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ORIGINAL ARTICLE

Effects of biochar-based fertilizers on nutrient leaching in a tobacco-planting soil

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Abstract Biochar is a soil amendment for increasing soil quality and decreasing nutrient leaching. However, there is little information on the impact of biochar-based fertilizer (BF) on soil nutrient leaching in agricultural soils. We conducted a soil column leaching experiment to study the effects of BF on the leaching of total nitrogen (TN), total phosphorus, and total potassium (TK) in tobacco soils. The distribution characteristics of NH_4^+-N, available P, and available K in soil profiles were analyzed after the application of BF. Biochar was prepared by pyrolysis of flue-cured tobacco stems. It was applied at four levels, 0%, 3%, 9%, and 15% (w/w), respectively, to the compound fertilizer. Compared with the control, the leaching loss of soil TN decreased by 8.36%, 6.72%, and 6.45%, and the loss of soil TK decreased by 9.18%, 9.31% and 11.82% in the 3%, 9%, and 15% BF treatments, respectively. However, BF had no significant effect on the P leaching due to the low movement of P in the soil profile. In addition, the BF addition increased the immobilization of NH_4^+-N, available P, and available K in the soil profile. These results indicate that addition of BF to a tobacco-planting soil reduced nutrient leaching, and suggest that BF could be an effective method of applying biochar to agriculture fields.

Keywords Biochar-based fertilizer · Soil column · Nutrient elements · Leaching loss · Immobilization

1 Introduction

Chemical fertilizer (CF) is critical to agricultural production. In recent years, the need to improve crop yield has led to a yearly increase in the amount of CF application. The inability of plants to utilize the excessive CF has resulted in nutrient runoff. However, the intense application of CF with low use efficiency (30%–35%) not only increases the cost of agricultural production, but also results in many environmental problems for the aquatic ecosystem (Liu et al. 2016; Cheng et al. 1989; Davidson et al. 2011; Zhuang and Li 2016). Therefore, the Ministry of Agriculture of China launched a campaign on the N Fertilizer "Zero Growth Action Plan" in different regions across China for the next 5 years (2015–2020) (Jiao et al. 2018). Under this background, it is necessary to improve CF-use efficiency and mitigate environmental pollution by various approaches.

The total annual tobacco stalk output in China is more than 5.21×10^6 t, which is generally decayed and burned during harvest season after removing the marketable leaves. This management practice may result in severe air pollution (Ai et al. 2015). If tobacco stems were returned to the fields by carbonization (biochar), these residual wastes could be treated effectively and used to mitigate pollution (Cheng et al. 2017). Biochar is an organic C-rich material derived from the pyrolysis of waste biomass, such as agricultural and forestry residues under an

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oxygen-limited environment. It is used to mitigate CO_2 emissions, and improve farmland soil and crop yield, due to its long term persistence in soils (Lehmann 2007; Yang et al. 2015), large surface area, highly microporous structure, presence of active organic functional groups, and generally high CEC and pH (Li et al. 2011; Xie et al. 2015; Cheng et al. 2018). However, the transportation and storage costs of biochar is high, which is associated with its low bulk density (Lohri et al. 2016). Therefore, some practical problems are connected to the application of biochar, such as transport disadvantage and dust pollution. Moreover, biochar itself does not provide a significant amount of nutrients to plants. These disadvantages limit its application in agriculture over a large area (Chen et al. 2013).

In recent years, biochar-based fertilizer (BF) (the synthesis of biochar and compound fertilizer) has become an active research topic in the agricultural field. However, the related studies of BF are still at the initial stage, and there has been relatively a few reports in literature (Li et al. 2017). Because of the dry–wet alternate and low utilization of fertilizer in the Guizhou province, the loss of soil nutrients in tobacco lands is a very serious threat, which has resulted in severe economic and environmental problems (Wang 2003; Pleysier and Jun 1981). Therefore, we examined changes of N, P, and K contents in the soil leachates and profiles following the soil columns amended with the 0%, 3%, 9%, and 15% BF treatments. Our objectives are to (1) determine the effect of BF in reducing the leaching loss of soil nutrient elements (N, P, and K), and (2) investigate the effects of BF addition on the distribution of nutrient elements in the soil profile.

2 Materials and methods

2.1 Soil characteristics

The soil was collected from the plough layer (0 ~ 20 cm depth) of the tobacco fields at the Longgang Tobacco Experiment Station (26°52′24.8″N, 107°06′ 40.8″E), Kaiyang county, Guizhou province, China. This region has a humid subtropical monsoon climate with a mean annual temperature of 13.5–14.6 °C, a mean annual precipitation of 1130–1206 mm and four distinct seasons (Cheng et al. 2018). Soil samples were air-dried, homogenized, and sieved (< 1 mm) before experimental use. The soil type is classified as a limestone soil (Chinese Soil Taxonomy) and had the following main properties: pH of 7.77; the NH_4^+-N, NO_3^--N, available P, and available K contents of 13.1, 80.27, 35.35, and 184.7 mg kg^{-1}, respectively (Table 1).

2.2 Characteristics of different BF

The biochar was manufactured from tobacco stalks. Air-dried tobacco stalks were carbonized under limited-oxygen conditions. Biochar was ground and sifted through a 1-mm sieve before being used as a compound fertilizer amendment in this study. The granular structure of BF was prepared by mixing biochar with compound fertilizer according to a certain mass ratio (0%, 3%, 9%, and 15%). The total C content was 5.05, 21.55, 64.26, and 99.46 g kg^{-1} in the 0%, 3%, 9%, and 15% BF treatments, respectively (Table 2).

2.3 Preparation of soil columns

Leaching test apparatus was a PVC cylindrical tube (30-cm height and 8.75-cm diameter). A quartz sand (3 cm) and fine nylon screen were used at the bottom of each column to prevent soil from entering the leachate. Mimicking the bulk density in the field, the air-dried soil was loaded into the cylinder pipe to simulate the soil column of the ploughing layer (20-cm). The soil column contained, successively, a 15-cm soil layer and a 5-cm mixed layer of BF, with a tobacco-planting soil above the column. Each column was artificially mixed with a dose of different BF at 0.5 gN kg^{-1}. Each treatment was replicated three times.

2.4 Soil column leaching

The experiment of soil column leaching was conducted at room temperature (25 °C). The first irrigation (60 mL) was applied to the columns for incubation over a 7-day period. After incubation, the irrigation events were applied at 7-day intervals, at a rate of 120 mL. At the 48th and 79th days, the amount of irrigation was 360 mL with 10-day intervals. All leachates were collected at the bottom of each soil column using glass bottles. In this experiment, simulated rainfall and its intensity were chosen to represent comparable rainfall amounts received in Guiyang city from July to August over the past 5 years.

2.5 Analysis methods

Available P and available K contents of the soil were extracted by the $NaHCO_3$ extraction and the CH_3COONH_4 extraction, followed by the Mo-Sb colorimetric method and flame photometry, respectively (Wang et al. 2016). The soil NH_4^+-N concentrations were determined by 2 M KCl extraction followed by the indophenol-blue method (Liu et al. 2016). The contents of TN, TP and TK in the leachate were determined using UV spectrophotometry, the molybdenum blue method and atomic absorption spectroscopy, respectively (Bao 2000).

Table 1 Physical and chemical characteristics of the tobacco-planting soil

Soil type	Bulk weight (g cm^{-3})	NH_4^+-N (mg kg^{-1})	NO_3^--N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	pH	EC (μs cm^{-1})
Limestone soil	1.16	13.1	80.27	35.35	184.7	7.77	121

Table 2 Physical and chemical characteristics of different BF treatments

BF treatments	Total C (g kg^{-1})	Total N (g kg^{-1})	Total P (g kg^{-1})	Total K (g kg^{-1})	pH (1:2.5)
0% BF	5.05	95.29	116.1	224.4	6.8
3% BF	21.55	92.1	117.1	221.3	7.2
9% BF	64.26	92.76	105.6	219.8	7.8
15% BF	99.46	92.99	108.6	220.1	8.5

2.6 Statistical analysis

The differences in the contents of N, P and K in the soil profiles and leachates among different BF treatments were compared through a one-way analysis of variance (ANOVA) with the least significant difference (LSD) test. A value of $p < 0.05$ was accepted as significant. All statistical analysis was performed by the SPSS software package (Version 24.0, SPSS Inc., Chicago, IL, USA).

3 Results

3.1 Changes of N in soil leachates and profiles at different incubation days

The average TN concentration in the leachate at the initial stage (the 13th day) of the experiment was 1705, 1877, 2306, and 2214 mg L^{-1} in the 0%, 3%, 9%, and 15% BF treatments, respectively, decreased rapidly during the experiment, with average concentration of 330, 271, 218, and 275 mg L^{-1} after 34 days (Fig. 1a). During the leaching process, the concentration of TN in the leachate increased with the increase of the proportion of biochar in BF treatments. However, there were no significant differences between the 9% and 15% BF treatments. After the 20th day, the concentration of TN decreased with the increase of the proportion of biochar in the BF treatments. As time progressed, the accumulated loss of TN in different BF treatments gradually increased, but the increase slowed down after the 48th day (Fig. 1b). Compared with the control (489.9 mg), the leaching loss of TN reduced by 8.63%, 6.72%, and 6.45% in the 3%, 9%, and 15% BF treatments, respectively. However, there were no significant differences among different BF treatments.

The content of NH_4^+-N in the soil profile increased with the increasing of the depth (Fig. 2). There was no significant difference in the content of soil NH_4^+-N between different BF treatments in the 0–6 cm layer. However, BF significantly increased the content of NH_4^+-N in the 9–14 cm layer. Compared with the control (50.79 mg kg^{-1}), the NH_4^+-N content in the 9–14 cm

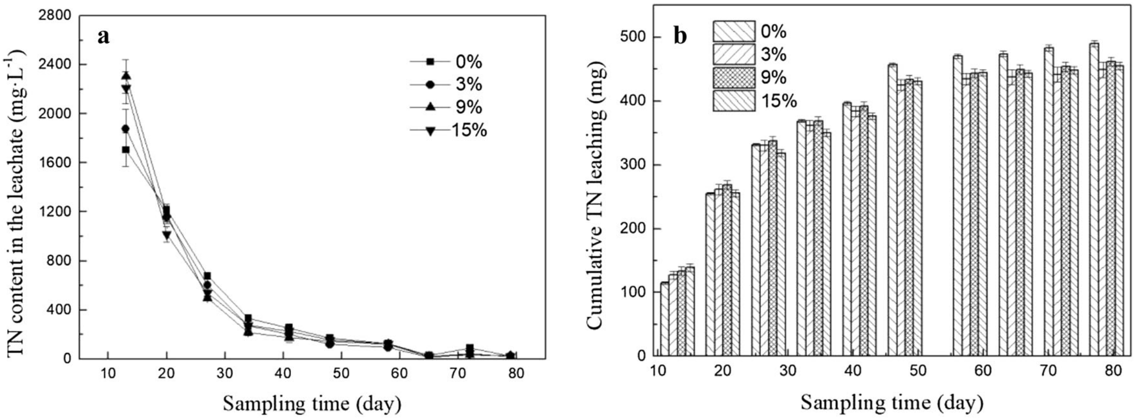

Fig. 1 Effects of BF on the concentration (**a**) and cumulative loss (**b**) of TN in the leachate at different incubation time

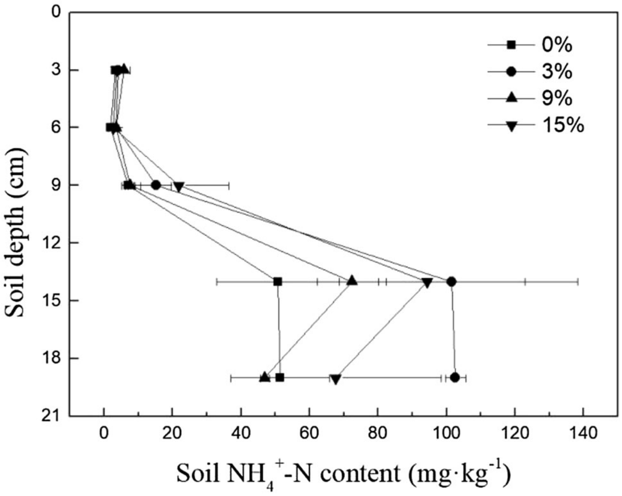

Fig. 2 Effect of BF on the distribution of NH$_4^+$-N in the soil profile

layer increased by 99.8%, 42.46%, and 85.76% in the 3%, 9%, and 15% BF treatments, respectively.

3.2 Changes of P in soil leachates and profiles at different incubation days

The concentrations of TP in the leachate under different BF treatments exhibited an increasing trend first and then deceased gradually (Fig. 3a). The concentrations of TP in the leachate reached peak at the 27th day, then it gradually decreased to the lowest at the 65th day. However, the concentration of TP in all leachates was low and the difference between different BF treatments was not significant ($p > 0.05$). The cumulative loss of TP in the leachate in the control was 0.21 mg. The corresponding values were 0.23, 0.24, and 0.23 mg in the 3%, 9%, and 15% BF treatments, respectively (Fig. 3b).

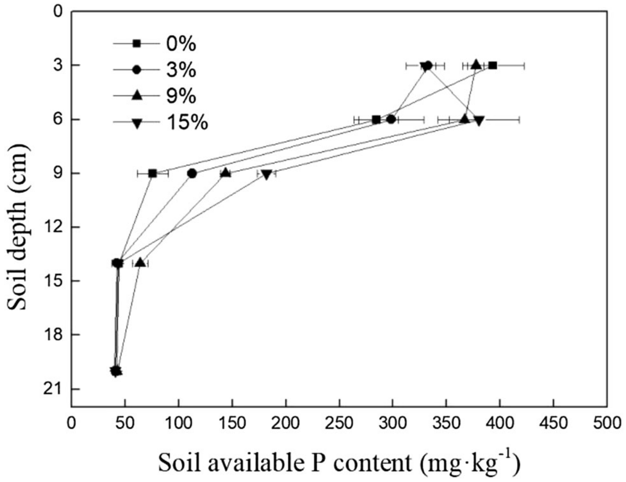

Fig. 4 Effect of BF on the distribution of available P in the soil profile

In the present study, the content of available P in the soil profile increased with the increasing content of biochar in BF treatments, but decreased with increasing soil depths (Fig. 4). For example, compared with the control, the content of available P in the soil 3–6 cm layer increased by 4.81%, 28.76%, and 32.41% in the 3%, 9%, and 15% BF treatments, respectively. In the 6–9 cm layer, the available P increased by 13.03%, 16.45%, and 25.66% in the 3%, 9%, and 15% BF treatments, respectively.

3.3 Changes of K in soil leachates and profiles after different incubation days

The TK concentration in the leachate decreased firstly and then gradually increased with time going on. The TK concentration reached the lowest on the 34th day (Fig. 5a). At the initial stage of leaching, the TK concentration in the leachate was higher. The TK concentrations at the 13th day were 24.91, 25.43, 27.65, and 24.49 mg L^{-1} in the 0%, 3%, 9%, and 15% BF treatments, respectively. The content of TK in the leachate changed little from the beginning of the leaching to the 34th day. On the 58th day, however, the

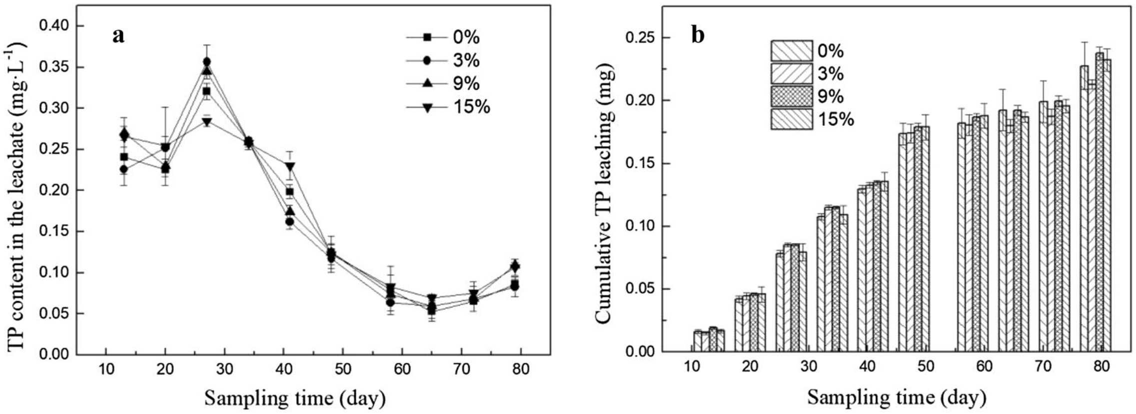

Fig. 3 Effects of BF on the concentration (**a**) and cumulative loss (**b**) of TP in the leachate at different incubation time

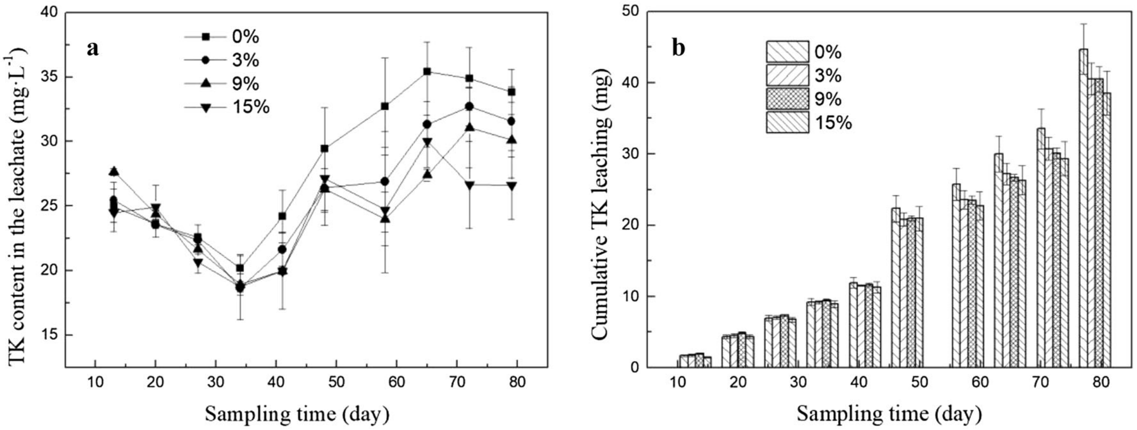

Fig. 5 Effects of BF on the concentration (**a**) and cumulative loss (**b**) of TK in the leachate at different incubation time

concentration of TK in the leachate decreased by 17.79%, 26.66%, and 24.52% in the 3%, 9%, and 15% BF treatments, respectively, compared with the control. The cumulative loss of TK in the different BF treatments increased gradually with time going on, especially at 41th and 72th days (Fig. 5b). The cumulative loss of TK decreased with the increasing content of biochar in BF treatments. Compared to the control (44.68 mg), the cumulative loss of TK decreased by 9.18%, 9.31%, and 11.82% in the 3%, 9%, and 15% BF treatments, respectively.

The content of soil available K in each treatment showed first an increasing and then decreasing trend with the increase of soil depths (Fig. 6), which was mainly distributed in the upper layer (0–9 cm) of soil profile. With the increase of leaching times, the available K in the soil began migrating to deeper layers of soil. There was no significant differences in available K among different BF treatments in the 0–3 cm layer. The application of BF improved the content of available K in the 3–6 cm layer. However, compared to the control, the content of available K in the 9–14 cm layer decreased by 9.61%, 7.19%, and 16.87% in the 3%, 9%, and 15% BF treatments, respectively.

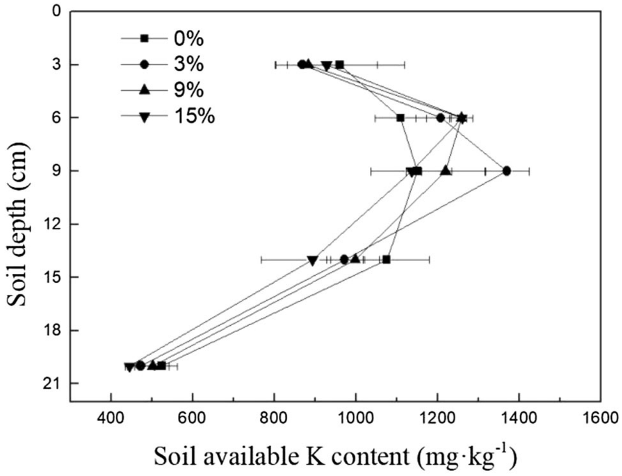

Fig. 6 Effect of BF on the distribution of available K in the soil profile

4 Discussion

The impacts of biochar on nutrient leaching depend on several complex processes, such as chemical, physical, and biological processes (Laird et al. 2010). In our study, the leaching loss of TN reduced by 8.63%, 6.72%, and 6.45% in the 3%, 9%, and 15% BF treatments, respectively, as compared with fertilizer without biochar addition (Fig. 1). This result is in accordance with previous studies (Laird et al. 2010; Ding et al. 2010; Zhao et al. 2013). All reports indicated that the addition of biochar to BF could reduce leaching and improve soil N retention (Zhao et al. 2013).

The biochar-induced changes of the soil NH_4^+-N contents enhanced N retention, which has been discovered in previous studies (Liu et al. 2017; Ding et al. 2010). For example, the NH_4^+-N leaching in a sandy soil was reduced from 15.0 to 12.9 mg pot^{-1} following the biochar amendment (Dempster et al. 2012). Moreover, application of biochar decreased the cumulative losses of NH_4^+-N via leaching by 15.2% (Ding et al. 2010). In the present study, BF significantly increased the content of NH_4^+-N in the soil profile, especially at the 9–14 cm layer. These findings may be attributed, at least in part, to the adsorption of NH_4^+-N by biochar through its high CEC (Ding et al. 2010). Moreover, the reduction in the movement of NH_4^+-N may also be related to the enhanced nitrification induced by biochar (Liu et al. 2017).

The cumulative loss of TP in the leachate was from 0.21 to 0.24 mg in all BF treatments, and there were no significant differences between different treatments. This result indicates that soluble P was considerably less mobile than either N or K, because P is often tightly bound by soils (Eghball et al. 1996; Laird et al. 2010). Available P is an important index to evaluate the capability of soil P supply, which is significantly affected by agricultural activities such as tillage, drainage, intercropping, rotation and fertilization, etc. (Hu and Lu 2003). BF addition increased the content of available P in the soil profiles and promoted P movement from the top to the bottom of the soil profile, which was similar to earlier results (Wu 2015; Dai et al. 2016). The effect of biochar on the availability and leaching of P is concerned with a complex process, including pH changes, microbial activity, phosphate mineralization and complexes (DeLuca et al. 2009).

From the beginning to the 38th day of the experiment, there was no significant difference in TK concentration between BF treatments. In the early stages of leaching, the leached K was mainly from the residual K in the subsoil of soil column. As the experiment proceeded, the K in the soil column was leached out gradually. Therefore, the concentration of K in the leachate decreased in all BF treatments. From the 38th day to the end of the experiment, the leached K in the control was significantly higher than those in other BF treatments ($p < 0.05$), which might be due to the fact that the leached K mainly came from BF amendments at this time. This may be due to the large specific surface area, porous structure and negative charge potential of biochar (Liang et al. 2006), which has a high sorption capacity for K^+. Therefore, the concentration of K in the leachate decreased with the increasing proportion of biochar in the BF treatments. In addition, BF increased the content of available K in the soil profile, especially at the 3–9 cm layer. This might be due to higher pH in the soil generated by the addition of biochar to fertilizer (Table 2), and the K fixation capacity of soils increased with the increasing of pH (Volk 1934). Therefore, the application of BF increased the fixation of K and slowed down the movement of K in the soil profile.

5 Conclusion

Compared to the control, the leaching loss of soil TN decreased by 8.36%, 6.72%, and 6.45% in the 3%, 9%, and 15% BF treatments, and the TK leaching loss decreased by 9.18%, 9.31%, and 11.82% in the 3%, 9%, and 15% BF treatments, respectively. However, BF had no significant impacts on the leaching loss of TP due to the low movement of P in the soil. In addition, the BF addition increased the retention of NH_4^+-N, available P and available K in the soil profile. Therefore, the BF addition reduced the risk of these nutrients entering into the water and other environmental media, which provided valuable information about the application of BF in agriculture fields to scientists, entrepreneurs, and farmers.

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