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Biochar-based fertiliser improved the yield, quality and fertiliser utilisation of open field tomato in karst mountainous area

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Abstract: Biochar-based fertiliser (BF) is beneficial to improve yield and quality, but the effect of BF on open field tomato remains unclear, especially in karst mountainous areas. The objective of this study was to identify the application effect and optimum application rate of BF. A field experiment was carried out in Southwestern China from 2019 to 2020 to study the effects of different application amounts of BF on the yield, quality, nutrients accumulation and fertiliser utilisation of open field tomatoes. The results showed that compared with the traditional fertilisation practice, BF can significantly increase the yield of open field tomato by 5–9% (2019) and 12–23% (2020), and significantly reduce nitrate content and increase vitamin C content of fruits. Meanwhile, nutrient accumulations, agronomic efficiency, and recovery efficiency of BF treatments were all significantly improved. In conclusion, the BF rate of 2 326 kg/ha improves yield and fertiliser utilisation in open-field tomatoes and could be recommended for tomato production in karst mountainous areas.

Keywords: potential productivity; nutritive value; nutrient uptake; fertiliser management strategies

Karst landform is a kind of geological landscape with special hydrological conditions and geological characteristics. The distribution area of the karst landform accounts for about 13% of the global land area (Yan et al. 2021a). The karst ecosystem is fragile and prone to rocky desertification, the soil cultivation layer in the karst area is shallow, and nutrient leaching is also severe (Liu et al. 2016). These factors are very unfavourable to agricultural production and economic development in karst regions.

About 900 million tons of agricultural and forestry waste and 3.8 billion tons of livestock and poultry manure can be collected in China every year (Hong et al. 2016). However, some of the resources are used to feed livestock and returned to the field at present, and about 20% are dumped or directly burned, which not only causes a serious waste of biomass resources but also leads to serious environmental pollution problems (Yin et al. 2018). In the current agricultural production, biochar is used to effectively reduce this waste and improve the utilisation efficiency of biomass resources.

As an important renewable resource, biochar is prepared through pyrolysis of biomass raw materials at 300–700 °C (Yan et al. 2021b), such as crop straw (Luo et al. 2016), livestock manure (Wang et al. 2019), and agricultural and forestry processing waste (Kong et al. 2021). Biochar is rich in carbon and is not easily decomposed by microorganisms due to the recalcitrant nature of carbon compounds (Dumroese et al. 2011). Pituello et al. (2018) showed that biochar increased soil porosity and reduced bulk density, thus improving soil physical structure. In addition, biochar can increase soil nutrient content, cation exchange capacity (CEC), and water retention capacity, and affects the diversity and structure of soil

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microbial communities directly (Kumar et al. 2022). Meanwhile, biochar can also participate in the soil nutrient cycle of farmland ecosystems (Zhang et al. 2021a) and has an important effect on the conversion, migration, and distribution of soil nutrients through their physicochemical properties or interaction with the soil (Sun et al. 2021). Furthermore, biochar's rich chemical-reaction-type functional groups also endow the biochar with extremely strong adsorption capacity, which makes biochar a good fertiliser synergist and makes it possible to compound with mineral fertilisers to improve its utilisation (Yan et al. 2021a). Therefore, biochar has enormous potential in improving soil physicochemical properties, soil fertility, and crop productivity. However, the global price of biochar was 192–621 USD/t, which was much higher than the average wage in some countries (Maroušek and Trakal 2021). This may make it difficult to realise high-dose application in current agricultural production.

Biochar-based fertiliser (BF) prepared by mixing biochar and fertilisers can not only increase the nutrients but also release the fertilisers slowly (Dong et al. 2021). This can help to improve soil quality and sequester carbon oxide while supplying nutrients to crops (Zheng et al. 2021). Hydrophilic groups in biochar can make the surfaces of BF absorb water in the soil, such as hydroxyl and carboxyl groups. In this case, the hydrophilicity and water retention capacity of biochar-based fertilisers can be improved by adjusting to the ratios of O/C and (N + O)/C (Pan et al. 2017). In addition, BF can directly increase the content of soil nutrients and affect the migration and transformation of original nutrients in the soil (Das and Ghosh 2021). Moreover, BF can enable nutrients to migrate toward plants and increase the ionic potential of plant root membranes, which can control plants to absorb nutrient cations and anions (Chew et al. 2020). In addition, BF increases the soil flux and the potential difference on the root membrane surface, which may help to save the energy required by plants to absorb nutrients (Joseph et al. 2015). Generally, biochar is mostly alkaline (pH 5–12) and can improve acidic soil (Liu et al. 2013). Therefore, BF can also adjust the structure of microbial communities in acidic soil to reduce the acidic functional groups, which is conducive to the growth and reproduction of microorganisms (Yang et al. 2021). Furthermore, BF can also inhibit the activity of nitrifying bacteria and reduce nitrogen loss by 11–12% in soil (Zhang et al. 2020). Therefore, we believe that BF may be conducive to managing agriculture in the karst mountains to increase crop yield and quality, fertiliser efficiency, and farmers' income.

Though the importance of biochar is increasingly understood, the existing research mainly focuses on greenhouse gas emission reduction and soil remediation. The influence of BF on yield and quality improvement is still poorly known, especially in the rare ecological environment. Therefore, strengthening the research on the macro and micromechanisms of BF will help to improve the comprehensive understanding level of BF and the global agricultural planting management technology. This study was conducted through a two-year field experiment to evaluate how BF potentially improve the biological effect and economic benefits of open field tomatoes in the karst mountainous areas. Therefore, the objectives of this study were to (*i*) research the effect of BF with different application amounts on the yield and quality of tomatoes; (*ii*) calculate nutrients accumulation of BF with different application amounts, and (*iii*) evaluate the fertiliser utilisation rates of BF application in open-field tomatoes. It is anticipated that the study results will be useful for formulating novel management ways for improving crop production in karst areas.

MATERIAL AND METHODS

Site description and sampling. The field experiment was carried out in Southwest China in 2019 and 2020. This region is a typical karst landform, with an average annual rainfall of 1 168.3 mm, an average annual temperature of 15.6 °C, and an average frost-free period of 276 days. The planting crops in the experiment region were open field tomatoes from May to October each year. The tested soil was a typical zonal yellow soil, which as a Dystric Luvisol (Ultisols) is widely distributed in south karst China. The basic physicochemical properties of the surface soil (0–20 cm) in the experiment region were: pH 5.9, organic carbon of 27.1 g/kg, total nitrogen of 0.31 g/kg, available phosphorus of 32.1 mg/kg, and available potassium of 108.5 mg/kg. Due to the strong leaching capacity of yellow soil in kast regions, the tested soil is weakly acidic and the soil fertility is low.

The tomato cultivar used in the experiment was Anma 161 (Guizhou Jinnong Technology Co., Ltd., Guiyang, China). The raw material of biochar was distillers' grains which are biomass waste generated from the production process of distilled spirits (Kweichow Moutai (Group) Circular Economy Industrial Investment and Development Co., Ltd., Zunyi, China), and the carbonisation temperature was 550 °C using a biological carbonisation furnace (SSDP-

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5000, Huai'an Huadian Environmental Protection Machinery Manufacturing Co., Ltd., Huai'an, China). The basic physicochemical properties of biochar were: pH 8.8, organic carbon of 279.4 g/kg, total nitrogen of 7.6 g/kg, total phosphorus of 10.6 g/kg, and total potassium of 21.4 g/kg. Fertilisers used in the experiment included organic fertiliser (Guizhou Dibao Co., Ltd., Guiyang, China), compound fertiliser (N-P_2O_5-K_2O 15-15-15, Guizhou Xiyang Industrial Co., Ltd., Guiyang, China), and biochar-based fertilisers (BF, N-P_2O_5-K_2O 15-6-18, with a biochar content of 20%, Guizhou Institute of Soil and Fertiliser, Guiyang, China).

The BF was prepared using the SKJ – 120 flat-grinding extrusion granulator (Shanghai Jiale Electromechanical Group Co., Ltd., Shanghai, China) through the extrusion granulation method. The specification was in the shape of a cylinder of 1–2 cm. The raw materials used were urea (N 46%, Guizhou Chitianhua Group Co., Ltd., Zunyi, China), mono-ammonium phosphate (N-P_2O_5 10-50, Guizhou Chitianhua Group Co., Ltd., Zunyi, China), potassium sulfate (K_2O 50%, Xinjiang Luobupo Hoevellite Co., Ltd., Korla, China), distillers' grains biochar and solid binder (Guizhou Jinnong Technology Co., Ltd., Guiyang, China). Firstly, the raw materials were crushed through a 0.38 mm standard screen and dried in a 45 °C constant temperature electric blast drying oven (DHG-9070A, Shanghai Jingqi Instrument Co., Ltd., Shanghai, China) for 24 h. Then, after all, kinds of raw materials were mixed evenly according to a certain proportion, fertiliser particles were formed by flat-grinding extrusion granulator. Finally, after the powder and small particles were removed through a 3.35 mm aperture screen, the fertiliser particles were baked in the drying oven at 45 °C for 6 h to obtain the finished BF. The surface of BF particles was flat and the structure was uniform. The pH of BF was 6.8 and the average compressive strength was 257.2 N.

Experimental design and management. This experiment included six treatments, these being the control of no fertiliser (CK); compound fertiliser of 3 000 kg/ha (TFP, traditional fertilisation practice); BF of 1 875 (BF1); 2 250 (BF2); 2 625 (BF3) and 3 000 (BF4) kg/ha. Except for CK treatment, all fertilisation treatments were applied with organic fertiliser of 1 500 kg/ha at the same time. The specific application amount of the nutrients in the treatments were shown in Table 1. Before the tomato seedlings were transplanted, the fertilisers were spread evenly on the surface of the soil, and then a hoe was used to mix fertilisers and the soil evenly. Tomato seedlings were transplanted 10 days after the ridging and mulching. The planting density was 2.7 × 10^4 plants/ha (with a plant spacing of 50 cm, row spacing of 70 cm). Each treatment was conducted in a random block and repeated three times, and the plot area was 33.6 m^2 (8.0 m × 4.2 m). The same fungicide, insecticide and herbicide were used in all treatments so that no diseases, pests or weeds occurred during the growing season. Other field management was consistent with the habits of local farmers.

Sampling and measurement. Soil samples (0–20 cm) were collected from 10 randomly selected spots of the main experimental area one day before fertilisation. The soil samples were composited and air-dried, ground and passed through 1 mm and 0.149 mm sieves for the determination of soil physicochemical characteristics. The physical and chemical properties of soil were determined according to Bao (2000), and the specific methods were as follows. Soil pH was measured in a 1:2.5 (soil:water ratio, *w*/*v*) extraction followed by reading using a pH meter (FE20K, Mettler

Table 1. Nutrients amounts of different treatments

Treatment	Basal dressing fertiliser (kg/ha)			Dressing fertiliser (kg/ha)		
	N	P	K	N	P	K
CK	–	–	–	–	–	–
TFP	225.00	98.24	186.70	225.00	98.24	186.70
BF1	281.25	49.12	280.05	–	–	–
BF2	337.50	58.94	336.05	–	–	–
BF3	393.75	68.77	392.07	–	–	–
BF4	450.00	78.59	448.09	–	–	–

N – nitrogen; P – phosphorus; K – potassium; CK – no fertiliser; TFP – traditional fertilisation practice; BF1 – 1 875 kg/ha of biochar-based fertiliser (BF); BF2 – 2 250 kg/ha of BF; BF3 – 2 625 kg/ha of BF; BF4 – 3 000 kg/ha of BF. N, P and K nutrients content in compound fertiliser were 15.0, 6.5 and 12.4%. N, P and K nutrients content in BF were 15.0, 2.6 and 14.9%

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Toledo, Zurich, Switzerland). Soil organic carbon (SOC) was measured *via* the potassium dichromate external heating method. Total nitrogen was determined using the Kjeldahl method after digestion by a mixture of concentrated $HClO_4$-H_2SO_4, without considering the influence of mineralisation. Available phosphorus (Olsen-P) was determined using the molybdenum blue method with a 0.5 mol/L $NaHCO_3$ solution at a soil/solution ratio of 1:20, mainly in the form of calcium-based phosphates (Olsen et al. 1954). Available potassium was extracted using 1 mol/L NH_4OAc for 30 min and then determined with a flame photometer (FP640, Jingke, Shanghai, China).

Six plants from each experimental plot were sampled before the final harvest, which were used to test the plant nutrition and fruit quality. The tomato plants were divided into two parts: stems-leaf and fruit, which were dried to constant weight at 60 °C after a heat at 105 °C for 30 min. All dried samples were ground and passed through a 0.25 mm sieve and digested with a mixture of concentrated H_2SO_4 and H_2O_2 to determine N, P and K concentrations. The N concentration was determined with a continuous flow analyser (AA3, Seal Analytical Inc., Southampton, UK), P and K concentration was determined with an ICP-OES (optic emission spectroscopy with inductively coupled plasma, Longjumeau, HORIBA Jobin Ibon S.A.S., Paris, France). The uptake of N, P and K were calculated based on the dry mass and element concentration. At the same time, some fresh fruit samples were used to determine the quality indexes. For the determination of nitrate content, 2 g fresh fruits were taken, added 10 mL deionised water, and placed in a boiling water bath for 30 min. 0.1 mL of the extraction solution was taken and mixed with 0.4 mL of 5% salicylic acid-sulfuric acid solution at 25 °C for 20 min. The solution was added 9.5 mL of 8% NaOH and measured the absorbance using a visible spectrophotometer (UV-3600i Plus, Shimadzu, Tokyo, Japan). The vitamin C (VC) content was determined using an HPLC (high-performance liquid chromatography, LC-2040, Nexera-i, Shimadzu, Japan) after grinding, centrifuging and filtering with 10 mL 0.2% metaphosphoric acid. For the content of soluble sugar, 0.2 g fresh leaves were taken and added 10 mL distilled water to extract in a boiling water bath for 30 min. 0.5 mL of the extract was taken in a test tube, and 0.5 mL ethyl anthrone and 5 mL sulfuric acid were added to the extract. The test tube was placed in a boiling water bath and incubated for 1 min. After taking it out, it was naturally cooled to room temperature and measured the absorbance at 630 nm. The content of soluble solids was detected by Abbe refractometer (NAR-1T, ATAGO, Tokyo, Japan). The final yield was an accumulation of the whole plot based on three batches of harvest.

Calculations and statistical analysis.

$$\text{Nutrient accumulation (kg/ha)} = \text{nutrient concentration (\%)} \times \text{dry mass (kg/ha)}/100 \quad (1)$$

$$\text{Agronomic efficiency (AE, kg/kg)} = (\text{yield of the fertilised plot} - \text{yield of the no fertiliser plot})/\text{applied nutrient rate} \quad (2)$$

$$\text{Recovery efficiency (RE, \%)} = (\text{total nutrient uptake of the fertilised plot} - \text{total nutrient uptake of no fertiliser plot})/\text{applied nutrient rate} \times 100\% \quad (3)$$

The yield and nutrient uptake in the upper formulas were calculated according to dry mass.

In order to explore the best application amount of biochar based fertiliser on tomatoes, the Linear plus platform model was used to describe the response of tomato yield to BF application rate in the experiment. For the linear plus platform model, Y increased linearly with increasing X ranging from 0 to a critical value and reached the maximum at the critical value; after exceeding the critical value, Y remained the maximum no matter how X increased.

The linear plus platform model was:

$$Y = AX + B\ (X \leq C);\ Y = P\ (X > C) \quad (4)$$

Y – yield (kg/ha); X – fertilisation application rate (kg/ha); A – regression coefficient; B – intercept; C – critical value; P – maximum yield (kg/ha).

Statistical analysis was performed using SPSS 18.0 (SPSS Inc., Chicago, USA). The data means were compared using the *LSD* (least significant difference) test ($P < 0.05$). The figures were prepared with Origin 8.0 (Origin Lab Corporation, Northampton, USA).

RESULTS AND DISCUSSION

Effects of biochar-based fertiliser on the yield of tomato. Yield is the first important factor to determine the price of tomatoes. Compared with CK treatment, the application of fertiliser (TFP and BF) significantly increased tomato production, with an average increase of 24 528 kg/ha in 2019 and an average increase of 38 620 kg/ha in 2020 (Figure 1). Compared with TFP treatment, the yield of tomatoes in BF-applied plots was increased by 3 471–6 918 kg/ha (5–9% increase) in 2019 and 8 199–15 995 kg/ha

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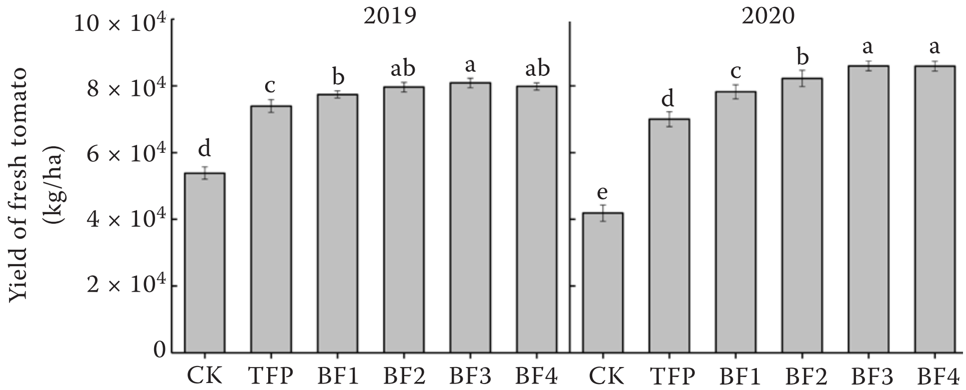

Figure 1. Effects of different fertilisation treatments on the yield of fresh tomato. CK – no fertiliser; TFP – traditional fertilisation practice; BF1 – 1 875 kg/ha of biochar-based fertiliser (BF); BF2 – 2 250 kg/ha of BF; BF3 – 2 625 kg/ha of BF; BF4 – 3 000 kg/ha of BF. Different letters indicate significant differences between different fertilisation treatments ($P < 0.05$). Error bars represent the standard error of the mean

(12–23%) in 2020. The BF3 treatment showed the highest tomato yield in two years, which were 80 086 and 86 019 kg/ha, respectively. This indicates that BF could improve the yield of open field tomatoes and contribute to the improvement of tomato economic value. However, it is not that the more BF application, the higher the crop yield. Xu et al. (2021) reported that excessive application of BF might not continually improve plant growth, as the high C/N ratios might immobilise N and decrease plant N uptake. The optimal application amount of the BF was calculated using the linear plus platform model (Figure 2), and it was found that the maximum yield can be obtained when the application amount of the BF was 2 326 kg/ha. Therefore, the appropriate BF application rate is an important premise to ensure a high yield of tomatoes.

Studies demonstrated that the vast majority of biochar application approaches will never be economical if only productivity gains are realised (Bach et al. 2016). Thus, an alternative that has attracted growing interest in recent years is the development of BF, which could make the biochar technology more cost-effective due to the enhanced efficiency and associated lower application rates (Joseph et al. 2013). For instance, Puga et al. (2019a) observed a 26% average increase in maize yield and 12% higher N use efficiency for biochar with urea over conventional urea. Qian et al. (2014) observed rice yield increases of up to 24% using BF over conventional NPK in the field. In this study, BF increased the yield of tomatoes (5–9% in 2019 and 12–23% in 2020) in karst areas (Figure 1), which shows the positive responses of BF on crop productivity over conventional fertilisers. Sim et al. (2021) have pointed out that BF might have superior characteristics for sustained release of nutrients as compared with conventional fertilisers, especially for controlled release of N fertilisers and reducing N losses under variable soil-plant-environment systems. Meanwhile, BF was more effective in eliminating those crop productivity constraints that conventional fertilisers could not sufficiently address, and have the potential to improve nutrient use efficiency and increase crop productivity by applying biochar in minor quantities (Melo et al. 2022).

Effects of biochar-based fertiliser on the fruit quality of tomato. Fruit quality is an important index of nutritional value and economic value. BF showed significant advantages in improving the yield and quality of crops (Sim et al. 2021), and the results of this study are similar to those of previ-

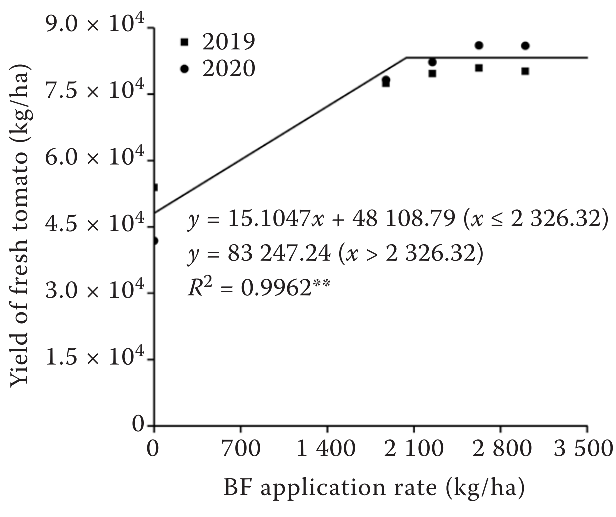

Figure 2. Effects of biochar-based fertiliser (BF) application rate on the yield of fresh tomato

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Table 2. Effects of different fertilisation treatments on nitrate, vitamin C, soluble sugar and total soluble solid of fresh tomato

Year	Treatment	Nitrate	Vitamin C	Soluble sugar	Total soluble solids
		(mg/kg)			
2019	CK	106.8 ± 3.6^{d}	130.1 ± 2.3^{c}	54.5 ± 2.3^{b}	45.0 ± 3.0^{b}
	TFP	134.2 ± 4.8^{a}	164.8 ± 6.7^{b}	56.2 ± 0.6^{ab}	45.0 ± 2.7^{b}
	BF1	115.8 ± 4.4^{b}	169.9 ± 3.9^{ab}	56.3 ± 0.7^{ab}	45.9 ± 0.8^{ab}
	BF2	114.6 ± 4.5^{bc}	176.0 ± 7.2^{a}	56.6 ± 0.7^{ab}	47.0 ± 1.8^{ab}
	BF3	107.9 ± 3.4^{cd}	180.0 ± 5.2^{a}	58.3 ± 0.7^{a}	49.2 ± 0.8^{a}
	BF4	106.4 ± 4.8^{d}	175.7 ± 8.3^{a}	58.0 ± 0.9^{a}	47.8 ± 2.0^{ab}
2020	CK	105.8 ± 4.8^{b}	154.2 ± 9.7^{d}	52.8 ± 2.1^{c}	42.5 ± 1.8^{b}
	TFP	126.1 ± 6.5^{a}	167.3 ± 5.0^{c}	56.5 ± 1.7^{b}	44.5 ± 1.5^{b}
	BF1	102.4 ± 3.0^{bc}	168.5 ± 5.5^{c}	58.4 ± 0.8^{ab}	47.8 ± 1.0^{a}
	BF2	98.2 ± 6.0^{bc}	183.6 ± 3.1^{b}	59.2 ± 1.5^{a}	48.9 ± 1.2^{a}
	BF3	97.6 ± 2.0^{c}	195.2 ± 3.9^{a}	60.3 ± 1.4^{a}	49.8 ± 1.4^{a}
	BF4	95.8 ± 2.3^{c}	186.3 ± 4.9^{ab}	60.0 ± 0.6^{a}	49.6 ± 1.0^{a}

CK – no fertiliser; TFP – traditional fertilisation practice; BF1 – 1 875 kg/ha of biochar-based fertiliser (BF); BF2 – 2 250 kg/ha of BF; BF3 – 2 625 kg/ha of BF; BF4 – 3 000 kg/ha of BF. Different letters in the same column indicates significant difference between different fertilisation treatments ($P < 0.05$)

ous studies (Sim et al. 2021). In this study, BF can significantly reduce the nitrate content in tomato fruits, and increase the content of VC, soluble sugar and the total soluble solid at the same time (Table 2). Compared with the TFP treatment, the BF treatments reduced the nitrate content in tomato fruits by 14–21% in 2019 and 19–24% in 2020. Tomato fruits in the BF4 treatment showed the lowest nitrate concentrations in the two years. BF treatments increased the VC content in tomato fruits by 3–9% in 2019 and 1–17% in 2020, and the VC content of tomato fruits treated with BF3 treatment was the highest. In addition, BF treatments also increased the content of the soluble sugar and the total soluble solids in tomato fruits, especially in 2020. Biochar is rich in mineral nutrients (Ca, Mg and Zn, etc.), which facilitates a balanced supply of nutrients (Liu et al. 2020). In addition, biochar possesses a strong capability of absorbing NH_4^+, which can regulate the rate of converting nitrogen from NH_4^+ to NO_3^- in BF, and avoid the accumulation of nitrate due to excessive nitrogen uptake by crops (Khajavi-Shojaei et al. 2020). The relatively low application rate of BF (lower application rate of nitrogen) and the application of a variety of microelements may be beneficial to the increase of VC content in the fruit (Zhang et al. 2021b). Therefore, BF could improve the quality of open field tomatoes.

Effects of biochar-based fertiliser on the nutrient accumulation of tomato. Biochar adsorbs nutrients from mineral fertiliser and later releases them to provide nutrients for plant growth, which could explain the persistent nutrients supply by BF (Yang et al. 2021). Compared with CK treatment, fertilisation significantly increased the accumulation of N, P and K by 100, 78, and 90%, respectively, in 2019 and 123, 93 and 108% in 2020 (Figure 3). Furthermore, compared with TFP treatment, these accumulations increased by 14–41, 6–32, and 6–42% respectively in 2019, and 6–33, 8–33, 15–47% respectively in 2020. The nutrient accumulations of N, P and K in the BF3 treatment were the highest, with 259.3, 37.4, 344.7 kg/ha respectively in 2019, and 263.3, 36.6, 351.2 kg/ha respectively in 2020. As we know, BF applied in soil could effectively act as the slow release of N fertiliser after one-time application which provides adequate N for plant growth (Ibrahim et al. 2020). On the other hand, the increased N uptake was associated with improved soil CEC, as soil with a high CEC is more likely to adsorb NH_4^+, which can effectively improve the utilisation of N in the soil (Liang et al. 2006). Moreover, Walter and Rao (2015) attributed the increased potassium uptake with BF to the presence of potassium in biochar itself and mineral fertiliser and enhanced potassium fertiliser use efficiency by biochar. It is worth noting that the increased potassium availability is vital for improving growth, biological nitrogen fixation, and the competitive ability of plants, as potassium is essential for bio-

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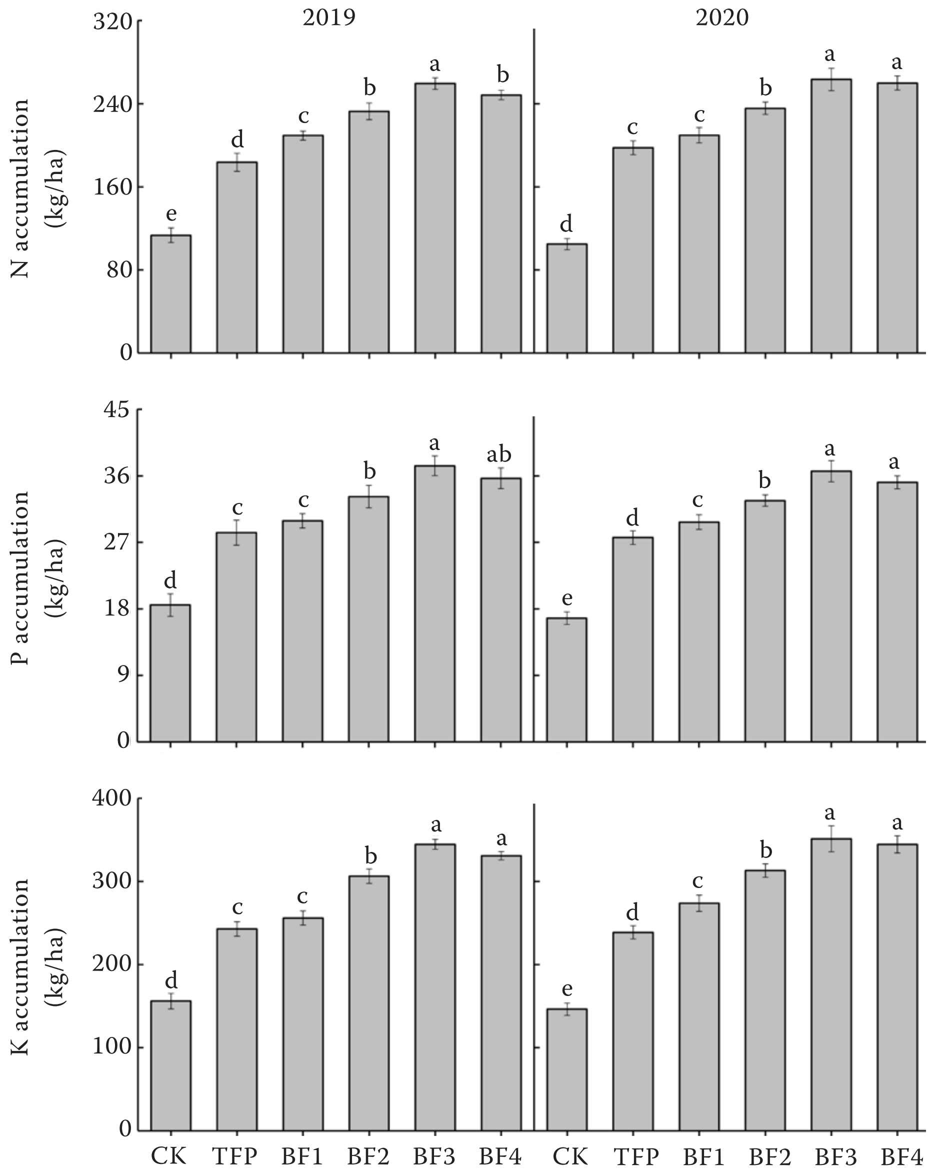

Figure 3. Effects of different fertilisation on nitrogen, phosphorus and potassium accumulations. CK – no fertiliser; TFP – traditional fertilisation practice; BF1 – 1 875 kg/ha of biochar-based fertiliser (BF); BF2 – 2 250 kg/ha of BF; BF3 – 2 625 kg/ha of BF; BF4 – 3 000 kg/ha of BF. Different letters indicate significant differences between different fertilisation treatments ($P < 0.05$). Error bars represent the standard error of the mean

logical nitrogen fixation (Oram et al. 2014). When applying biochar or BF, the co-cropping mode of tomato and leguminous green manure may reduce the amount of nitrogen application (Gu et al. 2021) and improve the biological availability of nitrogen (Gatsios et al. 2021).

Effects of biochar-based fertiliser on the fertiliser utilisation of tomato. The fertiliser utilisation rate is an important indicator for evaluating the absorption and utilisation of fertiliser nutrients by crops, which is closely related to factors that affect nutrient conversions such as soil aeration status, soil water content, and microbial activity (Peregrina et al. 2020). Compared with TFP treatment, the AE of N, P and K treated with the BF treatments increased by 20–71, 202–329, and 27–42% respectively in 2019, and 31–87, 229–365, and 10–56% respectively in 2020 (Table 3). The AE of N, P and K in BF1 treatment were both the highest, with 7.7, 19.3, and 6.4 kg/kg in 2019, and 9.7, 24.2, and 8.1 kg/kg respectively in 2020. The RE of N, P and K treated with the BF treatments increased by 92–138, 336–448, and 54–107% respectively in 2019, and 68–96, 318–417, and 78–111% respectively in 2020. The RE of N, P and

Table 3. Effects of different fertilisation on agronomic efficiency (AE) and recovery efficiency (RE)

Year	Treatment	AE (kg/kg)			RE (%)		
		N	P	K	N	P	K
2019	CK	–	–	–	–	–	–
	TFP	4.5 ± 0.8^{b}	4.5 ± 0.8^{c}	4.5 ± 0.8^{b}	15.6 ± 3.3^{c}	5.0 ± 0.3^{d}	23.2 ± 4.6^{d}
	BF1	7.7 ± 0.5^{a}	19.3 ± 1.3^{a}	6.4 ± 0.4^{a}	34.1 ± 3.9^{ab}	23.2 ± 1.5^{bc}	35.7 ± 6.2^{c}
	BF2	7.0 ± 0.8^{a}	17.5 ± 2.1^{a}	5.8 ± 0.7^{a}	35.3 ± 4.3^{ab}	24.9 ± 1.0^{b}	44.7 ± 5.3^{ab}
	BF3	6.9 ± 0.9^{a}	17.2 ± 2.3^{a}	5.7 ± 0.8^{ab}	37.1 ± 3.1^{a}	27.4 ± 1.1^{a}	48.1 ± 3.8^{a}
	BF4	5.4 ± 0.8^{b}	13.6 ± 2.0^{b}	4.5 ± 0.7^{b}	30.0 ± 2.5^{b}	21.8 ± 0.9^{c}	39.0 ± 2.9^{bc}
2020	CK	–	–	–	–	–	–
	TFP	5.2 ± 0.2^{e}	5.2 ± 0.2^{e}	5.2 ± 0.2^{d}	20.6 ± 0.9^{d}	5.6 ± 0.3^{d}	24.8 ± 1.3^{c}
	BF1	9.7 ± 0.6^{a}	24.2 ± 1.5^{a}	8.1 ± 0.5^{a}	37.3 ± 2.2^{bc}	26.5 ± 1.8^{b}	45.6 ± 2.9^{b}
	BF2	8.6 ± 0.3^{b}	21.6 ± 0.6^{b}	7.2 ± 0.2^{b}	38.8 ± 1.1^{ab}	27.0 ± 0.9^{ab}	49.6 ± 1.5^{a}
	BF3	7.9 ± 0.2^{c}	19.8 ± 0.6^{c}	6.6 ± 0.2^{c}	40.3 ± 1.4^{a}	28.9 ± 0.9^{a}	52.3 ± 2.1^{a}
	BF4	6.8 ± 0.5^{d}	17.1 ± 1.3^{d}	5.7 ± 0.4^{d}	34.5 ± 2.0^{c}	23.4 ± 1.6^{c}	44.2 ± 2.8^{b}

N – nitrogen; P – phosphorus; K – potassium; CK – no fertiliser; TFP – traditional fertilisation practice; BF1 – 1 875 kg/ha of biochar-based fertiliser (BF); BF2 – 2 250 kg/ha of BF; BF3 – 2 625 kg/ha of BF; BF4 – 3 000 kg/ha of BF. Different letters in the same column indicates significant difference between different fertilisation treatments (P < 0.05)

K in BF3 treatment were both the highest, with 37, 27, and 48% in 2019, and 40, 29 and 52% respectively in 2020. It can be seen that BF could improve the utilisation rate of fertiliser and reduce the loss of fertiliser nutrients.

Due to the presence of exchangeable ions and functional groups (Puga et al. 2019b), the biochar in biochar-based fertilisers can adsorb nitrogen (NH_4^+ or NO_3^-), which can avoid nitrogen leaching losses and gaseous losses, and thus improve nitrogen utilisation (Dong et al. 2019). Moreover, BF can not only change the physicochemical properties of soil, but also increase the enzyme activity related to soil nitrogen conversion, the abundance and activity of ammonia oxidising bacteria, and thereby increasing the biological availability of nitrogen (Liao et al. 2020). Meanwhile, the potassium content of biochar was relatively higher (Zornoza et al. 2016). In this experiment, the total potassium content of biochar was 21.4 g/kg, and the potassium in the biochar was mostly soluble (Tan et al. 2017). Therefore, the content of available potassium in the soil can increase quickly as well as be absorbed and used by crops in time after biochar is applied (Gwenzi et al. 2017). On the other hand, the temperature and pH of the soil as well as the content of organic carbon can be increased using biochar. This may indirectly increase the number and activity of solubilising silicate bacteria, which is conducive to the improvement of soil potassium fixation and utilisation (Gao et al. 2021). Therefore, using potassium in biochar to replace potassium fertiliser may be a practical method, which is of great significance to alleviate the lack of potassium resources in China and improve the utilisation of straw potash resources.

It is worth noting that the prerequisite for the large-scale application of biochar was the economic feasibility of biochar application (Aguirre et al. 2021), however, most of the current research still focuses on the environmental effects of biochar rather than the economic benefits (Owsianiak et al. 2021). The main reason was the excessively high input costs of biochar and relatively slow benefits due to a large amount of biochar applied and the high price. Therefore, it is necessary to reduce the cost of raw materials as much as possible in the future, and thus reduce the price of BF, so that it can be widely used to maximise farmers' economic benefits.

Consequently, replacing the traditional mineral fertiliser with BF has been proved to be an alternative solution for managing sustainable fertilisation on open field tomato in karst mountainous areas, and the application of 2 326 kg/ha BF is worthy of popularising. Moreover, many reports have shown the positive effects of BF on crop production, the research on the mechanism of BF is still lacking. Further research should focus on studying the effects of BF on soil quality and microecology, to clarify the ecological and environmental effects.

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