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Adsorption of sulfamethoxazole on biochar and its impact on reclaimed water irrigation

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ABSTRACT

Reclaimed water irrigation can satisfy increasing water demand, but it may also introduce pharmaceutical contaminants into the soil and groundwater environment. In this work, a range of laboratory experiments were conducted to test whether biochar can be amended in soils to enhance removal of sulfamethoxazole (SMX) from reclaimed water. Eight types of biochar were tested in laboratory sorption experiments yielding solid-water distribution coefficients (K_d) of 2–104 L/kg. Two types of biochar with relatively high K_d were used in column leaching experiments to assess their effect on reclaimed water SMX transport through soils. Only about 2–14% of the SMX was transported through biochar-amended soils, while 60% was found in the leachate of the unamended soils. Toxicity characteristic leaching experiments confirmed that the mobility and bioavailability of SMX in biochar-amended soils were lower than that of unamended soils. However, biochar with high accumulations of SMX was still found to inhibit the growth of the bacteria compared to biochar with less SMX which showed no effects. Thus, biochar with very high pharmaceutical sorption abilities may find use as a low-cost alternative sorbent for treating wastewater plant effluent, but should be used with caution as an amendment to soils irrigated with reclaimed water or waste water.

1. Introduction

Water stress and scarcity resulting from rapid population growth, global climate change, and pollution is among the greatest environmental problems today [1]. In the past decade, freshwater consumption by agriculture had been rising due not only to water-thirsty vegetables and meat, but also to the increase in biofuel crops [2]. Reclaimed water has been used for both agricultural and landscape irrigation to satisfy this demand. Globally, about 20 million ha of land is now irrigated with reclaimed water and this has become a key strategy in fighting water shortages [3,4].

However, the benefits and hazards associated with the application of reclaimed water must be considered. On one hand, reclaimed water typically contains some nutrient elements, such as nitrogen, so its application to agricultural fields may bring additional benefit to soil and crop systems and reduce the need for fertilizer application [5]. On the other hand, reclaimed-water irrigation may also pose environmental risks by introducing various pollutants, including organic pollutants and heavy metals, to irrigated soils and the underlying groundwater [6]. Another major concern with irrigation and direct injection of reclaimed-water is that active/infective human enteric viruses and bacteria might be delivered with the reclaimed-water to the subsurface environment [7–9]. Pharmaceutical residues, which are recognized emerging contaminants, are frequently detected in the discharge of treated effluent from wastewater treatment plants (WWTP) [10]. Various technologies including physical (e.g., filtration), chemical (e.g., chlorination), and biological (e.g., activated sludge) methods have been developed and applied in WWTP [11]. However, most of the wastewater treatment methods, except member filtration technologies (e.g., nanofiltration and reverse osmosis), cannot completely remove pharmaceuticals in the effluent [11]. Occurrences of pharmaceuticals in treated wastewater, surface water, and groundwater have been reported worldwide [10,12–14]. In

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a field study of pharmaceuticals in soil irrigated with treated urban wastewater, Furlong et al. [15] found that reclaimed-water irrigation resulted in leaching of pharmaceuticals, such as erythromycin, carbamazepine, and fluoxetine, through the vadose zone to contaminate groundwater. Soil and groundwater contaminations by reclaimed-water irrigation in agriculture caused by pharmaceuticals, such as antibiotics and hormones, have also been demonstrated in several other studies [6,12,16].

Sulfamethoxazole (SMX) is one of the most frequently detected pharmaceuticals in reclaimed water and other environmental samples [12,15]. As a sulfonamide bacteriostatic antibiotic, SMX is extensively used for treatment and prevention of both human and animal diseases [17]. It has been ubiquitously found in the high ng/L range in discharges from WWTP and in the low ng/L range in rivers and groundwater [18]. SMX is characterized as relatively unreactive to soil surfaces and shows high mobility in soils [19]. If released into aquatic systems through discharges from WWTP, SMX may have toxic effects on aquatic organisms and also may induce drug resistance in pathogens [20,21]. Occurrences of SMX in groundwater have been reported in the U.S. and other countries [12,16,22], so it is important to limit SMX leaching through the vadose zone during reclaimed-water irrigation. As suggested by Munoz et al. [12], there is a critical need to develop new methods or technologies for reclaimed-water irrigation in agriculture to reduce the contamination risk of pharmaceuticals, particularly with respect to SMX.

Recent development in biochar technology may provide such an opportunity to reduce the risk of pharmaceutical contamination of groundwater from reclaimed-water irrigation. Biochar, sometimes called agrichar, is a charcoal derived from the thermal decomposition of carbon-rich biomass. When biochar is used in agriculture as a soil amendment, it can effectively increase soil fertility and create a carbon sink to mitigate global warming [23–25]. In addition, a number of investigations have also revealed biochar's potential to be a low-cost adsorbent to control pollutant migration in soils [26,27]. Biochar converted from agricultural residues has demonstrated strong sorption ability for a variety of contaminants through various mechanisms [28–30]. Previous studies have showed that biochar has strong affinities for soil organic matters and organic pollutants such as phenanthrene (PHE), phenols, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) [28,31]. Although pharmaceuticals are emerging organic contaminants, very little research, if any, has been conducted to investigate the ability of biochar to remove pharmaceuticals from water. If shown to have sufficient sorption ability for pharmaceuticals such as SMX, biochar amendment could limit pharmaceuticals leaching from soil into groundwater or surface water in addition to improving soil fertility and carbon sequestration. This would increase the safety and feasibility of using reclaimed water for agricultural and landscape irrigation.

The overarching objective of this work was to develop a new technology to reduce the contamination risk of reclaimed-water irrigation. It is our central hypothesis that biochar, when amended in soils irrigated with reclaimed water, can sorb pharmaceutical contaminants to protect the soils and groundwater. To test this hypothesis and achieve the overarching objective, a series of laboratory experiments were conducted to study the adsorption of SMX, a common pharmaceutical contaminant in reclaimed water, on biochar and its impact on reclaimed-water irrigation. The specific objectives were to: (1) test the ability of different types of biochar to sorb aqueous SMX; (2) determine the leaching and retention of SMX in simulated reclaimed water through soils amended with selected biochar; and (3) evaluate the effect of SMX-laden biochar on the growth of *Escherichia coli*.

2. Materials and methods

2.1. Materials

A total of 8 biochar samples were produced from four commonly used feedstock materials: bamboo (BB), Brazilian pepper wood (BP), sugarcane bagasse (BG), and hickory wood (HW). The raw materials were converted into biochar through slow pyrolysis inside a furnace (Olympic 1823HE) in a N_2 environment at temperatures of 450 and 600 °C. The resulted biochar samples are here referred as BB450, BB600, BP450, BP600, BG450, BG600, HW450, and HW600. The biochar samples were then crushed and sieved yielding a uniform 0.5–1 mm size fraction. After washing with deionized (DI) water for several times to remove impurities, such as ash, the biochar samples were oven dried (80 °C) and sealed in a container for later use. Detailed information about biochar production procedures can be found in a previously published study [32].

Sandy soil was collected from an agricultural station at the University of Florida in Gainesville, FL. The soil was sieved through a 1 mm mesh (No. 18) and dried (60 °C) in an oven overnight and sealed in a container prior to use. Basic properties of the soil can be found in Supporting Information (Table S1).

Sulfamethoxazole (SMX, ACS 732-46-6) was purchased from Applichem (Germany). The physicochemical properties of SMX are summarized in Supporting Information (Table S2). All the other chemicals were analytical reagents supplied by Fisher Scientific. Artificial reclaimed water was synthesized to simulate a typical Florida conserve II reclaimed water and its major element chemical composition can be found in Supporting Information (Table S3) [5,33].

2.2. Characterization of sorbents

A range of physicochemical properties of the biochar samples were determined. The pH was measured using a biochar to deionized (DI) water mass ratio of 1:20 followed by shaking and an equilibration time of 5 min before measurement with a pH meter (Fisher Scientific Accumet Basic AB15). Elemental C, H, and N abundances were determined using a CHN Elemental Analyzer (Carlo-Erba NA-1500) via high-temperature catalyzed combustion followed by infrared detection of the resulting CO_2, H_2 and NO_2 gases, respectively [24]. Major inorganic elements were determined using the APHA standard method of acid digesting the samples for multi-elemental analysis by inductively coupled plasma emission spectroscopy (ICP-AES) [34]. The surface area of the biochar was determined on Micromeretics Autosorb1 and using the Brunauer–Emmett–Teller (BET) method in the 0.01 to 0.3 relative pressure range of the N_2 sorption isotherm [35].

2.3. Sorption of SMX

Batch sorption experiments were conducted to compare the sorption of SMX by the eight biochar samples in 68 mL digestion vessels (Environmental Express) at room temperature (22 ± 0.5 °C). Approximately 0.1 g of each biochar sample (accurately weighted) was added into the vessels and mixed with 50 mL 10 mg/L SMX solution in DI water. To show the effectiveness of the sorbents, the concentration of SMX solution used in this work (mg/L) was much higher than that in real environmental samples (i.e., μg/L or ng/L) [13]. This approach has been successfully used in several studies to examine the sorption of SMX on various sorbents [13,36,37]. The mixtures were shaken at 55 rpm in a mechanical shaker for 24 h, and the vials were then withdrawn. Vessels without either biochar or SMX were included as experimental controls. Following the sorption period, the mixtures were filtered through 0.22 μm

nylon membrane filters (GE cellulose nylon membrane) and the pH of the supernatant was measured. The concentration of SMX in the supernatant was measured with a dual beam UV/vis spectrophotometer (Thermo Scientific, EVO 60) [38]. The SMX detection wavelengths were set at 280 nm (BB450, BP450), 267 nm (BB600, BP600, BG600, HW450 and HW600), and 290 nm (BG450) to minimize the effect of background absorbance and the detection limit was about 0.1 mg/L. The pH of the standard solutions was adjusted to match that of each supernatant and the correlation coefficients (r^2) for all the spectrophotometric standard curves were higher than or equal to 0.999. Sorbed SMX concentration was calculated based on the difference between initial and final aqueous SMX concentration. Solid-water distribution coefficients (K_d), defined as the ratio between adsorbed concentration on solid phase divided by the equilibrium concentration in solution, were used to compare the SMX sorption abilities of the various biochar types.

All the experimental treatments were performed in duplicate and the average values are reported. Additional analyses were conducted whenever two measurements showed a difference larger than 5%.

2.4. Transport of SMX in reclaimed water through soil columns

Two biochar samples, BG450 and BB450, were selected to study their effect on SMX retention and transport in combination with soil. Simulated reclaimed water spiked with SMX was applied to laboratory soil columns to simulate reclaimed-water irrigation. The soil columns were made of acrylic cylinders measuring 16.5 cm in height and 4.0 cm in internal diameter, and the bottom of the columns were covered with a stainless steel mesh with 60 μm pore size to prevent soil loss. The sandy soil with or without biochar was wet-packed into the column following the procedures reported by Tian et al. [39]. Three types of soil columns, in duplicate, were used: (1) soil amended with 2% BB450 (by weight), (2) soil amended with 2% BG450 (by weight), and (3) soil with no biochar. The total amount of soil or biochar-amended soil in the columns was a uniform 200 g. About one pore-volume of artificial reclaimed wastewater (i.e., 51 mL) was first poured into the soil columns each day for two days to precondition the column. On days 3 and 4, same amount of reclaimed wastewater spiked with 2 mg/L SMX was applied to the soil columns. After that, the columns were flushed with one pore-volume SMX-free reclaimed water each day for another five days. The leaching process in each day took less than an hour, and all the leachate samples were collected from the outlet at the bottom of the columns and immediately filtered through 0.22 μm filters for further analyses.

Reverse phase high-performance liquid chromatography (HPLC, Waters 2695, Milford, MA) equipped with a Phenomenex Gemini C18 column (150 mm × 4.6 mm I.D., 5 μm) at room temperature was used to determine SMX concentration in the leachate samples. A Waters 2489 ultraviolet detector was used to detect SMX at a wavelength of 270 nm. The SMX detection limit of this method was 20 μg/L and the working range was 50–1000 μg/L with linear correlation coefficients $R^2 > 0.99$.

2.5. TCLP extraction

The toxicity characteristic leaching procedure (TCLP) was applied to the soil and soil–biochar mixtures following column experiments and entails extracting the adsorbed SMX following the USEPA Method 1311 [40]. The TCLP has been used to determine the mobility and bioavailability of both organic and inorganic contaminants in soils [27]. Soil was removed from the columns and air-dried and homogenized after the transport experiments. Extraction fluid of the TCLP was prepared by adding 5.7 mL glacial acetic acid and 64.3 mL of 1 N NaOH separately into 500 mL reagent water and then diluting to a volume of 1 L. The pH of the extraction fluid was 4.9. Solid-phase samples were then mixed with the extraction fluid at a weight ratio of 1:20, respectively, in standard extraction vessels. The vessels were shaken for 18 h at room temperature and the liquid component was separated from solid phases by filtering through 0.7 μm pore size borosilicate glass fiber filters. The filtrates were analyzed for SMX concentration by HPLC as described previously. Three independent extraction experiments were conducted for each soil sample and a one-way ANOVA test with a significance level of 0.05 ($p < 0.05$) was used to check for differences between treatments.

2.6. Growth inhibition

To obtain SMX-laden biochar for the growth inhibition experiments, 0.1 g of BB450 or BG450 was mixed with 50 mL SMX solution of three different concentrations (20, 30, and 50 mg/L) and the mixture was shaken for 24 h. After filtration, SMX-laden biochar samples were collected and oven dried at 80 °C. The SMX-laden biochar was labeled as BB450S20, BB450S30, BB450S50, BG450S20, BG450S30, and BG450S50 based on the initial SMX concentration.

E. coli DH5α was used in the test and was cultured overnight at 35 °C by constant agitation in a biochemical incubator. Biochar and SMX-laden biochar samples were sterilized in an autoclave to kill native bacteria in the samples. Pre-experiment comparing the growth inhibition effects of SMX and sterilized SMX showed the autoclave treatment had no effect on the antibiotic properties of SMX because of its good thermal stability as reported in the literature [41,42]. 83 mg BG450S20 and BB450S20, 56 mg BG450S30 and BB450S30, and 33 mg BG450S50 and BB450S50 were then added to 5 mL fresh nutrient broth medium to test their effect on bacterial growth. The amount of the adsorbed SMX in each of BG treatments was around 0.15 mg, which was much higher than that of BB treatments (0.10 mg each). SMX-free biochar (33 mg) and blank controls without biochar were also included in the experiment. The pour-plate method was used to enumerate *E. coli* following APHA standard procedures [34]. Briefly, 0.5 mL of the diluted *E. coli* sample was placed on the center of a sterile petri dish (100 mm diameter) using a sterile pipette. Sterile, molten plate count agar (45–50 °C) including biochar and SMX-laden biochar or blank controls was added and mixed with the sample by swirling the plate. The mixture was allowed to cool at room temperature until solidified and then were incubated (SenxinGRP-9160, Shanghai, China) at 35 °C for 48 h. Colonies in the medium were counted to determine bacterial concentration following the standard procedures [34]. The growth experiments were repeated six times for all tested samples and results were statistically analyzed with the *t*-test and one-way ANOVA with a significance level of 0.05 ($p < 0.05$).

3. Results and discussion

3.1. Biochar properties

CHN analysis indicated that all the eight biochar samples prepared and used in this work were carbon rich and contained 75.6–83.6% carbon (Table 1), which is typical of pyrolyzed biomass [24,30]. The oxygen and hydrogen contents of all the samples ranged 11.5–18.1% and 2.2–3.6%, respectively, some of which are likely as surface functional groups, which are commonly found on biochar surfaces [30]. The biochar samples contained relatively small amount of nitrogen (0.1–0.9%), but most of those values are still much higher than that of most of the natural soils in the US [43]. Element analysis showed that all the biochar samples had relatively low levels of phosphorous and metal elements, except the two BP biochar had more than 2% of calcium (Table 1).

Table 1
Properties and elemental composition of biochar used in this study.

	BET surface area	pH	Elemental composition (%, mass based)											
			C	H	O[a]	N	P	K	Ca	Mg	Zn	Cu	Fe	Al
BB450	10.2	8.70	76.89	3.55	18.10	0.23	0.36	0.35	0.29	0.19	0.01	–[b]	–[b]	0.04
BB600	375.5	8.93	80.89	2.43	14.86	0.15	0.54	0.52	0.34	0.23	0.01	–[b]	–[b]	0.04
BP450	0.7	9.36	75.63	3.59	17.22	0.28	0.08	0.29	2.59	0.26	0.01	–[b]	0.01	0.04
BP600	234.7	9.67	76.99	2.18	17.65	0.10	0.09	0.26	2.42	0.25	0.01	–[b]	0.01	0.04
BG450	13.6	8.95	78.60	3.52	15.45	0.92	0.07	0.25	0.83	0.18	0.01	–[b]	0.06	0.11
BG600	388.3	7.70	77.91	2.42	17.76	0.41	0.08	0.15	0.91	0.21	0.01	–[b]	0.05	0.11
HW450	12.9	8.04	83.62	3.24	11.45	0.17	0.02	0.33	0.92	0.18	0.01	–[b]	0.01	0.06
HW600	401.0	9.36	81.81	2.17	14.02	0.73	0.02	0.24	0.82	0.13	–[b]	–[b]	0.01	0.06

[a] Determined by weight difference assumed that the total weight of the samples was made up of the tested elements only.
[b] <0.01%.

Measurements of the pH indicated that all the biochar were alkaline (8.04–9.67) (Table 1), suggesting that they could be used as amendments to reduce soil acidity. The BET surface area measurements showed that biochar produced at 450 °C had very low surface areas (0.7–13.6 m^2/g), which is common for low-temperature wood and grass biochar (Table 1) [44]. When the pyrolytic temperature increased to 600 °C, the surface area of the biochar increased dramatically to 243.7–401.0 m^2/g. Strong positive correlation between N_2-measured surface area and pyrolytic temperature was also observed in several previous biochar studies [44,45].

3.2. Sorption of SMX

All the tested biochar showed certain ability to remove aqueous SMX. The solid-water distribution coefficient (K_d) of the biochar ranged 2–104 L/kg with HW450 having the lowest sorption ability (Fig. 1). The BG biochar had the highest K_d values of 104 and 94 L/kg for BG450 and BG600, respectively. Other than for the biochar made from HW, biochar made at 450 °C showed better adsorption ability than the 600 °C biochar. This contrasts with the findings of Kasozi et al. [28] showing an increase in biochar sorption of catechol with increasing combustion temperature but similar to the same study in their finding that grass biochar sorb catechol to a greater extent than hard wood biochar. Because biochar made at lower temperature may contain more surface functional groups than that prepared at a higher temperature [44,46,47], the higher sorption of SMX onto lower temperature biochar suggests that surface function groups on biochar may play a more important role in interactions between SMX and biochar than other factors such as surface area or hydrophobicity. Previous studies have indicated that, in soil, SMX has very small K_d values (0.6–3.1 L/kg) and is highly mobile [19,37]. The K_d values of seven out of eight biochar used in this work were an order of magnitude greater than that of soils, suggesting that those biochar, when amended in soils, can reduce the mobility of SMX in the soil matrix.

3.3. Transport in soil columns

Two types of biochar, BG450 (K_d = 104 L/kg) and BB450 (K_d = 64 L/kg), which had relatively high sorption ability for SMX, were used in the column experiments. As expected, both biochar reduced the transport of SMX in reclaimed water through the soils (Fig. 2). When the SMX-free artificial reclaimed water was added to the soil columns, there was no detectable SMX in all the leachate, suggesting no background SMX in the soil or biochar–soil mixtures (Fig. 2). Although the SMX-spiked reclaimed water was added to the columns on day-3, SMX was not detected immediately as the solution simply replaced the soil pore water. SMX was detected in all column leachates on day-4, but the breakthrough concentration of SMX in BG450 – (5 μg/L) and BB450 – (54 μg/L) amended columns were several orders lower than that of the unamended soil columns (329 μg/L). The breakthrough concentration of SMX in the unamended soil on day-5 was the highest (819 μg/L), and was more than 40% of the input concentration (i.e., 2 mg/L). The average peak breakthrough concentrations of the SMX in the biochar-amended soil columns were much lower (i.e., 139 and 25 μg/L for BB450- and BG450-amended soil columns). The BG450-amended soil columns had the lowest SMX breakthrough concentration, which was consistent with the results obtained from the sorption experiments. When the SMX-free reclaimed water was used to flush the columns on day-6, the SMX concentration of all leachates decreased (Fig. 2). Compared to the biochar-amended columns, however, the unamended soil columns still showed much higher SMX breakthrough concentration. Mass balance calculation indicated that more than 60% of the SMX in the reclaimed water was transported through the unamended soil column by the end of the experiment,

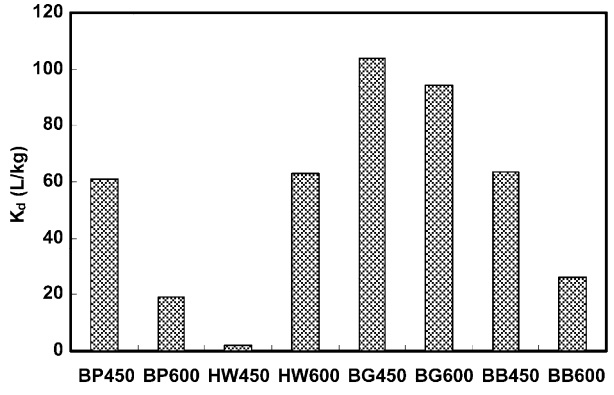

Fig. 1. The solid-water distribution coefficients (K_d) of SMX adsorption on different types of biochar (see text for abbreviations).

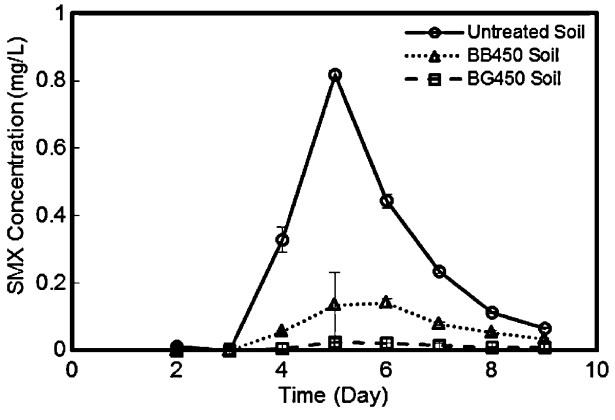

Fig. 2. Concentration of SMX in simulated reclaimed water leachates transported through biochar-amended and unamended soil columns.

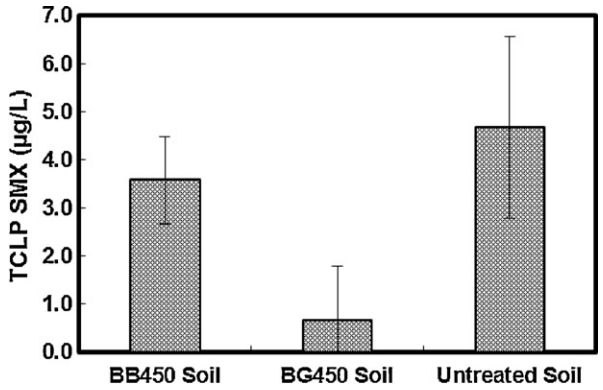

Fig. 3. Concentration of SMX in TCLP extracts of biochar-amended and unamended soils irrigated with simulated reclaimed water with SMX.

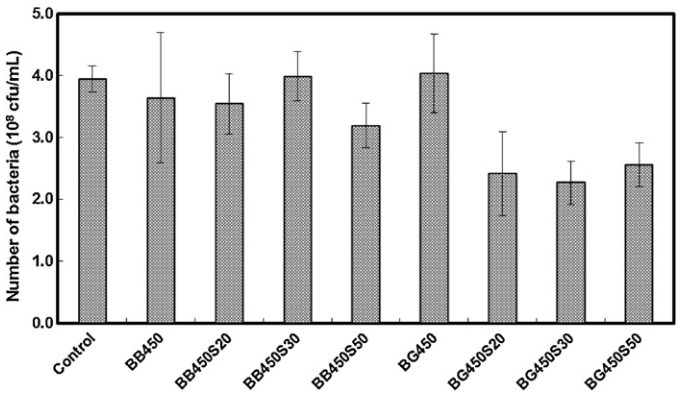

Fig. 4. Effect of SMX-laden biochar on the growth of *E. coli*.

confirming that SMX has a high mobility in soils. The transport of SMX in the biochar-amended soil columns, however, was much lower, with only about 15% and 2% of the SMX in the reclaimed water transported through the soil columns amended with BB450 and BG450, respectively. The leaching column experimental results suggest that biochar can be used as an amendment in agricultural soils irrigated with reclaimed water to adsorb SMX and to limit its mobility in the vadose zone, thus protecting groundwater quality.

3.4. TCLP extraction

Although there was much more SMX retained by the biochar-amended soils, the TCLP-extractable SMX levels in the biochar-amended soils was significantly less than that of the unamended soils (Fig. 3) with the one-way ANOVA analysis showing the differences among the tested samples was statistically significant ($p = 0.028$). The average SMX concentration in the TCLP extraction from the two biochar-amended soils was only about 76% (BB450) and 14% (BG450) of that from the unamended soils. This result suggests that, in addition to reducing SMX mobility in soil, the bioavailability of SMX in soils will be reduced by biochar amendment, even if it is highly accumulated in the biochar. The effect of biochar on reducing the mobility and bioavailability of organic contaminants, such as pesticides, in soils was also observed in several recent studies [27,48,49]. In a recent study, Cao et al. [27] found that biochar prepared from animal manure could reduce atrazine and lead concentrations in the TCLP extractions by 53–77% and 70–89%, respectively.

3.5. Growth inhibition

The growth response of *E. coli* varied among the different samples, but all showed growth of bacterial colonies reaching colony forming units (cfu) on the order of 10^8 cfu/mL (Fig. 4). The average number of bacteria in the blank control was 4.0×10^8 cfu/mL, which was almost identical to that of the BG450-treated growth media (4.0×10^8 cfu/mL) and was slightly higher than that in BB450 media (3.7×10^8 cfu/mL). The one-way ANOVA analysis showed there were no significant differences in the bacterial growth number among these three treatments ($p = 0.664$), suggesting that the SMX-free biochar does not have any antibiotic effect on *E. coli*. Previous studies showed that biochar amendment can often benefit soil microorganisms by providing them suitable habitats, and additional organic carbon and mineral nutrient sources [50,51]. The statistical analysis of the bacterial growth numbers among all the nine tested treatments (i.e., one control, two blank biochar, and six SMX-laden biochar); however, showed statistically significant differences ($p = 0.014$). Those results indicated that some of the SMX-laden biochar may inhibit the growth of the bacteria.

Comparisons of treatments of three SMX-laden BB biochar to that of the controls showed that the SMX-laden BB biochar had no inhibition effect on *E. coli* growth ($p = 0.208$). The average *E. coli* number in the BB450S30 treated growth medium (4.0×10^8 cfu/mL) was even slightly higher than that in the control and SMX-free BB450 media. The one-way ANOVA analysis of the growth experimental data of the BG biochar, however, indicated that the three of the SMX-laden BG biochar showed statistically significant inhibition of the growth of the bacteria ($p < 0.001$). The average *E. coli* numbers in the BG450S20, BG450S30, and BG450S50 treated growth medium were 2.4×10^8, 2.3×10^8, and 2.6×10^8 cfu/ml, respectively. This suggests that high levels of immobilized pharmaceuticals in biochar could cause adverse effect to the microbial population which is important for soil and plant health. When selecting biochar as a soil amendment to reduce the environmental impacts of reclaimed water irrigation, biochar with the highest pharmaceutical sorption abilities may not be the best choice. As shown in this study, although BB450 showed lower sorption ability to SMX, it could be a better amendment than BG450 to soil irrigated with reclaimed water. Because the biochar (BB450) with higher amount of SMX showed slight antibiotic effect on the tested bacteria, it could potentially affect the indigenous soil microbial community when applied to soils irrigated with reclaimed water. Further investigations are still needed to test the effect of pharmaceutical-laden biochar to the soil ecosystems including the microecosystems.

4. Conclusions

Biochar land application has been suggested to be an effective way to sequester carbon as well as improving soil quality [23]. Our results suggest that biochar soil amendment also has the potential to be used as a safeguard against the leaching of pharmaceuticals into surface or ground waters, which is of particular concern during application of reclaimed water to irrigate landscapes and agricultural fields. We found that mobility and bioavailability of SMX in biochar-amended soils were lower than that of unamended soils. Biochar soil amelioration, therefore, should be promoted in areas where reclaimed water or waste water is used for irrigation. Because high-level accumulation of pharmaceuticals in biochar could cause adverse effect on the indigenous soil microbial community, comprehensive environmental risk assessments are recommended when selecting biochar to amend soils irrigated with reclaimed water.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhazmat.2012.01.046.

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