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ORIGINAL ARTICLE

Potassium-enriched biochar-based fertilizers for improved uptake in radish plants

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Abstract Biochar-based fertilizers (BBFs) enriched with potassium (K) can increase the efficiency of K use by plants. This study evaluated the effect of a new K-enriched sewage sludge biochar in the pellet and granule forms, applied at full and reduced application rates, compared with a conventional K fertilized control (KCl), on soil chemical attributes, nutrition and relative chlorophyll content (SPAD index) of radish plants grown in a greenhouse. Both BBF forms (granule and pellet) showed good performance in supplying K and other nutrients to the plants. On average, BBF in the granule form increased the concentration of K in radish sap by 30% compared to BBF in the pellet form and KCl. Even when applied at half the recommended rate (174 kg ha^{-1} of K), BBFs were efficient in supplying K and other nutrients to the plant. BBF in the pellet form increased the tuber dry mass, which was on average 150% higher than KCl and BBF in the granule form. In general, the results of the present study indicate that the better supply of K promoted by the BBF also contributed to higher SPAD index values in the radish crop. More studies should be carried out to better understand the effect of BBF on the performance of crops with different cultural cycles (short and long).

Keywords Soil amendment · Slow released fertilizer · Sewage sludge biochar · K fertilizer

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Introduction

Studies on biochar have been conducted in several research areas in the last two decades (Islam et al. 2021). In agriculture it shows great potential as a soil conditioner and fertilizer, promoting the recycling of nutrients and the accumulation of carbon in the soil (Chagas et al. 2022). The concentration of nutrients in the biochar depends on the type of raw material and pyrolysis conditions, including temperature and residence time (Najafi-Ghiri et al. 2020). When produced from sewage sludge (SS), biochar may contain up to 6% phosphorus (P), approximately 3.2% N, 0.82% Ca and 540 mg kg^{-1} of Zn (Figueiredo et al. 2018; Faria et al. 2018). However, SS biochar (SSB) is deficient in potassium (K) because SS has low K levels in its composition (Tontti et al. 2016); thus, blending SSB with mineral fertilizer is a suitable strategy to make biochar a balanced source of nutrients (Arif et al. 2017; Shin et al. 2019).

Biochar enrichment with mineral fertilizers can be achieved using different techniques such as simple mixing in powder form, granulation, pelletizing and others (Ndoung et al. 2021; Melo et al. 2022). When compared to highly soluble mineral fertilizers, biochar-based fertilizers (BBFs) can improve the efficiency of plant nutrient use (Lustosa Filho et al. 2020; Puga et al. 2020). This is possible because SSBs can reduce K and N losses via leaching by acting as slow-release fertilizers (Luo et al. 2021; Fachini et al. 2022). Additionally, SSBs can reduce N losses by volatilization (Puga et al. 2020), minimize the specific adsorption of P in the soil and increase the P availability for plants (Lustosa and Filho et al. 2020). As a result, SSBs can increase crop yields by 10% and 186% compared to fertilized and unfertilized controls, respectively (Melo et al. 2022).

There are several techniques to enrich biochar with nutrients including pre- and post-pyrolysis procedures. K-enriched BBFs were obtained via pre-pyrolysis; and composite biochars showed slow-release characteristics (Wu et al. 2021). However, post-pyrolysis is the most used technique to produce BBFs (Ndoung et al. 2021). In recent years new BBFs enriched with mineral fertilizers have been evaluated, with an emphasis on P enrichment (Chia et al. 2014; Nguyen et al. 2017; Lustosa Filho et al. 2019). In the specific case of BBF from sewage sludge the biochar itself is the source of P (up to 6%) and N (approximately 3.2%), even though most N and P are not readily available to plants; this reduces the production cost since only potassium sources are needed for its enrichment. In this sense, a K-enriched sewage sludge BBF was recently developed (Fachini et al. 2021a). This new fertilizer ensured a 75-fold increase in soluble K content when compared to pure biochar. Under laboratory conditions this new fertilizer functioned as a slow-release K fertilizer, reducing K leaching rates in pure silica (Fachini et al. 2022). Therefore, BBFs provide better synchronization of nutrient release and the nutritional demand by plants, increasing the K use efficiency (Adu-Gyamfi et al. 2019). However, both the release dynamics and the K uptake of BBF need to be evaluated under real conditions in the presence of plants where nutritional, physiological and productivity aspects of the crop are investigated.

Despite the potential of K-enriched biochar fertilizers, there is still a lack of information on the agronomic performance of these inputs. Given this lack of studies, the objective of the present work was to evaluate the effect of SSB enriched with K on potassium absorption, nutrition and the SPAD index of radish plants. It was hypothesized that BBFs have a better efficiency than conventional K fertilizer to improve the soil available nutrients and plant nutrition, and therefore increased radish productivity.

Materials and methods

The study was carried out in a greenhouse located at Embrapa Hortaliças, Brasília, DF, Brazil, with radish plants grown in 1.5-L pots measuring 112.8 mm in diameter and 150 mm in height. Pots were filled with 1.5 kg of soil. Fertilizers based on sewage sludge biochar enriched with K (using KCl) were produced in the granule and pellet forms, using starch as a binding agent, whose production details are presented in Fachini et al. (2021a). For SSB preparation, SS samples were air-dried (to approximately 10% moisture content), passed through a 4 mm sieve and then pyrolyzed at 300 °C. Pyrolysis was performed in a muffle furnace (Linn ElektroTherm, Eschenfelden, Germany) at a mean temperature increase rate of 2.5 °C min^{-1} and residence time of 5 h, as described by Figueiredo et al. (2018). The furnace was equipped with a mechanism to prevent oxygen flow (via forced draft fan, helping gas and oil vapors exit the furnace).

BBFs were produced from a physical mixture of SSB, KCl and additives. The feedstocks were mixed to obtain a final mass of 1.0 kg of each BBF. Thus, 50 g of KCl were added to supply 2.49% K. As a binding agent, 65 g of pre-gelatinized starch was also added to produce granules and pellets. As a source of N and P, SSB was added to complete 1.0 kg of the formulation. The SSB and KCl were crushed in an industrial device (Philco PLQ 1400), and later passed through a 0.500 mm mesh sieve. The formulations SSB + KCl + starch were subjected to the granulation and pelleting processes.

The pellets were produced in a laboratory pelletizer (ENG-MAQ, model ENG 0200 V, São Paulo, Brazil). For each 1.0 kg batch of BBF, 140 mL of distilled water were used to facilitate mixing of the raw materials. At the end of this process, pellets measuring 6 mm in diameter and 10 mm in length were produced. After this process, the pellets were dried in an oven at 65 °C for 24 h. The granules were produced in a laboratory granulator composed of a cylindrical tray measuring 7 cm high by 36 cm in diameter, inclined at an angle of 70°, coupled to a motor operating at 40-rpm. During granulation, distilled water was also added by spraying on the raw material. Afterward, the granules were passed through a set of 3 sieves with different meshes, according to the sequence: 4 mm, 2 mm and 1 mm. Granules larger than 4 mm and smaller than 1 mm were crushed again and granulated to obtain granules between 1.0 and 4.0 mm. Finally, the granules were dried in an oven at 65 °C for 24 h. The chemical and physical characteristics of the fertilizers are presented in Table 1 and Table S1. Mean values of pH, and elemental C and N were 7.75, 25.4% and 3.34%, respectively, and are within the reference value ranges for several enriched biochars: pH = 5.7–9.9; TC = 5.6–39.5%; TN = 0.9–1.2% (Blackwell et al. 2015; Darby et al. 2016; Farrar et al. 2018; Gondek et al. 2018; Nardis et al. 2020).

Table 1 Characteristics of K-enriched biochar fertilizers (BBFs)

Variable[a]	BBFs	
	Granule	Pellet
pH ($CaCl_2$)	5.7 ± 0.1	5.8 ± 0.1
TC (%)	25.3 ± 0.4	25.5 ± 1.5
TN (%)	3.0 ± 0.1	3.7 ± 0.3
C/N	8.2 ± 0.4	7.8 ± 0.6
P (%)	2.3 ± 0.1	2.3 ± 0.1
K (%)	2.5 ± 0.0	2.5 ± 0.1
Ca (g kg^{-1})	5.6 ± 0.0	5.6 ± 0.0
Mg (g kg^{-1})	1.6 ± 0.0	1.4 ± 0.4
S (g kg^{-1})	1.2 ± 0.0	1.3 ± 0.2
Fe (g kg^{-1})	17.3 ± 0.0	18.3 ± 1.0
B (mg kg^{-1})	25.6 ± 0.4	27.2 ± 1.1
Mn (mg kg^{-1})	89.0 ± 2.2	89.0 ± 0.3
SA (m^2 g^{-1})	17.5	14.0
PV (mm^3 g^{-1})	74	56
PMV (mm^3 g^{-1})	19	15
C-FA (g kg^{-1})	33.9 ± 0.2	33.2 ± 0.3
C-HA (g kg^{-1})	11.1 ± 0.2	11.9 ± 0.6
C-HU (g kg^{-1})	205 ± 3.3	211 ± 6

TC total carbon; *TN* total nitrogen; *SA* surface area; *PV* total pore volume; *PMV* micropores volume; *C–FA, C–HA, C–HU* Carbon in fulvic acid, humic acid and humin, respectively, extracted with NaOH 0.1 mol L^{-1}, according to the differential solubility technique (Swift 1996) and the carbon contents were determined according to the method of Yeomans and Bremner (1988). Adapted from Fachini et al. (2021a)

[a] Average values ± standard deviation (n = 3)

Soil and laboratory analysis

Samples from a Latossolo Vermelho according to the Brazilian Soil Classification (Santos et al. 2018), clayey Oxisol (Typic Haplustox) (Soil Survey Staff 2014), Gibbsic Ferralsol (IUSS Working Group WRB 2014), with 82% clay, were collected from the 0.40–1.00 m layer in a profile located at the Experimental Farm of the University of Brasília (15° 56′ 45’’ S, 47° 55′ 43’’ W; 1095 m), Brasília, DF, Brazil. Before and after the experiment, the soil samples were chemically characterized for pH, CEC, P, K^+, Ca^{+2}, Mg^{+2} and Al^{+3} according to the methodologies of Teixeira et al. (2017).

Conducting the experiment

Based on the results of soil chemical analysis before the experiment, a rate equivalent to 4 Mg ha^{-1} of dolomitic limestone was applied to increase the base saturation to 80% as required by the radish crop (Raij et al. 1997). Next, as corrective fertilization, an application rate of 183 kg ha^{-1} of P was applied in the form of monobasic calcium phosphate (11.6% of P), according to Sousa and Lobato (2004). Soil chemical parameters before and after acidity correction and P correction fertilization are presented in Table 4.

Radish seeds (*R. sativus* L.), variety Saxa (ISLA seeds®), were sown in commercial substrate and later (10 days after the sowing) transplanted into 1.5-L pots containing the corrected soil. Seeds of the variety Saxa take 30–35 days to mature and present a yield potential of 10–15 tons per hectare.

The recommended fertilization for radish was carried out according to Raij et al. (1997). The total amounts of N (source: Urea), P (source: Monobasic calcium phosphate) and K (source: Potassium chloride) applied were 130, 360 and 210 kg ha^{-1}, respectively. In addition to these nutrients, in order to supply zinc (Zn), boron (B), sulfur (S) and magnesium (Mg), fertilization was also carried out using a nutrient solution with zinc sulfate (20% of Zn and 10.5% of S), boric acid (17% of B) and magnesium sulfate (9% of Mg and 12% of S).

Two levels of K supply via the BBFs were evaluated: 0.5 and 1 times the recommended K application rate for the radish crop. The BBFs in the form of granules and pellets had the same concentration of K (2.5%). Thus, to provide 0.5 and 1 times the recommended rate of K for the radish crop, rates equivalent to 3.5 and 7 Mg ha^{-1} of BBF were applied, respectively. The quantities of BBF applied for the two different fertilization levels are shown in Table S2. A commercial KCl treatment was applied as a reference (fertilized control) to provide the recommended K rate for the crop (174 kg ha^{-1} K or 0.26 g pot^{-1} of KCl).

In order for all treatments to receive the same nutrient quantities, for the supply of P and N via solution the amount of these nutrients supplied via the BBF was discounted. The BBF composition presented averages of 3.3 and 2.3% of total N and total P, respectively (Table 1). To consider the real contribution, the soluble P and N contents of the SSB were considered. In SSB pyrolyzed at 300 °C, 24% of the total P is soluble in citric acid (Figueiredo et al. 2021) and 1.4% of the total N is mineral N (nitrate and ammonium) (Figueiredo et al. 2019). Therefore, in Table S3 the application rates used are presented as a function of the concentrations of P soluble in citric acid and mineral N in the BBFs.

The application of fertilizers (BBFs and KCl) was carried out on the same day that the seedlings were transplanted. Fertilization of P, N, Zn and B was carried out via a solution at 7 days after transplanting for a total supply of 360, 40, 3 and 4 kg ha^{-1}, respectively. After 13 days of transplanting, one more topdressing was carried out using a solution to supply 40, 80 and 41 kg ha^{-1} of N, sulfur (S) and magnesium (Mg), respectively. The last topdressing fertilization was performed 28 days after transplanting to supply 50 kg ha^{-1} of N. All recommendations were performed according to Raij et al. (1997).

Irrigation management was performed by controlling the water tension in the soil (15 kPa) using the Irrigas® device. When necessary, irrigation was performed by drip (flow rate of 2 L/h) for an average of 3 min per day. The insecticide Pirate (Clorfenapir®) was applied to control whitefly. The radish was harvested 38 days after transplanting.

Treatments and experimental design

The experimental design was completely randomized, with 5 treatments and four replications, totaling 20 pots. The treatments evaluated were: KCl (174 kg ha^{-1} of K via granulated mineral KCl) as a fertilized control, BBF-G0.5 (87 kg ha^{-1} of K via granulated BBF), BBF-G1 (174 kg ha^{-1} of K via granulated BBF), BBF-P0.5 (87 kg ha^{-1} of K via pelleted BBF) and BBF-P1 (174 kg ha^{-1} of K via pelleted BBF). All BBFs were enriched with the same KCl used in the control as the K source.

Crop agronomic indices and nutrient absorption

At radish harvest, 38 days after transplanting, the following biometric characteristics of the plant were evaluated: height, leaf area, K content in the sap, fresh aerial part mass and mass of the commercial part (tuber). The plant height was measured using a millimeter ruler. To determine the leaf area, a fully healthy and expanded leaf of each plant was used to perform the calculation in the ImagemJ™ software (PMC5554542) (Schneider et al. 2012). To determine K in the sap of the leaves, sample collection (leaf and petiole) was carried out in the most recent fully expanded leaf and in the morning between 8 and 11 am. Pressing/crushing of leaves with petioles was performed immediately after collection. A stainless-steel crusher was used and measuring of the fluid was performed with the Horiba LAQUATwin 741 device (HORIBA, Japan) after calibration.

The fresh mass (FM) of the aerial part and of the tuber was determined using a precision scale, and weighing was done immediately after harvest. The dry mass (DM) of the aerial part and of the radish was determined after drying in an oven for 72 h at 60 °C. Leaf thickness was evaluated 25 days after transplanting, using the MultispeQ device (PhotosynQ INC, USA).

The levels of macro and micronutrients absorbed by the plant were determined according to methodologies described in Malavolta et al. (1998). Leaves with petiole samples were stored in paper bags and dried in an oven with air circulation at 65 °C until reaching constant weight. Ground samples were then submitted to nitric-perchloric acid digestion. N was determined by the semi-micro-Kjeldahl analysis, and titration with H_2SO_4. P by colorimetry of metavanadate, K by atomic absorption spectrometry, with a K hollow cathode lamp and S content by barium sulfate turbidimetry. The contents of Ca and Mg were analyzed by atomic absorption spectrophotometry. Finally, the micronutrients manganese (Mn), cobalt (Co) and Zn were estimated by atomic absorption spectrophotometry, with direct determination in the nitric-perchloric extract of vegetables.

Relative chlorophyll content (SPAD Index)

The radish SPAD index was evaluated 25 days after transplanting using the MultispeQ device (PhotosynQ INC, USA), by means of the PhotosynQ platform (http://www.photosynq.org). The SPAD index measurement after 25 days was based on previous studies whose values ranged from 19 to 30 days after transplanting (Stagnari et al., 2018; Kalaji et al. 2018). Readings were taken on 2 healthy and fully expanded leaves per plant. The SPAD index was evaluated in the morning when the average temperature inside the greenhouse was 34 °C and humidity was 49%.

Statistical analyses

Data was initially analyzed for residual normality and homoscedasticity using the Lilliefors and Cochran test. When presenting a normal distribution, the data was submitted to analysis of variance (ANOVA) and the means were compared by Fisher's LSD test ($P < 0.05$) using the XLSTAT software (Addinsoft 2013).

Results

Radish biometric indices and nutrient absorption

BBF in the pellet form increased the DM of the tubers, which was on average 150% higher than KCl and BBF in the granule form. The other biometric indicators of the plant were not affected by the fertilizers (Table 2).

K uptake by plants, estimated from leaf + petiole biomass, in response to the application of BBFs is shown in Fig. 1. The fertilizers behaved differently and can be grouped into three groups. Full application rate BBFs (BBF-G1 and BBF-P1) promoted greater K uptake in plants (average of 47%) than mineral fertilizer (KCl). The reduced BFF rate (BBF-G0.5 and

Table 2 Biometric characteristics of the radish plants fertilized with biochar based fertilizers and KCl*

Treatments	Height mm		Leaf area mm^2		Leaf thickness mm	
KCl	282 ± 40	a	44,690 ± 7030	A	0.68 ± 0.04	a
BBF-G0.5	222 ± 9	a	49,750 ± 6850	a	0.64 ± 0.06	a
BBF-G1	250 ± 22	a	51,890 ± 2290	a	0.70 ± 0.07	a
BBF-P0.5	219 ± 10	a	54,790 ± 6220	a	0.80 ± 0.10	a
BBF-P1	222 ± 18	a	57,180 ± 9000	a	0.68 ± 0.10	a

Treatments	Fresh mass (FM)				Dry mass (DM)			
	Aerial part		Tuber		Aerial part		Tuber	
	(g)							
KCl	14.1 ± 2.1	a	2.1 ± 1.1	A	1.3 ± 0.3	a	0.14 ± 0.06	b
BBF-G0.5	15.6 ± 0.9	a	2.2 ± 1.1	A	1.3 ± 0.2	a	0.13 ± 0.06	b
BBF-G1	15.7 ± 1.4	a	2.1 ± 0.1	A	1.5 ± 0.2	a	0.14 ± 0.01	b
BBF-P0.5	14.3 ± 0.7	a	1.8 ± 0.5	A	1.3 ± 0.1	a	0.15 ± 0.05	ab
BBF-P1	15.3 ± 1.5	a	4.9 ± 2.0	A	1.53 ± 0.13	a	0.35 ± 0.12	a

Means with the same letters do not show statistical differences according to Fisher's LSD test ($P < 0.05$)

[*] Average values ± standard error (n = 4)

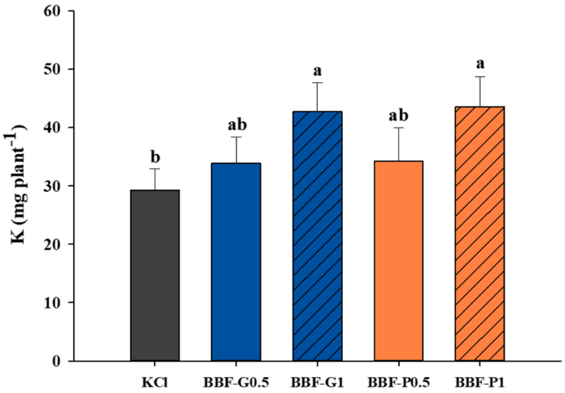

Fig. 1 K uptake by the radish plant in response to BBF application. Means with the same letters do not show statistical differences according to Fisher's LSD test ($P < 0.05$). Error bars represent the standard error (n = 4)

BBF-P0.5) showed an intermediate behavior and did not differ from the other fertilizers. Despite promoting differences in K uptake, all fertilizers maintained adequate K levels in the plant (15 to 30 g kg^{-1}) for the radish crop (Burdine 1976; Sanchez et al. 1991; Hochmuth et al. 2022).

The contents of the other macronutrients (N, P, S, Ca and Mg) in the plant are shown in Table 3. In addition to K absorption, only the N and S contents were affected by application of the fertilizers ($P < 0.05$). In general, the BBFs promoted N and P concentrations in the plant similar to the conventional fertilizer. Among biochar-based fertilizers, BBF-P0.5 showed lower N content than both BBFs in granule form and lower S content than BBF-G1.

Potassium in plant sap and the Relative Chlorophyll Index (SPAD)

The K concentrations in the sap of radish plants (K-sap) in response to different fertilizers are shown in Fig. 2. Plant sap analysis provides an early determination of the plant nutrient status since it relies on real-time information (Esteves et al. 2021). Plants fertilized with BBF-G1 showed a higher concentration of K-sap than the other fertilizers (Fig. 2; $P < 0.05$), remaining within the appropriate range for several vegetables in different development periods, with values between 1800 and 5000 mg L^{-1} (Hochmuth et al. 2022). The other fertilizers resulted in similar K-sap concentrations which were below the appropriate range (< 1800 mg L^{-1}), regardless of the application rate used. Therefore, half of the added BBF rate promoted a K-sap concentration equivalent to the full rate of KCl.

The relative chlorophyll content (SPAD index value) of radish plants is shown in Fig. 3. The SPAD index was 18% higher in plants fertilized with BBF-G1 in relation to KCl ($P < 0.05$), with no difference among the other fertilizers.

Table 3 Nutrient content in radish plants fertilized with biochar-based fertilizers and KCl as a fertilized control *

Treatments	N g kg^{-1}		P		K	
KCl	42.0 ± 0.4	ab	4.8 ± 0.3	a	9.4 ± 0.4	ab
BBF-G0.5	43.5 ± 0.9	a	4.9 ± 0.6	a	9.1 ± 0.8	ab
BBF-G1	44.3 ± 1.5	a	5.1 ± 0.4	a	8.0 ± 0.4	ab
BBF-P0.5	29.5 ± 1.5	b	3.6 ± 0.6	a	6.3 ± 0.8	b
BBF-P1	40.0 ± 1.1	ab	4.7 ± 0.3	a	9.7 ± 0.5	a
Treatments	S g kg^{-1}		Ca		Mg	
KCl	9.4 ± 0.03	ab	29.5 ± 2.0	a	6.0 ± 0.1	a
BBF-G0.5	9.1 ± 0.03	ab	31.5 ± 1.1	a	5.7 ± 0.3	a
BBF-G1	8.0 ± 0.04	ab	31.8 ± 0.7	a	6.0 ± 0.4	a
BBF-P0.5	6.2 ± 0.04	b	21.7 ± 1.6	a	4.2 ± 0.4	a
BBF-P1	9.7 ± 0.04	a	31.1 ± 0.4	a	5.3 ± 0.3	a

Means with the same letters do not show statistical differences according to Fisher's LSD test ($P < 0.05$)

[*] Average values ± standard error (n = 4)

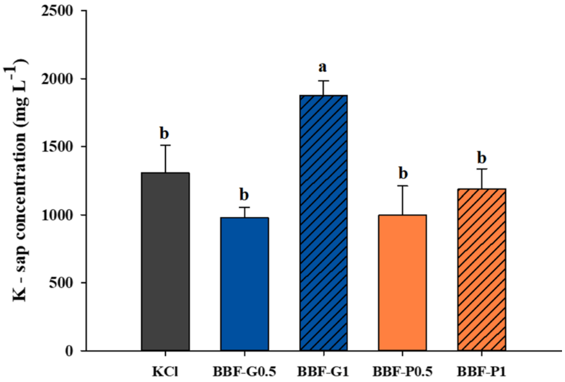

Fig. 2 K content in the sap of radish leaves fertilized with different fertilizers and their respective application rates. Means with the same letters do not show statistical differences according to Fisher's LSD test ($P < 0.05$). Error bars represent the standard error (n = 4)

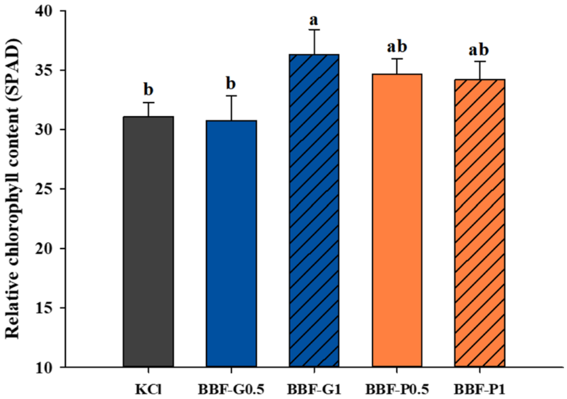

Fig. 3 SPAD index in radish leaves fertilized with biochar-based fertilizers. Reading was performed 25 days after transplanting. Means with the same letters do not show statistical differences according to Fisher's LSD test ($P < 0.05$). Error bars represent the standard error (n = 4)

Soil fertility indicators

The chemical attributes related to soil fertility after radish harvest are presented in Table 4 and Table S4. In general, fertilizers affected pH and the contents of OM, P and Ca (Table 4). The fertilizers did not change the base saturation (*V* value) of the soil during radish cultivation, but BBF-P0.5 reduced the pH when compared to BBF-G0.5. A 50% reduction in the application rate of pelletized BBF (BBF-P0.5) resulted in a small reduction in OM, Ca and P contents compared to the full BBF application rate.

At the end of cultivation, the soil showed similar levels of available K in the soil. In general, after radish harvest the K contents were similar to the K contents of the soil before fertilizer application (Table S4). The application of BBF-G1 promoted higher *P* content than the other fertilizers, with the exception of BBF-G0.5 ($P < 0.05$). Soil P content in BBF-G1 was 29% higher than in KCl. When reducing the application rate by 50%, BBF-P0.5 reduced the Ca supply by 22 and 26% compared to BBF-G1 and BBF-P1, respectively. Soil Mg levels were not affected by the fertilizers applied ($P > 0.05$).

Discussion

BBFs increase nutrient uptake and K-sap in the radish plant

In the present study there did not appear to be K deficiency in plants fertilized with the different fertilizers (Table 2). All fertilizers maintained adequate K levels in the plant (15 to 30 g kg^{-1}) for the radish crop (Burdine 1976; Sanchez et al. 1991; Hochmuth et al. 2022), demonstrating that the radish plants had a good K supply, even when half of the BBF was available. K deficiency would limit plant growth, development and reproduction (Kusaka et al. 2021), as this nutrient is involved in most of the plant's metabolism (Hasanuzzaman et al. 2018). Overall, for all fertilizers both the FM and DM of the radish aerial part (Table 2) were similar to the results reported by Sakamoto et al. (2021) in their experiment with radish in hydroponics, where the plant received all nutrients in a balanced rate.

The results of the present study indicate that BBF, regardless of the form (granule or pellet) and even with a 50% reduction in the application rate, had a similar effect to KCl on development of the radish plant. Previous studies have demonstrated the positive effects of BBFs on DM of the aerial part of plants with values equivalent to mineral P fertilizer (Lustosa Filho et al. 2019) and other mineral fertilizers (Zhang et al. 2017; Khajavi-Shojaei et al. 2020; Borges et al. 2020; Carneiro et al. 2021), as well as when compared to unenriched biochar (Gunes et al. 2014; Kizito et al. 2019). Results from a recent meta-analysis indicate that BBF increases crop yields by 10%

Table 4 Effect of biochar-based fertilizers and KCl on soil chemical attributes after radish harvest *

Treatments	pH $CaCl_2$		OM g kg^{-3}		P mg dm^{-3}		Ca^{2+} $cmol_c$ dm^{-3}	
KCl	6.1 ± 0.04	ab	12.0 ± 0.0	a	18.8 ± 0.8	B	2.8 ± 0.1	ab
BBF-G0.5	6.2 ± 0.04	a	11.0 ± 0.1	ab	20.8 ± 1.1	ab	2.9 ± 0.1	ab
BBF-G1	6.0 ± 0.11	ab	12.5 ± 0.1	a	24.3 ± 1.8	A	3.0 ± 0.1	a
BBF-P0.5	5.9 ± 0.08	b	10.0 ± 0.0	b	20.0 ± 0.8	B	2.4 ± 0.3	b
BBF-P1	6.1 ± 0.04	ab	11.5 ± 0.0	ab	19.8 ± 1.4	B	3.1 ± 0.1	a
Prior[a]	4.4		21		1.9		1.1	
After	5.9		12		18.7		3.1	

Means with the same letters do not show statistical difference according to Fisher's LSD test ($P < 0.05$)

*Average values ± standard error (n = 4)

[a] prior and after liming (4 Mg ha^{-1} of limestone) and phosphorus (420 kg ha^{-1} of monobasic calcium phosphate) correction

and 186% when compared to fertilized and unfertilized controls, respectively (Melo et al. 2022).

Even when half the recommended rate was applied, the BBFs provided similar K absorption to the full KCl rate (Fig. 1). This better performance of BBF in supplying K is probably a result of the slow K release mechanism provided by this fertilizer (Fachini et al. 2022). This slower release may have contributed to the increased K uptake. Several studies indicate possible explanations for this slower release of BBFs, such as the formation of new low-solubility precipitates after biochar enrichment (Luo et al. 2021), strong electrostatic attraction on the surface of the biochar (Gwenzi et al. 2017), physical protection of the soluble fraction by the pores (Lustosa Filho et al. 2020), action of the micropores (Kim et al. 2014), the hydrophobic nature of the biochar (Chia et al. 2015) and strong nutrient adsorption capacity (Li et al. 2018). Additionally, biochar has good C levels of humic and fulvic acids (extracted with NaOH 0.1 mol L^{-1}) in its composition that can act as chelating and complexing agents that may have complexed K and contributed to a slower release of this nutrient (Fachini et al. 2022). Moreover, considering the soil nutrient contents after radish harvest, in the present study there was no leaching of nutrients from the pots. This may be considered a further indication of higher K use efficiency promoted by the BBFs.

Biochar-based fertilizers produced from different raw materials combined with N and P have also shown greater nutrient use efficiency than conventional mineral fertilizers. In the study of Carneiro et al. (2021), BBF resulted in similar P uptake by plants to the mineral source of the same nutrient in the short term, however in the long term BBF increased P uptake. This greater P absorption was related to protection and consequent slower release of this nutrient (Lustosa Filho et al. 2020). Greater N uptake was also found when a N-enriched BBF was used (Khajavi-Shojaei et al. 2020). According to the authors, this increase in uptake was related to slower N release and reduced losses via leaching when compared to the mineral nitrogen fertilizer.

For the absorption of other macronutrients, in general the BBFs promoted N and P concentrations in the plant that were similar to the conventional fertilizer. It should be highlighted that the total amount of N and P in the conventional fertilizer treatment was in soluble forms. On the other hand, N and P in BBF treatments came from both soluble fertilizers and undefined chemical forms (present in the BBFs). The lower N content in BBF-P0.5 when compared to the granule forms may have been the result of lower N mineralization in the pellet, since in calculation of the N application rate the concentration of this nutrient in the biochar was likely considered better protected by pelleting. In the case of S, the lowest application rate of BBF-P0.5 was not sufficient for adequate supply of this nutrient. In general, the results indicate that the use of BBF did not limit the absorption of nutrients by the radish, in addition to providing K more efficiently.

Despite the lack of difference among the BBFs with regards to K uptake by the plant, the higher K content in the sap of plants fertilized with BBF in the form of granules (Fig. 2) indicates that this fertilizer was more efficient for the continuous and adequate supply of K during the entire plant development period. Plant sap analysis provides an early determination of the plant nutrient status since it relies on real-time information (Esteves et al. 2021). Furthermore, granules have characteristics that facilitate the diffusion of water into the fertilizer, such as a lower apparent and particle density (Fachini et al. 2021a), contributing to greater KCl solubility and a higher K release than pellets. In the present work the K-sap values of the radish (Fig. 2) fertilized with BBF-G1 (1875 mg L^{-1}) were within the adequate range for several vegetables in different development periods, with values between 1800 and 5000 mg L^{-1} (Hochmuth et al. 2022), while for the other fertilizers the values were below the reference range. These lower values may be due to remobilization of K from the leaves to the storage organs, the tubers, reinforced by the higher tuber dry mass promoted by BBF-P1 compared to BBF-G1 (Table 2).

BBFs increase the relative chlorophyll content of radish plants

In the present work it was possible to observe an increase in the SPAD index in the BBF-G1 treatment, coincident with a high foliar nitrogen content. Potassium availability has previously been positively correlated with plant photosynthetic production, however the effect of its limitation on the process and efficiency of photosynthesis is still not fully understood (Kusaka et al. 2021). Nutritional deficiency negatively influences the structure of the photosynthetic apparatus in different plants, such as the brassica family, resulting in reduced SPAD index and chlorophyll fluorescence (Kalaji et al. 2018; Sakamoto et al. 2021). In the radish crop the low supply of nutrients resulted in a decrease in both the quantum yield of photosystem II and the SPAD index (Sakamoto et al. 2021). In fact, there is a potential relationship between the characteristics of leaf nitrogen content, chlorophyll a fluorescence, photosynthetic pigments and the SPAD index (Netto et al. 2005).

In the leaves of K-deficient plants there may occur chloroplast degradation and decrease in chlorophyll content (Jin et al. 2011). Therefore, the higher K content in the leaf sap (Fig. 2) and higher K absorption (Fig. 1) of the radish plant fertilized with BBF-G1 may have influenced the higher SPAD index values compared to KCl and BBF-G0.5. In the present study all fertilizers, regardless of the rate considered, promoted leaf SPAD indices typical of radishes grown with adequate nutrient supply (Yousaf et al. 2021; Sakamoto et al. 2021; Kusaka et al. 2021).

Based on the results of the present study, better supply of K promoted by the BBF allows for speculating improved performance of the plant photosynthetic system. Nevertheless, future studies should evaluate photosynthetic indicators throughout the plant cycle since different responses were observed in younger and older radish leaves (Kusaka et al. 2021).

Soil fertility attributes after radish harvest amended with BBFs and KCl

The pH values of all samples are within the ideal range (5.5 to 6.3) for soils in the Brazilian Cerrado region (Sousa and Lobato 2004). The small differences in reductions of OM, Ca and P contents with the use of BBF-P0.5 compared to the full BBF application rate (for Ca) and BBF-G1 (P and OM) may have resulted from the lower application rate of BBF-P0.5, which also reduced carbon input to the soil from biochar. Although the increase in soil C levels with the use of biochars is already well established (Chagas et al. 2022), there are still questions regarding the effect of BBF on the accumulation of C in the soil. In the study of Winarso et al. (2020) the enrichment of biochar with NKP accelerated the decomposition of biochar, decreasing its stability in the soil and resulting in lower supply of organic C in the soil compared to pure biochar. Carneiro et al. (2021) affirmed that the enrichment of biochar with a mineral source is efficient for sustaining agricultural production in the medium and long term, in addition to contributing to the addition of a stable carbon fraction in the soil.

After radish harvest the K contents were close to the K contents of the soil before fertilizer application (Table S4), showing a good relationship between the application rates and consumption by the crop, without the appearance of K deficiency symptoms in the plant. Similar performance of BBFs compared to mineral sources for providing the nutrient with which the biochar was enriched has also been reported previously (Lustosa Filho et al. 2019; Carneiro et al. 2021).

The application of fertilizers provided similar amounts of P. Despite this, the available P content of the soil in BBF-G1 was higher than the other fertilizers, demonstrating that P of the biochar present in the fertilizer granule can become available in the soil, even in a short cultural cycle. This synchronized release of P from sewage sludge biochar has already been demonstrated by Figueiredo et al. (2020). In the mineral KCl treatment, all P was supplied via solution, i.e., all P was applied in the available form so a portion may have been adsorbed in the soil since soils of tropical regions have a high P adsorption capacity. When compared to treatments in the form of pellets, the granules, because they have a greater specific surface area and greater porosity (Fachini et al. 2021a, b), may have facilitated the entry of water into the fertilizer and increased the release of P via supply of SSB when compared to pelletized BBF. Results of the present study show the potential of SSB for the production of BBF, in which enrichment would be necessary only to supply K, since SSB efficiently supplies P in the soil.

According to Faria et al. (2018), SSB is efficient in replacing the use of inorganic fertilizers, but the authors highlighted the need for mineral supplementation to supply K. By presenting a slower release of K when compared to the mineral fertilizer KCl (Fachini et al. 2022), BBF contributes to a better use of this nutrient by the plant and minimizes K losses by leaching. In addition to reducing the need for applications of large amounts of KCl in all crops, this also reduces Brazil's dependence on fertilizer imports. Therefore, the practice of pyrolyzing SSB followed by enrichment with a mineral K source contributes to the recycling of SS in agriculture, yielding a final product that is environmentally friendly, in addition to developing a sustainable fertilizer with great potential in agriculture.

Conclusions

This study presents the first report on the performance of special K-enriched sewage sludge biochar-based fertilizers for nutrition and growth of radish plants. Our findings confirmed that BBFs are more efficient in supplying K for radish than conventional fertilizer (KCl). Among the BBF forms, the pellet promoted greater tuber production and the granule promoted greater accumulation of nutrients in the soil. This study offers a realistic insight into the potential of sewage sludge BBFs to make more efficient use of K in agriculture, thus contributing to an adequate and sustainable destination of sewage sludge, in addition to reducing the use of soluble mineral fertilizers in agriculture. More studies should be carried out to better understand the effect of BBFs on the performance of crops with different cycles (short and long). In addition, a full economic feasibility assessment must be carried out.

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Declarations

Competing interests The authors declare no competing interests.

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