



Moderate sewage sludge biochar application on alkaline soil for corn growth: a field study

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Abstract

In view of the risks induced by the inhibitory effects of applying impracticably large amounts of sewage sludge biochar (SSB) to the alkaline soil, this field study investigated the influence of moderate biochar amendments (0, 1500, 4500, and 9000 kg/hm²) on corn growth, alkaline soil properties, and the uptake of potentially toxic elements (PTEs). The results showed that applying more SSB would decrease the ammonium nitrogen concentration and increase the available phosphorus and potassium concentrations, which inhibited corn plant growth because of high background nutrient levels of the alkaline soil. When the alkaline soil was amended with 1500 kg/hm² SSB, the dry weight of 100 niblets increased from 32.11 g in the control to 35.07 g. There was no significant variation in the total concentration of PTEs in the soil. The concentrations of Mn, Ni, Cu, and Zn in niblets decreased from 5.54, 0.83, 2.26, and 27.15 mg/kg in the control to 4.47, 0.62, 1.30, and 23.45 mg/kg, respectively. Accordingly, the health risk from corn consumption was significantly reduced. Furthermore, the combination of SSB and fertilizer improved corn growth and reduced the risk of consumption of PTEs. Therefore, considering the increase in corn fruit yield and the decrease in consumption risk, applying 1500 kg/hm² of biochar to alkaline soils is a realistically achievable rate, which can broaden the utilization of SSB for remediation of different types of soil.

Keywords Sewage sludge biochar · Alkaline soil · Corn growth · Soil property · Potentially toxic elements · Soil remediation

Abbreviations

SSB Sewage sludge biochar
PTE Potentially toxic element
EC Electrical conductivity
EDI Estimated daily intake
HQ Hazard quotient

1 Introduction

Pyrolysis is a proven and promising technology for the harm-free treatment of sewage sludge while generating functional products such as biochar, oil, and gas. In slow pyrolysis with a low heating rate (< 10 °C/min) and long residence time (> 1 h), biochar is the main byproduct (Oni et al. 2019). Converting sewage sludge into sewage sludge biochar (SSB) has additional advantages such as volume reduction, pollutant elimination, and nutrient retention (Wu et al. 2019). Additionally, some potentially toxic elements (PTEs: Cr, Mn, Ni, Cu, Zn, As, Cd, and Pb) in untreated sewage sludge can cause potential threats to humans via the food chain (Khan et al. 2020). In our previous study, we studied the migration and transformation behavior of PTEs in the sewage sludge pyrolysis process from laboratory- to pilot-scale experiments, and found that most of the PTEs remained in the SSB and were converted from bioavailable fractions to a more stable fraction combined with silicate minerals (Li et al. 2018a, 2021; Xie et al. 2020a). Considering the high

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concentrations of PTEs in SSB, its proper utilization still attracts much attention and requires further investigation.

Currently, the application of biochar for soil remediation is an attractive method with numerous benefits. For example, the porosity of biochar can increase the water-holding capacity and decrease the bulk density of soil, which increases vegetable productivity and reduces irrigation frequency (Liu et al. 2020). Functional groups such as -COO^- and O^- in the surface of biochar can react with H^+ in soil to improve the buffering capacity of soil (Wu et al. 2020b). Additionally, the chemical properties and enzymatic activities of the soil are significantly improved after biochar amendment (Pokharel et al. 2020; Rafael et al. 2019). Biochar can also reduce the bioavailability and toxicity of soil by adsorbing and degrading organic contaminants (Wu et al. 2020a).

SSB differs from other types of biochar, and further investigation is needed on the safety of SSB with high PTE concentrations applied to large-scale plantings (Purakayastha et al. 2019). It has been reported that excess PTEs have a negative effect on vegetative growth. More specifically, excess Zn can cause chlorosis in plant leaves, excess Cu may cause negative effects on plant nutrients, and large amounts of Ni and Co can reduce seed germination and inhibit the growth of plant tissues (Khan et al. 2020; Mohamed et al. 2017). Therefore, several studies have been conducted to investigate the accumulation of PTEs in plant tissues after addition of biochar to soil. The results showed that biochar significantly decreased the concentrations of mobile fractions (water-soluble, exchangeable, and bound-to-carbonate fractions) of Ni, Zn, Cd, and Pb in soil, and reduced their concentrations in oilseed rape tissues (Shaheen and Rinklebe 2015; Shaheen et al. 2015). Khan et al. (2013) found that 5–10 wt% SSB amendment decreased the uptake of some PTEs (As, Cr, Co, Ni, and Pb) in rice tissues as a result of increasing the pH, cation exchange capacity, pore structure, and dissolved organic carbon concentration of acidic soil. In addition, the reduction in PTE bioaccumulation of SSB has been verified in other plants such as grass, Chinese cabbage, and tomato (Hossain et al. 2010; Yu et al. 2018; Yue et al. 2017). In our previous study, we found that 5–10 wt% SSB is the suitable proportion to use in soilless cultivation, and only small amounts of the PTEs in biochar were taken up by cucumber plants (Xie et al. 2020b). Nonetheless, the health risk associated with food consumption from applying SSB to agriculture needs further verification based on a field study.

Most studies have focused on the effect of biochar addition on acidic and infertile soils (Mohamed et al. 2017; Wu et al. 2020b). The observed benefits are that the addition of alkaline biochar can significantly increase soil pH, which influences the microbial response and PTE solubility (Zhu et al. 2017). In northern China, where corn is the main crop, most soils are alkaline, containing NaCO_3 and NaHCO_3 . Low water retention and organic matter levels also restrict

the development of local agricultural production (Liu et al. 2020), and SSB may have a positive effect in alkaline soils because of its pore structure, functional groups, and nutrients. However, based on a field soil study considering the volume and cost of biochar, 5–10 wt% SSB ($\sim 100,000 \text{ kg/hm}^2$) is not practicable (Kocsis et al. 2020; Zhang et al. 2016). Additionally, excessive application of SSB adversely affects plant growth and PTE availability if the soil pH is greater than 8.0 (Artiola et al. 2012). Therefore, the application of moderate levels of SSB ($< 10,000 \text{ kg/hm}^2$) to alkaline soil is worthy of further attention for broadening the utilization of SSB on different types of soil.

In view of the few reports in this regard, a field trial was conducted to study the effect of moderate SSB addition on the alkaline soil for corn planting. We analyzed the influence of SSB on soil properties, including water retention, pH, electrical conductivity (EC), and nutrient content during corn growth. Furthermore, the concentrations and chemical speciation of PTEs in soil were also studied to investigate their accumulation in corn fruits and the potential health risks posed to humans. Our primary objective was to verify, in a field study, whether moderate applications of SSB are suitable for alkaline soils.

2 Materials and methods

2.1 Biochar and planting location

SSB was prepared by pyrolysis of hydrothermally treated sewage sludge at $600 \text{ }^\circ\text{C}$ for 45 min in a sewage sludge treatment plant in Xiamen City, Fujian Province, China, to reduce the pollutant risk (Li et al. 2018a; Tian et al. 2019). The obtained biochar was ground and passed through a 3.2 mm sieve prior to use in the field trial. The planting experiment was conducted at a national corn farm in Tianjin, China ($39^\circ 25.459 \text{ N}$, $117^\circ 29.295 \text{ E}$), where the annual average temperature is $12\text{--}15 \text{ }^\circ\text{C}$ and the total annual precipitation is 550–600 mm, with a temperate continental monsoon climate. The basic properties of the soil and SSB are described in Table 1.

2.2 Field trial

Four different treatments with SSB amendments (0 [CK], 1500 [C1], 4500 [C3], and 9000 kg/hm^2 [C4]) were used to investigate the influence of SSB addition on alkaline soil properties and corn growth under normal fertilization conditions. Additionally, to study the influence of fertilization, treatment with 1500 kg/hm^2 SSB application without fertilization (C2) was established. The total length and width of the trial site were 65 m and 26 m, respectively. The area of each treatment was approximately 333 m^2 , which was

Table 1 Basic properties of the soil and sewage sludge biochar

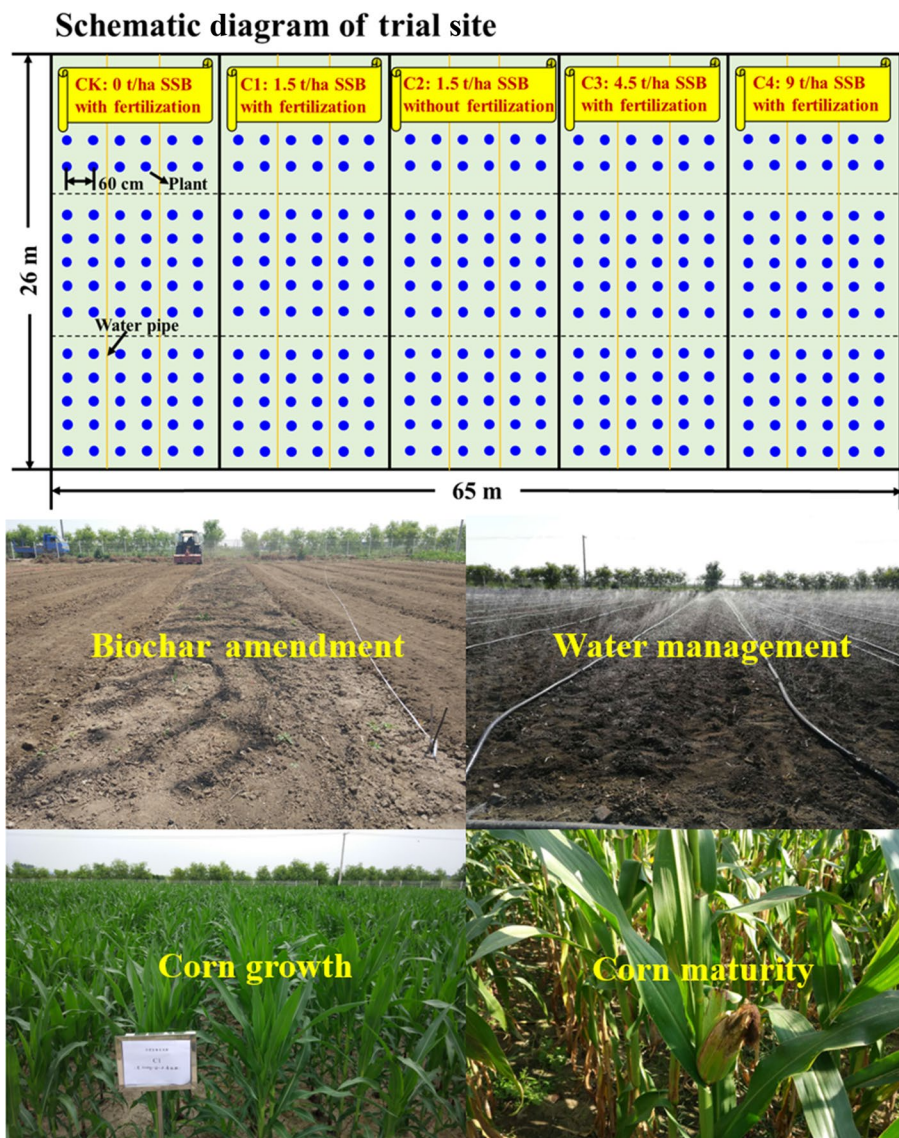
Items	Soil	SSB	Items (mg/kg)	Soil	SSB
pH	7.65	8.13	Cr	62.62	9623.30
EC (mS/cm)	2.06	2.68	Mn	433.83	958.65
C (%)	1.27	7.81	Ni	22.77	1409.99
H (%)	1.19	1.32	Cu	14.82	8608.33
N (%)	0.38	0.35	Zn	79.37	8293.10
S (%)	0.09	1.71	As	44.88	39.97
K (g/kg)	23.02	9.93	Cd	– ^a	2.32
P (g/kg)	1.56	47.62	Pb	21.52	130.23

^aNot detected

divided into three zones, as shown in Fig. 1. Before sowing corn seeds (Jingnongke 728), SSB was added to the

soil surface, and an agricultural rotary tiller was used to mix the surface soil and SSB fully (15 cm in depth). The row spacing for corn sowing was 60 cm. The corn growth period was divided into the initial stage (before seeding), budding stage, jointing stage, filling stage, and maturity stage. Water management was conducted according to the practical operation of the local farm. At the initial stage, 600 kg/hm² of base fertilizer (N–P₂O₅–K₂O ≥ 46%) was added to the top 10–15 cm of soil. Additionally, 450 kg/hm² of urea (N ≥ 46%) was added after the jointing stage. At each growth stage, approximately 1 kg of soil sample was collected by the quartering method in each zone. Corn fruits, including niblets and corncobs, were collected separately after harvest. All samples were transferred to the laboratory for further analysis. Photographs of the field plantings are shown in Fig. 1.

Fig. 1 Schematic diagram and photographs of the field plantings



2.3 Analysis methods

After corn maturity, nine plants were randomly selected from each treatment. The height of each plant was measured from the soil surface to the uppermost growing point. The leaf area was calculated from the maximum length and width. The stem diameter was measured at a location 1 cm below the largest leaf. Further details have been described in our previous study (Xie et al. 2020b). The dry weight of 100 niblets was measured and used as an important growth parameter. The obtained soil and corn fruits were dried until their weight could be determined, then ground, sieved (<0.15 mm), and stored in a vacuum desiccator. The moisture content of the soil was determined by the mass difference before and after drying at 105 °C for 12 h according to the Chinese standard (NY/T 52–1987). The pH and EC of the soil were measured with a pH meter (Ultra Basic, US) and a conductometer (Teltracon 325, Germany), respectively, according to the Chinese standards (NY/T 1377–2007 and HJ 802–2016). The concentrations of nutrient elements (ammonium nitrogen, available phosphorus, and available potassium) were measured by a colorimetric method using a high-precision soil fertilizer nutrient meter (HMQ800, China). The total concentrations of PTEs (Cr, Mn, Ni, Cu, Zn, As, Cd, and Pb) were digested using a mixture of nitric acid, perchloric acid, and hydrofluoric acid (5:5:2, v/v/v) in a graphite digester at 190 °C. The chemical speciation (F1: exchangeable, F2: reducible, F3: oxidizable, and F4: residual fractions) was determined by a three-step extraction procedure. The samples (0.5 g) were extracted in turn using 20 mL of acetic acid (0.11 mol/L), 20 mL of hydroxylamine hydrochloride (0.5 mol/L), 10 mL of hydrogen peroxide (30%) digestion, and 25 mL of ammonium acetate (1 mol/L). Detailed information has been reported in the previous study (Xie et al. 2019, 2020b). Specifically, F1 is the fraction from acid-soluble or carbonate-combined metals, F2 is the fraction combined with iron and manganese oxides, F3 is the fraction associated with sulfur or organic matter, and F4 is the fraction bound to silicate minerals. All solutions were tested with inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7500cx, USA) after filtration.

2.4 Health risk assessment

The estimated daily intake (EDI) and hazard quotient (HQ) indices of PTEs, which have been widely used in the health risk assessment of cilantro, spinach, and rice plantings (Khan et al. 2014, 2020; Zhang et al. 2016), were calculated using the following equations:

$$EDI = (\text{Con}_{\text{PTE}} \times \text{IR}_{\text{niblet}}) / \text{BW}, \quad (1)$$

where Con_{PTE} , $\text{IR}_{\text{niblet}}$, and BW represent the PTE concentration in niblets (mg/kg), the corn intake rate [398.2 g/adult/day (Zheng et al. 2007)], and average body weight [56.8 kg (Khan et al. 2014)], respectively.

$$HQ = EDI / R_{\text{fD}}, \quad (2)$$

where R_{fD} represents the oral reference dose, and the values of Cr, Mn, Ni, Cu, Zn, As, Cd, and Pb are 1500, 140, 20, 40, 300, 0.3, 3, and 3.5 $\mu\text{g}/\text{kg}/\text{day}$, respectively (Khan et al. 2020; Shehata and Galal 2020).

2.5 Statistical analysis

All statistical tests were performed using the Statistical Package for the Social Sciences (SPSS) Version 20.0. One-way analysis of variance (ANOVA) and Tukey's honest significant difference test were used to determine the differences in treatments. Data from different treatments showed significant differences when P was less than 0.05. Pearson correlation was used to show the relationships between soil properties and the chemical speciation of PTEs.

3 Results and discussion

3.1 Effects of SSB amendments on corn growth

The effects of SSB additions on different growth parameters after maturity are shown in Fig. 2. An increased amount of SSB amendment ($\geq 4500 \text{ kg}/\text{hm}^2$) significantly decreased the plant height, leaf area, and stem diameter of corn plants (Fig. 2a–c). Additionally, treatment without fertilization (C2) markedly inhibited the growth of corn leaves. A small leaf area indicates weakening of chlorophyll synthesis and photosynthesis during growth (Li et al. 2018b). However, the variation in dry weight of 100 niblets after SSB application was not affected by inferior plant height, leaf area, and stem diameter, as shown in Fig. 2d. The dry weight of 100 niblets of corn plants increased by 9.2%, 6.4%, and 7.1%, respectively, with the addition of 1500, 4500, and 9000 kg/hm^2 of SSB (C1, C3, and C4 treatment) compared with CK. Moreover, the absence of fertilizer (C2) caused a reduction in the dry weight of 100 niblets compared with the C1 treatment (decreased from 35.07 to 32.56 g). The impact of SSB on corn growth was determined by soil properties, which will be discussed in the next section. In general, the addition of SSB could increase the yield of corn fruits, although it inhibited plant growth, and the combination of SSB and fertilizer could yield better results. The SSB rate of 1500 kg/hm^2 was optimal as an alkaline soil amendment for corn

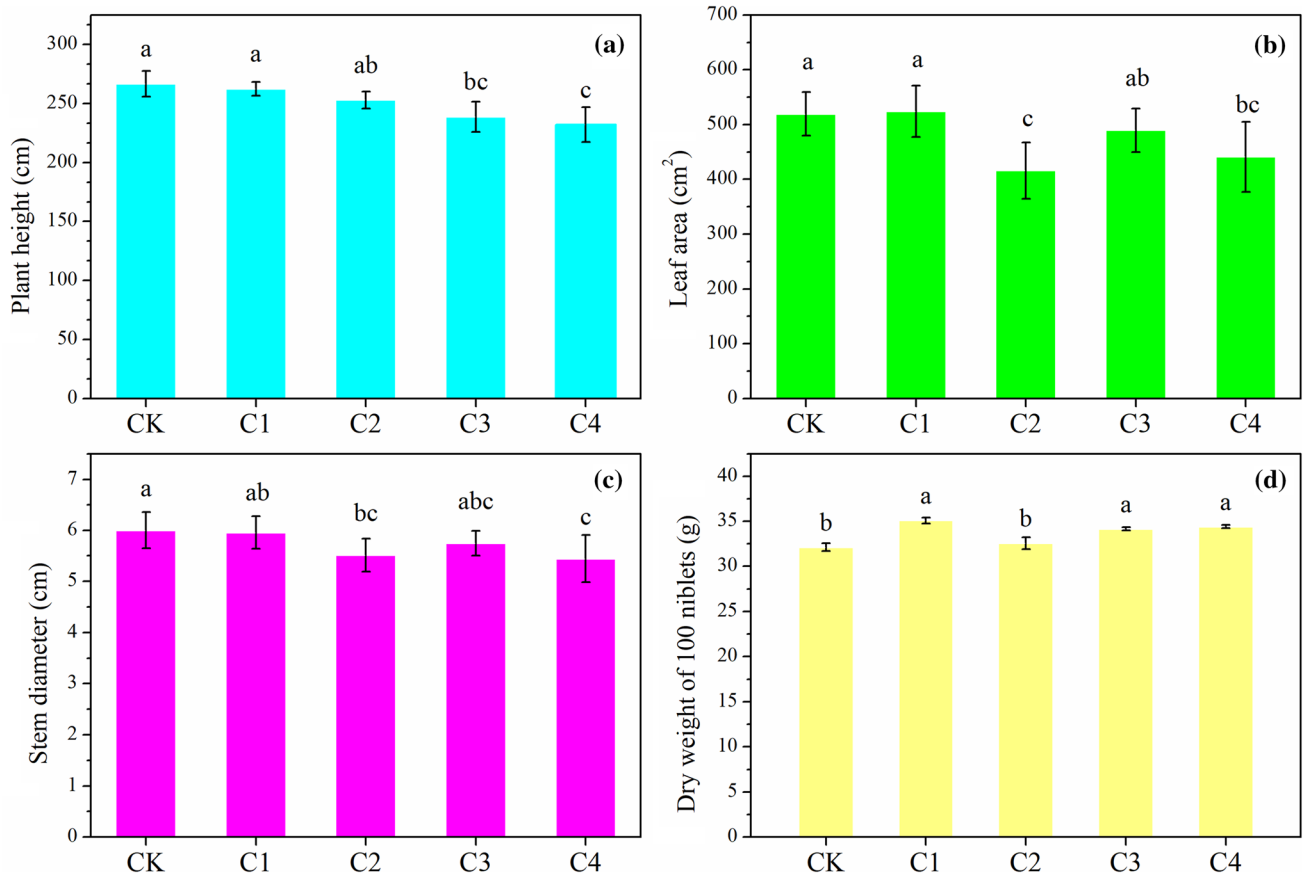


Fig. 2 Growth performance of corn plants after maturity in different treatments. Letters indicate significant differences among treatments ($P < 0.05$)

growth, ensuring the highest fruit yield. Zhang et al. (2016) also reported that modest applications of SSB ($< 5000 \text{ kg/hm}^2$) increased rice grain yields in a field study.

3.2 Effects of SSB amendments on physicochemical properties of soil

3.2.1 Soil moisture, pH, and EC

The basic properties of the alkaline soil, including moisture, pH, and EC, were investigated at different growth stages. Before seeding, there was an insignificant difference among the five trial areas with 14–18% of soil moisture (Fig. 3a).

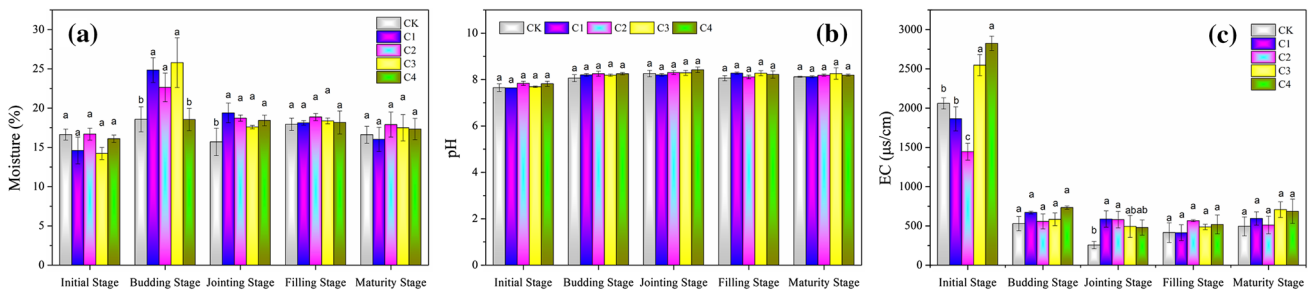


Fig. 3 Variation in a soil moisture, b pH and c electrical conductivity during growth. Letters indicate significant differences among treatments ($P < 0.05$)

The increase in moisture during the budding stage can be attributed to artificial water management based on local experience. Furthermore, moderate SSB amendments increased soil moisture at the budding and jointing stages compared with CK, indicating that, owing to its porous structure, SSB can improve the water-holding capacity of soil when corn needs water to grow, similar to the findings of Haider et al. (2017). There was no significant change in soil moisture at other stages because the water-holding capacity of SSB is not sustainable and will change with soil environmental variation (Li et al. 2020). Moreover, the pH range of soil for the five treatments was 7.6–7.9 (Fig. 3b). The soil pH was in dynamic equilibrium and showed insignificant variation during corn growth. This is because soil pH is controlled by the leaching of basic cations (Ca, Mg, K, and Na), the release of H^+ from carbonic acid produced by CO_2 dissolution, organic matter humification, and the input and output of N (Liu et al. 2020; Neina 2019). However, a small amount of SSB application could not markedly increase the pH of the alkaline soil because of its high background level, indicating that the current SSB amount is reasonable because higher soil pH may have adverse effects on plant growth and PTE availability (Artiola et al. 2012). For soil EC (Fig. 3c), there were significant differences among the five treatments (1400–2600 $\mu\text{S}/\text{cm}$) and a greater amount of SSB ($\geq 4500 \text{ kg}/\text{hm}^2$) significantly increased the soil EC. Specifically, the C1 and C2 treatments were rated as non-saline soil (0–2000 $\mu\text{S}/\text{cm}$) and other treatments were classified as slightly saline soil (2000–4000 $\mu\text{S}/\text{cm}$) (Scianna 2002). The EC in all treatments presented a trend of first decrease and then stabilization during growing stages because the accumulated nutrients and minerals in the soil would have been adsorbed and utilized by corn plants (Negasa et al. 2017). In addition, the differences in EC for the five trial areas reduced after corn planting, which suggests that plant cultivation can modify the EC level of soil. Additionally, there was no significant difference in soil EC in the other stages, although the EC level of the C2 treatment was lower than that of CK in the initial stage. This is because SSB gradually releases the available nutrients (K^+ ,

Ca^{2+} , Mg^{2+} , and PO_4^{3-}) and increases the amount of total dissolved salts (Figueiredo et al. 2018; Yue et al. 2017). SSB should be applied to alkaline soils at controlled proportions to avoid potential toxicity to corn plants.

3.2.2 Soil nutrient elements

Ammonium nitrogen is an important nutrient component in soil and can be easily absorbed by plants because of its high solubility. However, acidic ammonium ions will be neutralized in alkaline soils and lead to nitrogen volatilization (Mandal et al. 2016). As shown in Fig. 4a, the concentration of ammonium nitrogen first increased and then decreased as growth progressed. The increase in ammonium nitrogen in the filling stage was attributed to the second fertilizer application. In the budding stage, the ammonium nitrogen concentrations in other treatments with SSB application were lower than 91.25 mg/kg in CK, and their concentrations were lower for C3 and C4 treatments. A similar phenomenon also occurred at the maturity stage. These results indicate that an increase in SSB application to alkaline soils will decrease the concentration of ammonium nitrogen in the soil and promote volatilization of ammonia. The loss of nitrogen may have a negative impact on corn growth. Sun et al. (2019) also observed that NH_3 volatilization and N_2O emissions increased in acidic soils after the addition of more wheat straw alkaline biochar (20,000 kg/hm^2). Phosphorus and potassium, as essential elements, have been shown to enhance fruit growth (Hossain et al. 2011; Zeeshan et al. 2020). The variation in available phosphorus and potassium concentrations showed a similar trend during growth (Fig. 4b, c). In particular, their concentrations in the soil were markedly elevated after the addition of increased SSB amendments (C3 and C4 treatments) in the budding stage. Therefore, SSB application had a positive influence on soil fertility by increasing the concentrations of available phosphorus and potassium. Furthermore, SSB had no effect on available nutrient concentration in the soil at the filling and maturity stages because the immobilization of available nutrient mitigated this increasing trend. However, the corn

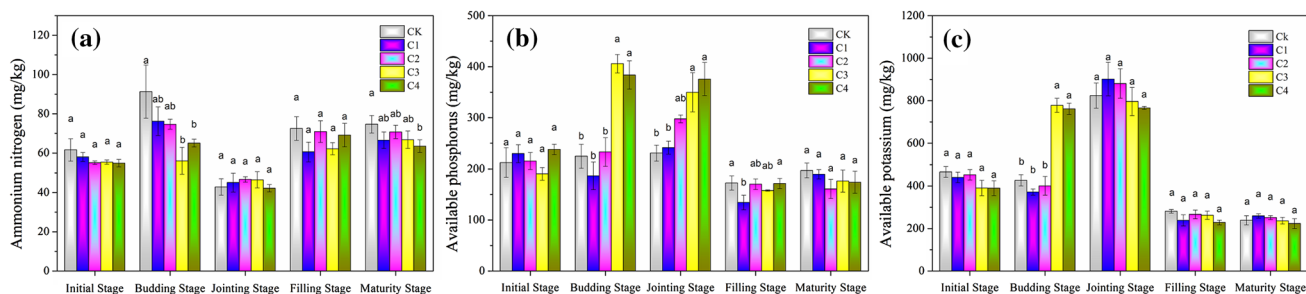


Fig. 4 Variation in **a** ammonium nitrogen, **b** available phosphorus, and **c** available potassium concentrations in the soil during growth. Letters indicate significant differences among treatments ($P < 0.05$)

plants in the C3 and C4 treatments had a weaker growth status than those in CK. These results can be attributed to the fact that the alkaline soil used in the present study, with high background nutrient levels, can reduce nutrient uptake and inhibit plant growth after higher amounts of SSB are added (Ding et al. 2016; Zhang et al. 2010). Corn fruit accumulates more nutrients than other tissues, which is why corn yield has not been affected (El-Fouly et al. 2012). However, the detailed reason needs to be further investigated.

3.3 Effects of SSB amendments on PTE in soil

3.3.1 Total PTE concentrations

Although SSB has high PTE concentrations, as listed in Table 1, moderate SSB amendments had no significant effects on total PTE concentrations in the soil in the initial stage (Table 2), whose values were lower than the risk screening values based on the Chinese standard (GB 15618–2018, Cr: 250 mg/kg; Ni: 190 mg/kg; Cu: 100 mg/kg; Zn: 300 mg/kg; Cd: 0.6 mg/kg; and Pb: 170 mg/kg), indicating a lower risk. The concentration did not exceed

the risk intervention value (100 mg/kg) for soil contamination of agricultural land, although it was higher than the risk screening value (25 mg/kg). The Cd concentration in the soil could not be detected in the initial stage owing to its extra low level. Yue et al. (2017) verified that the concentrations of Zn, Cu, Cr, Pb, As, and Cd the potting soil significantly increased in response to increasing amounts (1–50 wt%) of applied SSB. Therefore, the proportion of SSB applied should be considered, and a moderate proportion would bring low environmental risk for soil in terms of total PTE concentrations. During the growth process, the soil concentrations of Cr, Ni, Cu, Zn, and As showed decreased trends, indicating that these PTEs migrated from soil into corn plants. Moreover, the concentrations of Mn, Cd, and Pb varied irregularly due to the synergy between organic matter decomposition and plant uptake (Li et al. 2017; Xie et al. 2020b). Minor differences were also observed between CK and other treatments with the addition of SSB at the maturity stage. Furthermore, the concentrations of As and Pb at the maturity stage and the Cd concentrations at the jointing, filling, and maturity stages in the C2 treatment were higher than those in the C1 treatment, indicating that the absence

Table 2 Potentially toxic element concentrations in the alkaline soil during growth

Stage	Treatment	Cr	Mn	Ni	Cu	Zn	As	Cd	Pb
Initial	CK	62.62a ^a	433.83a	22.77a	14.82a	79.37a	44.88a	– ^b	21.52a
	C1	59.68a	410.58a	21.77ab	14.02ab	77.43a	42.63a	–	20.21ab
	C2	61.33a	418.15a	22.16a	12.78b	77.98a	44.52a	–	18.52ab
	C3	55.15a	361.43b	19.52b	12.65b	69.38b	41.34a	–	18.05b
	C4	59.23a	417.55a	20.86ab	14.99a	78.72a	42.30a	–	19.07ab
Budding	CK	47.60a	330.57a	16.83a	13.21a	49.96a	22.8a	0.20a	26.23a
	C1	45.88a	333.43a	16.64a	13.08a	48.15a	21.21ab	0.21a	27.09a
	C2	47.04a	311.5ab	15.87ab	13.53a	46.17a	19.35bc	0.17b	24.82ab
	C3	46.07a	312.2ab	16.05ab	12.55a	49.76a	20.93ab	0.2a	25.85a
	C4	43.06a	295.03b	14.61b	12.67a	49.85a	18.23c	0.17b	21.84b
Jointing	CK	43.46a	343.17ab	15.92a	12.06a	41.00a	19.53b	0.19b	25.36a
	C1	43.55a	357.13ab	15.72a	12.18a	38.41a	20.16ab	0.20b	25.80a
	C2	43.50a	376.47a	16.11a	12.62a	40.88a	22.06a	0.23a	28.47a
	C3	45.17a	334.30b	16.45a	12.41a	42.10a	21.44ab	0.20ab	27.82a
	C4	43.06a	336.28b	15.46a	12.56a	39.18a	20.41ab	0.20ab	24.45a
Filling	CK	38.37a	310.88c	15.41a	10.56b	38.36a	16.38b	0.17b	24.30ab
	C1	41.15a	392.67a	12.92a	10.99ab	39.42a	20.64a	0.18b	24.28ab
	C2	41.91a	332.87b	13.93a	10.86ab	39.39a	20.75a	0.20a	25.24a
	C3	41.18a	284.15d	13.26a	11.18ab	44.01a	18.09b	0.14c	20.88c
	C4	40.43a	304.2c	11.89b	12.12a	43.97a	16.97b	0.16bc	21.56bc
Maturity	CK	35.56a	291.63ab	12.78a	9.66b	38.75ab	16.45abc	0.15cd	18.93b
	C1	34.09a	270.35b	12.92a	9.76b	37.10b	16.08bc	0.17b	18.01b
	C2	39.13a	331.30a	13.93a	10.74ab	35.25b	19.46a	0.23a	22.84a
	C3	39.20a	288.18b	13.26a	12.20a	42.71a	17.31ab	0.16bc	19.34b
	C4	34.36a	283.45b	11.89a	11.32ab	39.69ab	13.94c	0.13d	17.54b

^aLetters after the numerical value show significance differences with each column of data ($P < 0.05$)

^bNot detected

of fertilizer poses a greater risk to plant uptake of PTEs. Unlike the application of fertilizer that would induce large amounts of Cd, Pb, and As into soil, as reported by Atafar et al. (2008), this variation in PTE concentrations may be influenced by water runoff and organic matter decomposition. However, the total PTE concentrations in soil are not the only factors affecting plant uptake. The chemical speciation and distribution also affect the PTE concentrations in crop fruits (Khan et al. 2013; Yue et al. 2017).

3.3.2 Chemical speciation of PTE

Based on the extraction of chemical species of PTEs, F1 and F2 fractions are identified as bioavailable fractions that can be easily adsorbed by plants, and the F4 fraction stably exists in soil (Fuentes et al. 2008). With corn growth, the percentage of the F1 and F2 fractions of Mn and Zn significantly increased in the soil for the five treatments, and the percentage of the F4 fractions of Mn, Ni, Cu, Zn, and As decreased markedly (Fig. 5). These results indicate that corn growth has negative effects on the immobilization of PTEs, which was also observed in the soilless cultivation of plants (Xie et al. 2020b). Throughout the growth stages, there were minor variations and the F4 fraction was the main chemical speciation of Cr and Pb in the soil, suggesting that these PTEs stably exist in soil and are adsorbed with difficulty by corn plants.

SSB amendment had different effects on the chemical fractions of other PTEs. Specifically, compared with CK, 1500 kg/hm² of SSB amendment significantly increased the percentage of the F4 fraction of Ni in the budding stage, the percentage of the F4 fraction of Cu in the budding, jointing, filling, and maturity stages, the percentage of the F4 fraction of Zn in the budding stage, and the percentage of the F4 fraction of Cd in the filling, and maturity stages. Accordingly, the percentage of the F1 and F2 fractions of Zn and Cd for the C1 treatment showed a decreasing trend compared with CK. These results indicate that low amounts of SSB amendments can promote immobilization of PTEs in the soil during different stages and reduce the risk of uptake by corn plants, which can be attributed to the modified microbial activity and the interaction between biochar and inorganic contaminants via ion exchange, anionic attraction, cationic attraction, and precipitation (Zhu et al. 2017). Additionally, the development of the pore structure of soil after the addition of SSB will increase the number of exchange sites and decrease the mobility of PTEs (Khan et al. 2013). These positive effects on the immobilization of PTEs have also been verified in other studies (Shaheen and Rinklebe 2015; Shaheen et al. 2015). However, an increase in SSB amendment had a negative influence on the stability of the chemical speciation of Ni, Cu, and Cd. Furthermore, the chemical speciation of Cr and Pb showed no significant variation after

the addition of SSB. Our previous study verified that Cr and Pb mainly existed in SSB as stable fractions combined with silicate minerals, similar to soil (Li et al. 2021).

Unlike other treatments with fertilizer, the percentage of the F4 fraction of Cd in the soil for the C2 treatment (without fertilizer) showed an increasing trend with growth. This indicates that the plant uptake of Cd will not have significant changes, although the concentration of Cd in the soil increased in the absence of fertilizer. This inhibition of Cd stability is attributed to the release of NH₄⁺ from fertilizer, which can displace Cd from adsorption sites (Han et al. 2018). Ammar et al. (2016) also observed that the application of commercial NPK fertilizer enhances the mobility of Cd in soil. Furthermore, compared with the C2 treatment, the addition of fertilizer in the C1 treatment increased the percentage of the F4 fraction of Cu at the jointing stage and the percentage of the F4 fraction of Zn at the budding stage, suggesting a lower risk of uptake of PTEs by plants. This immobilization effect can be attributed to the importance of phosphorus fertilizers for the immobilization of PTEs via the adsorption or complexation of the phosphate surface on PTE ions and the formation of metal–phosphate precipitates (Xu et al. 2018; Zeeshan et al. 2020).

3.4 Relation of PTE speciation with soil properties

The Pearson correlation coefficient shows the degree of correlation between different factors and is widely applied in soil research. Liu et al. (2020) analyzed the correlation of soil characteristics with soybean growth and yield parameters and found that pH and available nitrogen had a greater impact on the growth of soybean under alkaline soil conditions. Wu et al. (2020b) used this method to analyze soil properties, mineral nutrients, and fruit quality. In the present study, the Pearson coefficient was used to determine the relationships between the F4 fraction of the PTEs in soil and soil physiochemical properties (Fig. 6). The size and color of the squares indicate the strength of correlation, which can be shown by skew-symmetric numbers. The cross suggests a non-significant correlation among the different factors ($P > 0.05$). Chemical speciation of PTEs was markedly influenced by soil pH, EC, and the concentrations of available phosphorus and potassium. There were significant negative correlations between pH and the F4 fractions of Mn, Ni, Cu, Zn, and As, suggesting that the increase in soil pH inhibited the immobilization of these PTEs. This is because these compounds are stable over a range of pH values and higher pH will decrease their solubility in alkaline soils (Wuana and Okieimen 2011). Compared with pH, the correlation demonstrated the opposite trend between EC and the F4 fractions of Mn, Ni, Cu, Zn, and As. Additionally, strong positive correlations were detected between the F4 fractions of Cr and Zn and the concentrations of available

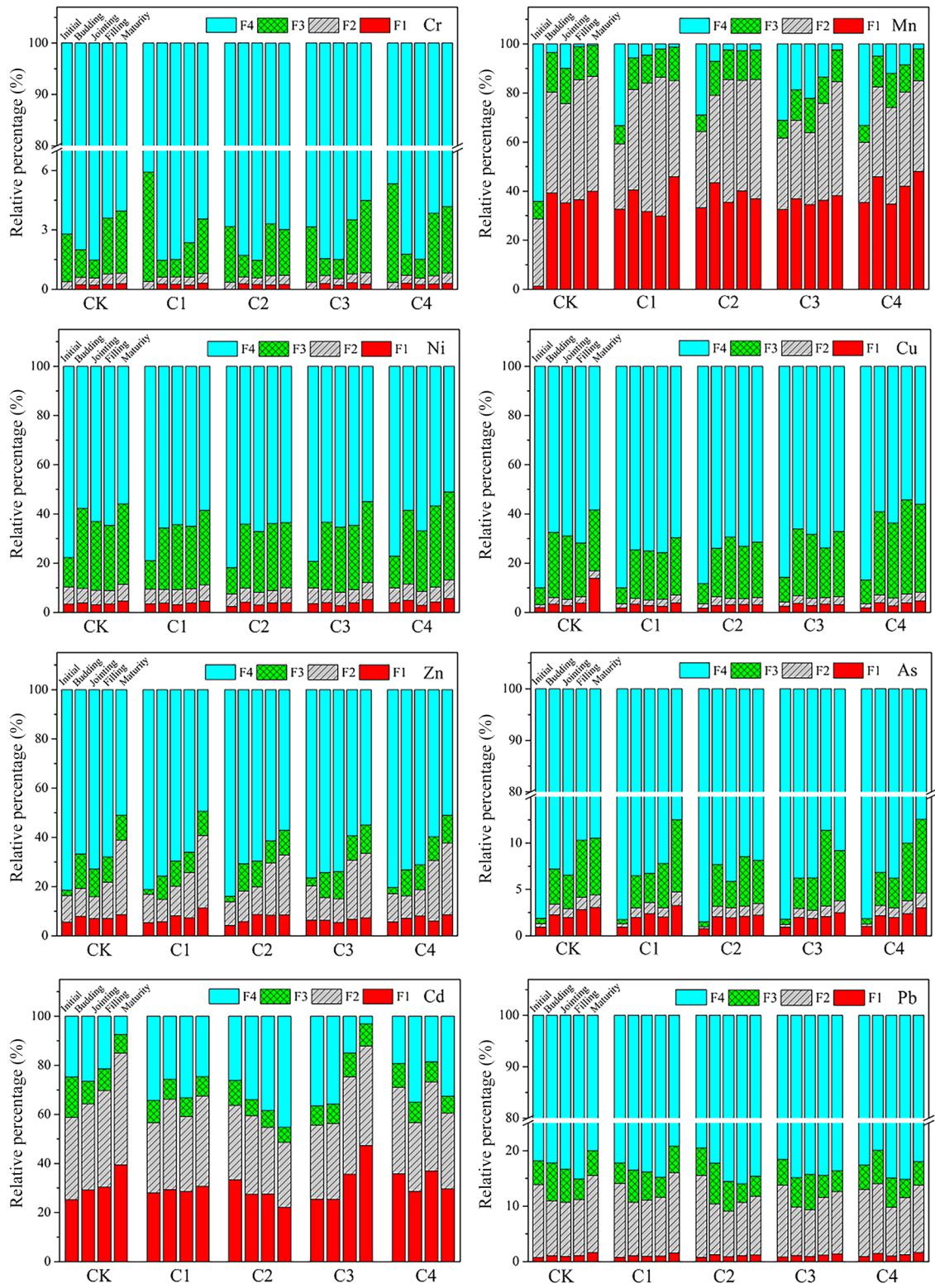


Fig. 5 Variation in the chemical speciation of potentially toxic elements in the soil during growth



Fig. 6 Pearson correlation between the F4 fractions of potentially toxic elements and soil properties. *H₂O* soil moisture, *AN* ammonium nitrogen, *AP* available phosphorus, *AK* available potassium

phosphorus and potassium. This could be attributed to the fact that an increase in inorganic matter induces precipitation of PTEs, which enhances the transformation of chemical speciation from bioavailable fractions to a more stable fraction (Yue et al. 2017).

3.5 Corn uptake of PTE and health risk assessment

The PTE concentrations in the corn fruits (niblets and corncobs) under different treatments are listed in Table 3. Corn fruits had higher levels of Zn than those of other PTEs because Zn, as an important element, plays a role in enzymatic and redox reactions (Singh et al. 2019). This can be verified in other plants, such as cucumber, rice, and tomato (Hossain et al. 2010; Waqas et al. 2014; Zhang

et al. 2016). Concentrations of Cr, Mn, Ni, Cu, and Zn were lower in the niblets than those in the corncobs, indicating a low consumption risk of PTEs. Additionally, SSB added at 1500 kg/hm² significantly decreased the concentrations of Cr, Mn, Ni, Cu, Zn, and Pb in the niblets and corncobs. Specifically, the concentrations of Mn, Ni, Cu, and Zn in the niblets decreased by 19.3%, 25.3%, 42.5%, and 13.6%, respectively, which was closely related to the immobilization of PTEs in the soil. However, a greater amount of SSB increased the Cu and Zn concentrations in the corncobs. Al-Wabel et al. (2015) also verified that applying 1.0–5.0 wt% of *Conocarpus* biochar significantly reduced Mn, Zn, Cu, and Cd concentrations in corn shoots. The reduction in corn shoots of Cr and Cu was observed after the addition of 5 wt% biochar obtained from jujube leaves and manure (Rafique et al. 2020). Furthermore, the As and Pb concentrations in the niblets and the Cr, Mn, Ni, Cu, and Zn concentrations in the corncobs for the C1 treatment were significantly decreased compared with those in the absence of the fertilizer (C2) treatment, indicating that the absence of fertilizer increases the consumption risk of corn plants.

EDI and HQ are associated with the health risk of PTEs via niblet intake, as listed in Table 4. The estimated EDI values of PTEs (except As) for the control were lower than the tolerable limit (or R_pD), indicating that the intake of PTEs in humans was without substantial risk over a whole lifetime. Furthermore, the addition of moderate SSB decreased the EDI values of Cr, Mn, Ni, Cu, Zn, and Pb, which was influenced by the PTE concentrations in the niblets. If the HQ of food plants is lower than 1, there is no health risk associated with their consumption. It was found that the HQ values of PTEs (except As) were far lower than the regulated threshold and all HQ values were lower than those obtained in contaminated soils (Khan et al. 2020, 2014). Additionally, lower HQ values were obtained in the treatments combining SSB and fertilizer, suggesting a reduction in the health risk of niblets.

Table 3 Potentially toxic element concentrations in the corn fruits from different treatments

Sample	Treatment	Cr	Mn	Ni	Cu	Zn	As	Cd	Pb
Niblet	CK	0.92a ^a	5.54a	0.83a	2.26a	27.15a	0.08b	0.02a	0.20b
	C1	0.86a	4.47b	0.62b	1.30b	23.45b	0.08b	0.02a	0.18bc
	C2	0.78a	4.66b	0.60b	1.25b	23.35b	0.10a	0.02a	0.41a
	C3	0.21c	3.61c	0.31c	1.30b	18.99c	0.08b	0.02a	0.16bc
	C4	0.59b	4.00bc	0.33c	1.32b	16.89c	0.03c	0.02a	0.14d
Corncob	CK	9.32a	8.98a	4.43a	2.71b	35.70a	0.06c	0.02a	0.18a
	C1	4.00c	5.20d	1.70d	1.96c	18.59c	0.06c	0.02a	0.11c
	C2	5.71b	6.81b	2.33c	3.19a	27.38b	0.06c	0.02a	0.11c
	C3	6.95b	8.56a	3.49b	3.05a	32.72a	0.08b	0.03a	0.12bc
	C4	3.63c	6.46bc	1.17e	2.67b	35.71a	0.13a	0.02a	0.14b

^aLetters after the numerical value show significance differences with each column of data (*P* < 0.05)

Table 4 Estimated daily intake ($\mu\text{g}/\text{kg}/\text{day}$) and hazard quotient for potentially toxic elements associated with the consumption of corn

	EDI					HQ				
	CK	C1	C2	C3	C4	CK	C1	C2	C3	C4
Cr	6.45	6.03	5.47	1.47	4.14	0.00	0.00	0.00	0.00	0.00
Mn	38.84	31.34	32.67	25.31	28.04	0.28	0.22	0.23	0.18	0.20
Ni	5.82	4.35	4.21	2.17	2.31	0.29	0.22	0.21	0.11	0.12
Cu	15.84	9.11	8.76	9.11	9.25	0.40	0.23	0.22	0.23	0.23
Zn	190.34	164.40	163.70	133.13	118.41	0.63	0.55	0.55	0.44	0.39
As	0.56	0.56	0.70	0.63	0.21	1.87	1.87	2.34	1.87	0.70
Cd	0.14	0.14	0.14	0.14	0.14	0.05	0.05	0.05	0.05	0.05
Pb	1.40	1.26	2.87	1.12	0.98	0.40	0.36	0.82	0.32	0.28

4 Conclusions

With the amendment of $1500 \text{ kg}/\text{hm}^2$ sewage sludge biochar applied to the alkaline soil, the fruit yield of corn plants was increased. However, higher biochar applications ($4500\text{--}9000 \text{ kg}/\text{hm}^2$) inhibited the growth of corn plants due to the high nutrient levels. Moderate sewage sludge biochar amendments had no significant effect on total potentially toxic element concentrations and promoted the immobilization of Ni, Cu, Zn, and Cd in the alkaline soil, which was markedly influenced by soil pH, electrical conductivity, and available phosphorus and potassium concentrations. In particular, the concentrations of Mn, Ni, Cu, and Zn in niblets decreased significantly after the addition of $1500 \text{ kg}/\text{hm}^2$ biochar, and the health risk associated with fruit consumption was reduced. Furthermore, the combination of biochar and fertilizer improved the effect on corn growth and reduced the risk of potentially toxic elements. Collectively, this work shows that $1500 \text{ kg}/\text{hm}^2$ of sewage sludge biochar applied to alkaline soils is a realistically achievable rate considering the increase in corn fruit yield and the decrease in consumption risk.

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