysis (PCA) was performed to evaluate the correlation between soil properties and yield of onion cultivated in a no-tillage system in 2017 (Figure 4A) and 2018 (Figure 4B) crop seasons. Onion yield positively correlated with P, Cu, S, K concentrations and with pH in 2017 crop season (Figure 4A) for B1 + PM, B4 + PM and B10 + PM treatments. Regarding to 2018 crop season (Figure 4B) onion yield positively correlated with P, OM, K and Ca concentrations for B4 + PM, B10 + PM and B10 + MF treatments. In both years, onion yield positively correlated with P and K concentrations of soil and in soils treated with increasing biochar rates. Results depicted in Figure 4 suggest that the use of biochar in the cultivation of onion in a no-tillage system increase the soil fertility degree, increasing nutrient availability in biochar-treated soil, and, possibly, onion yield as well.

**Table 5.** Surface (0.0–0.1 m) soil macro and micronutrients after the two evaluated onion crop seasons.

| Treatment | Extractable | | Exchangeable | | | | | | Extractable | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | P mg dm$^{-3}$ | | K | | Ca | | Mg | | S | | Cu | | Zn | |
| | | | – – – – – – – cmol$_c$ dm$^{-3}$ – – – – – – – | | | | | | – – – – – – – – – mg dm$^{-3}$ – – – – – – – – | | | | | |
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| C | 7.37 bA | 8.70 dA | 0.39 c | 0.84 a | 6.95 a | 7.62 b | 3.55 a | 3.62 a | 39.2 bA | 35.4 aA | 0.92 a | 1.10 a | 4.21 aA | 4.55 bA |
| MF | 14.9 bB | 34.9 cA | 0.33 c | 0.76 a | 6.20 b | 6.65 b | 3.25 a | 2.80 b | 45.5 aA | 45.1 aA | 0.77 a | 0.95 a | 2.77 bB | 4.42 bA |
| PM | 15.8 bB | 40.5 bA | 0.45 c | 0.95 a | 6.62 a | 7.12 b | 3.42 a | 3.47 a | 47.1 aA | 43.9 aA | 0.75 a | 1.20 a | 3.75 aB | 6.39 aA |
| B1 + MF | 12.6 bB | 30.0 cA | 0.37 c | 0.83 a | 6.02 b | 7.07 b | 3.20 a | 3.22 a | 47.5 aA | 50.5 aA | 0.67 a | 1.05 a | 2.75 bB | 3.78 bA |
| B1 + PM | 27.3 aB | 48.9 aA | 0.44 c | 1.12 a | 6.85 a | 7.80 b | 3.27 a | 3.35 a | 50.2 aA | 45.4 aA | 0.94 a | 1.17 a | 4.39 aB | 6.93 aA |
| B2 + MF | 22.7 aB | 32.9 cA | 0.39 c | 0.95 a | 6.05 b | 6.50 b | 3.17 a | 2.80 b | 36.5 bB | 49.3 aA | 0.82 a | 1.00 a | 2.97 bB | 4.32 bA |
| B2 + PM | 18.4 bB | 39.4 bA | 0.41 c | 0.93 a | 6.22 b | 7.57 b | 3.32 a | 3.40 a | 42.4 bA | 43.3 aA | 0.95 a | 1.15 a | 4.17 aB | 6.46 aA |
| B4 + MF | 14.3 bB | 29.1 cA | 0.40 c | 0.93 a | 7.00 a | 7.85 b | 3.50 a | 3.37 a | 48.2 aA | 42.2 aA | 0.70 a | 1.02 a | 2.97 bB | 3.90 bA |
| B4 + PM | 22.3 aB | 51.8 aA | 0.52 b | 0.99 a | 6.67 a | 7.45 b | 3.37 a | 3.12 b | 52.2 aA | 46.2 aA | 0.87 a | 1.02 a | 4.02 aB | 7.40 aA |
| B10 + MF | 13.9 bB | 49.5 aA | 0.51 b | 1.02 a | 6.90 a | 8.92 a | 3.30 a | 3.02 b | 46.4 aA | 44.4 aA | 0.82 a | 0.92 a | 3.20 bB | 4.40 bA |
| B10 + PM | 26.6 aB | 50.4 aA | 0.68 a | 1.31 a | 7.32 a | 9.92 a | 3.35 a | 3.30 a | 55.6 aA | 44.0 aB | 0.85 a | 0.97 a | 3.87 aB | 6.67 aA |
| Anova | | | | | | | | | | | | | | |
| T | * | | * | | * | | * | | * | | ns | | * | |
| Y | * | | * | | * | | ns | | ns | | * | | * | |
| T × Y | * | | ns | | ns | | ns | | * | | ns | | * | |

Means followed by same lower case letters in the columns are not significantly different ($p < 0.05$) by the Scott-Knott test within each year (n = 4). Means followed by same capital letters in the lines of each soil chemical properties, between years, are not significantly different ($p < 0.05$) by the Scott-Knott test. OM = organic matter; BS = base saturation; CEC*p* = potential cation exchange capacity. C = control; MF = mineral fertilizer; PM = poultry manure; B1+ MF = 1 Mg ha$^{-1}$ of biochar + MF; B1+ PM = 1 Mg ha$^{-1}$ of biochar + PM; B2+ MF = 2 Mg ha$^{-1}$ of biochar + MF; B2 + PM = 2 Mg ha$^{-1}$ of biochar + PM; B4+ MF = 4 Mg ha$^{-1}$ of biochar + MF; B4+ PM = 4 Mg ha$^{-1}$ of biochar + PM; B10+ MF = 10 Mg ha$^{-1}$ of biochar + MF; B10+ PM = 10 Mg ha$^{-1}$ of biochar + PM; T = treatment; Y = year. * = significant at 5% level of probability; ns = not significant at 5% level of probability.

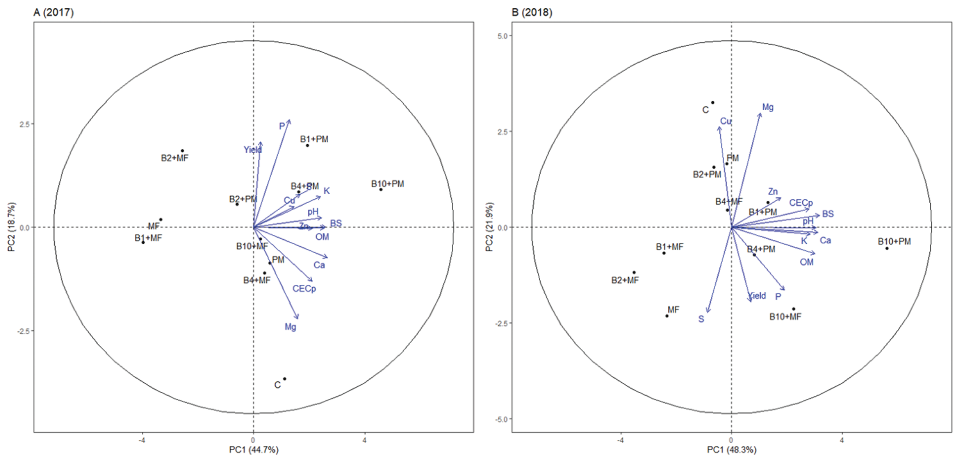


**Figure 4.** Principal component analysis (PCA) of the onion yield and soil properties of treatments in relation to the first two principal components (PC1xPC2). Legend: A = PCA of 2017 crop season; B = PCA of 2018 crop season; C = control; MF = mineral fertilizer; PM = poultry manure; B1+ MF = 1 Mg ha$^{-1}$ of biochar + MF; B1+ PM = 1 Mg ha$^{-1}$ of biochar + PM; B2+ MF = 2 Mg ha$^{-1}$ of biochar + MF; B2+ PM = 2 Mg ha$^{-1}$ of biochar + PM; B4+ MF = 4 Mg ha$^{-1}$ of biochar + MF; B4+ PM = 4 Mg ha$^{-1}$ of biochar + PM; B10+ MF = 10 Mg ha$^{-1}$ of biochar + MF; B10+ PM = 10 Mg ha$^{-1}$ of biochar + PM; OM = organic matter; BS = base saturation; CEC*p* = potential cation exchange capacity.

## Discussion

### *Onion nutritional status*

In general, except for K in 2017, the combined use of biochar and PM or MF did not change nutrient concentrations in onion leaves over control. Jay et al. (2015) also showed an increase of K concentration in barley grain and strawberry leaf with the use of biochar, though no significant effect of biochar on tomato fruit nutrient concentrations at harvest. Considering the results of this study, Joseph et al. (2020) observed small changes in nutrients concentration in leaf of avocado grown in a biochar-treated soil. A higher leaf Ca, Mg, and Zn concentrations in the second year over control (Table 3) may be due to nutrient cycling by cover crops (CFSEMG 1999), as well due to a greater availability of nutrients in soil. A higher leaf Mg concentration in the control treatment, in 2018, compared to the other treatments, was probably due to the increase of soil K concentrations, caused by the biochar application and to the competition of this nutrient with Mg (Faquin 2005). This may also explain a higher leaf K concentration in plants of the other treatments in the second year over control.

### *Onion yield*

Biochar has no short-term effect on barley, strawberry, and potato production in soils with built fertility, as well as little influence on nutrient concentration in plant tissues (Jay et al. 2015). Conversely, a short-term positive effect of biochar on onion yield was found in this study (Figure 3), though it was due to the combined use of biochar with mineral fertilizers. The combination of biochar with mineral fertilizers triggers a synergistic effect of biochar on crop yield, though a single mechanism is not enough to explain how biochar acts enhancing plant growth (Steiner et al. 2007) probably because several factors that we did not measure in this study may be working together. Gao et al. (2020) showed that biochar as an individual factor had no significant effect on onion yield, whilst they found that the irrigation and its interaction with biochar significantly affected the onion yield. In some cases, the increase in the crop yield is due to the liming effect and CEC increase in biochar-treated soils (Ye et al. 2020).

The use of biochar combined with poultry manure did not generate the same effect as the combination of biochar with mineral fertilizers due to the lower mineralization rate of the poultry manure, which should be immediately irrigated when applied in the soil surface to accelerate the waste mineralization, and the release of nutrients in available forms to onion (Higashikawa and Menezes Júnior 2017). Quilliam et al. (2012) found no influence of biochar on shoot biomass production of the dwarf bean, nor on foliar nutrient concentrations, even after three years of reapplication of up to 50 Mg $ha^{-1}$ of biochar. According to these authors, the benefits of biochar application to temperate agriculture soil appear to be short term or transient. The reapplication of biochar in the second year of cultivation resulted in a linear increase of the onion yield when the biochar was combined with mineral fertilizers (Figure 3), although the biochar was not generally effective in improving onion nutrition (Table 3). The overall higher onion yield in the second year over the first onion growing season (Figure 2) might be attributed to the better distribution and higher volume of precipitation (566.6 mm) during the 2018 crop season (Figure 1), compared to 2017 (486.2 mm). Besides, the favourite climate conditions in 2018 increased the beneficial effects of biochar on onion, since the onion yield linearly increased over biochar rates combined with mineral fertilizers (Figure 3). The increase in soil organic C due to the successive application of eucalyptus biochar (Kimetu et al. 2008) probably contributed to the overall higher onion yield with reapplication of biochar in the second year (Figure 2). In line with Quilliam et al. (2012), no adverse effect of biochar application on plant growth was found.

### *Biochar action on soil fertility status*

Adekiya et al. (2019) found the highest leaf nutrient concentrations and the highest yield of radish were verified with the combination of 50 Mg $ha^{-1}$ of biochar and 5 Mg $ha^{-1}$ of poultry manure. Such results are similar to data reported in this study, as the use of biochar increases pH, OM and available P concentrations when biochar is combined with poultry manure (Table 4 and Table 5). The use of biochar is a strategy to increase soil organic matter levels since the biochar is mainly composed by recalcitrant C compounds (Reed et al. 2017). Although biochar stimulates native C losses in low organic matter soils, the positive priming effect of biochar labile C decreases over time, and biochar stabilization of soil C due to organo-mineral interactions is supposed to happen as time evolves (Singh and Cowie 2014). Additional loss of inherent soil C due to biochar priming effect is not sufficient to offset the gain of organic matter due to a higher persistence and stability in soil of the C derived from charred matrices (Singh and Cowie 2014).

Application of biochar at 10 Mg $ha^{-1}$(B10 + MF and B10 + PM), caused in soil the highest values for P and Ca in 2018 (Table 5). Similarly, Wu et al. (2020) found a significant increase concentration of available P and Ca with the application of biochar due to the increase in the soil pH. Van Zwieten et al. (2009) reported elevation of exchangeable Ca and liming effect in the Ferrosol with the application of two biochars derived from the slow pyrolysis of paper mill waste. The use of biochar increased soil P and Ca availability in B10 + MF and B10 + PM treatments (Table 5), thus, further studies are required for subsequent crop cycles regarding the residual availability of these nutrients present in soils treated successively with biochar. Additionally, biochar applied at 10 Mg $ha^{-1}$ (B10 + MF and B10 + PM) presented the highest soil pH values (Table 5) in both years, which are in line with Wu et al. (2020) who affirmed that biochar could increase soil pH continuously. Besides, they suggest that the biochar is better than lime to improve acidic soil due to the presence in the charred matrix of carbonates and oxides of Ca, K and Mg and functional groups such as – $COO^-$ and $O^-$ that could react and neutralize $H^+$. The increase of soil pH with the application of biochar may be caused by the fact that biochar is alkaline and contains carbonates and alkaline oxides in the ash; however, the effect of biochar to change the pH is smaller when as much closer the pH value of the soil is to pH value of biochar (Wang et al. 2020). Probably for B10 + MF and B10 + PM treatments an increase of pH with the addition of biochar increased the negatively charged surface density, which induced the electrostatic repulsion of soil colloids to P species ($H_2PO_4^-$, $HPO_4^{2-}$, and $PO_4^{3-}$), consequently increasing P availability (Baquy et al. 2020). Also, in the case of B10 + MF and B10 + PM treatments, the application and reapplication of biochar (Table 5) probably improved soil P availability (Figure 4) through direct inputs or due to the P retention of the fertilizer (Zhang et al. 2016). As was shown in Table 5, it is possible to observe an increase in P levels due to the application of biochar and an increase in Zn levels by the application of poultry manure alone or combined with biochar. P and Zn are elements that can accumulate in the soil due to the application of animal manure and other organic waste (Westerman and Bicudo 2005). Therefore, the combination of biochar with poultry manure makes possible to save mineral fertilizers when the objective is to improve soil fertility. Kimetu et al. (2008) also found high base saturation in the 0.0–0.10 m soil layer after three successive applications of eucalyptus biochar at 7 Mg ha$^{-1}$ added to soil cultivated with maize over control. Similarly, in this study, a higher base saturation (Table 4) was found in the second onion crop season for B10 + MF and B10 + PM treatments, compared to control. This indicates a cumulative effect of the application of 10 Mg ha$^{-1}$ of biochar in the soil. Increasing soil nutrient available concentrations (Table 4) with reapplications of biochar may reduce the need for fertilizers in subsequent onion crops. Therefore, biochar application improves the soil fertility status and allows a reduction in the use of fertilizers and, consequently, decreasing costs of food production (Rafael et al. 2019). However, it is necessary to monitor the soil fertility status annually after onion harvest to avoid excessive increases in soil nutrient concentrations and pH.

The cultivation of onion in the no-tillage system increases the chemical attributes of the topsoil in relation to the cultivation of onion in the conventional system (Loss et al. 2020). Additionally, the use of cover crops can increase by 2.5 Mg ha$^{-1}$ the onion yield (Oliveira et al. 2016). However, there are no studies in the literature evaluating the use of biochar in the cultivation of onion in the no-tillage system. Findings of our study suggest that the use of biochar in the cultivation of no-tillage-onion may be a soil management practice that provides more benefits for soil fertility status than for the crop itself (Figure 4). Besides, the use of biochar is an effective strategy to increase crop yield, improve soil structure and carbon stocks and also can increase nutrient use efficiency (Zhang et al. 2020). Use of biochar can increase the use efficiency of nutrients and saves high costs with mineral fertilizers massively imported in Brazil.

## Conclusions

Findings from the study revealed that the combination of biochar with mineral fertilizers increased onion yield in a short time with positive response since the first year of biochar application. However, in general, the nutritional status of the onion plants was not significantly changed across the several treatments tested. The use of 10 Mg ha$^{-1}$ of biochar combined with MF or PM resulted in higher values of soil pH, base saturation, P and Ca over control, mainly in the second onion growing season. Use of PM alone or combined with biochar increased soil Zn availability in both onion growing years. For this reason, the combined use of biochar and poultry manure is a suitable practice to improve the fertility status of the Humic Cambisol . According to results reported in this study, we suggest the use of biochar in the cultivation of onion in the no-tillage system either to improve soil fertility status and boost onion yield.

## Disclosure statement

There is no conflict of interest to report.

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