Effects of root exudates on the sorption of polycyclic aromatic hydrocarbons onto biochar

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ABSTRACT
The effect of oxalic acid on phenanthrene sorption was varied from that on pyrene sorption. 1.0 mg L\(^{-1}\) of oxalic acid inhibited phenanthrene sorption, whereas 20, 50 and 100 mg L\(^{-1}\) of oxalic acid enhanced the sorption. However, pyrene sorption onto biochar was all inhibited among different concentrations of oxalic acid. New functional groups and increased polarity were observed in the biochar coexisted with oxalic acid, moreover, a high concentration of oxalic acid led to an increased specific surface area of the biochar. These changed factors contributed to biochar sorption to phenanthrene, which was dominated by surface adsorption. Weakened aromaticity and increased release of dissolved organic carbon from biochar may have been the main reason for inhibited pyrene sorption onto biochar by oxalic acid. Therefore, this study suggested that root exudates could greatly influence the sorption behavior of biochar towards PAHs in soil rhizosphere, which deserves attention in agricultural systems.

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Introduction
Polycyclic aromatic hydrocarbons (PAHs), which are ecotoxic, carcinogenic and mutagenic contaminants, are widespread in the environment [1]. The plentiful PAHs could pose great health risks to humans. Sixteen PAHs have been listed as priority pollutants by the U.S. Environmental Protection Agency (EPA), Europe and China [2]. Therefore, many concerns have been raised about controlling the environmental hazards posed by their transportation and toxicity.

Biochar is a porous carbon-rich material obtained by pyrolysis of biomass in a monoegetic or anaerobic environment [3]. Studies have shown that the sorption capacity of biochar to hydrophobic organic compounds is far higher than that of natural materials [4] because of its large specific surface area (SSA), porous structure and abundant functional groups [5,6]. Therefore, biochar is usually regarded as an effective amendment for immobilizing heavy metals and organic pollutants in soil. Sorption undoubtedly influences the environmental fates of contaminants in soil. On the one hand, biochar promotes the immobilization of contaminants, thereby reducing their toxic risks to organisms [7]. On the other hand, biochar sorption inhibits the bioavailability of contaminants, thereby slowing their biodegradation [8]. Thus, biochar may be a controversial strategy for soil remediation.

To remove PAHs from soil thoroughly, biodegradation is suggested as a feasible strategy. In particular, the biodegradation of organic contaminants is more effective in rhizosphere soil than in bulk soil [9,10]. Phytoremediation is considered a more environmentally friendly and cost-effective strategy for sustainable development of the environment [11]. This advantage is ascribed to root exudates, which play an important role in promoting the bioavailability of contaminants in...
soil, thereby aiding their biodegradation in the rhizosphere [12,13]. Moreover, our previous study has shown that in biochar-amended soil rhizosphere, the total and bioavailable PAH concentrations were both lower than those without biochar amendment and the effects were more significant for high-ring PAHs than for low-ring PAHs [14]. The environmental behaviors of PAHs differ because of their different physicochemical properties. The sorption of PAHs onto biochar is reasonably speculated to be affected by root exudates, and the effects should with the molecular weights of the PAHs. However, the potential mechanism remains unclear.

The main goal of this study was to determine the effects of root exudates on the sorption isotherm of PAHs onto biochar and try to elucidate its potential mechanisms. Phenanthrene and pyrene, two common pollutants in PAH-contaminated soil, were selected as model PAHs. Oxalic acid, which is a major root exudate of ryegrass cultivated in PAH-contaminated solutions, was used as a model root exudate. Batch sorption experiments of PAHs onto biochar with and without oxalic acid were conducted. The changes of biochar properties caused by oxalic acid were measured by elemental analysis, SSA analysis, Raman spectroscopy and Fourier transform infrared spectroscopy (FTIR).

**Materials and methods**

**Chemicals**

Standard phenanthrene and pyrene (purity ≥99%) were obtained from Dr. Ehrenstorfer GmbH (Augsburg, Germany). Oxalic acid (purity ≥97%) and solid CaCl₂ (purity ≥96%) were obtained from Aladdin Industrial Corporation (Shanghai, China). Ultrapure water (Milli-Q, USA) was used in all of the experiments. The stock background solution and stock liquid of phenanthrene and pyrene (200 mg/L) were prepared with ultrapure water and acetonitrile (chromatographical purity), respectively, and the prepared solutions were stored at 4°C.

**Biochar preparation**

The biochar was produced from maize straw under a pyrolysis temperature at 500°C in an oxygen-limited condition. Briefly, the raw materials were dried at 80°C for 12 h and then transferred into an oxygen-poor environment with an initial temperature of 200°C. The temperature was raised from 200 to 250°C and then to 500°C, with continuous pyrolyzing for 1.5 h at each temperature point. The pyrolysis was conducted until no more smoke was emitted. The biochar was dried at 70°C and then homogenized and passed through a 60-mesh metallic sieve for the experiments. The main properties of the biochar are shown in Table 1. The pH value was measured in 0.01 M CaCl₂ (biochar/liquid = 1:5) with a pH meter (Orion 4-Star, Massachusetts, USA). The cation exchange capacity (CEC) of biochar was determined by the method of NH₄Ac exchange. The ash contents (%) were the proportion of biomass with biochar burned to a constant mass at 750°C. The surface area and pore size of biochar were determined via the Brunauer-Emmett-Teller (BET) method using a V-Sorb 2800P analyzer (Gold APP Instruments Corporation, Beijing, China). Oxalic acid on the sorption of phenanthrene onto biochar was determined via a V-Sorb 2800P analyzer (Gold APP Instruments Corporation, Beijing, China). The elemental compositions, including carbon (C), nitrogen (N), hydrogen (H) and oxygen (O), were measured with an elemental analyzer (ANA1500, Carlo Erba, Milano, Italy). Dissolved organic carbon (DOC) was determined with a TOC-V CPH total carbon analyzer (Shimadzu, Japan) equipped with an automatic sampling system and a TN M⁻¹ unit. The functional groups in biochar were measured by FTIR in the wavenumber range from 4000 to 500 cm⁻¹ with a NEXUS 870 FT infrared spectrophotometer (Thermo Nicolet, Madison, Wisconsin, USA). The graphene structure of biochar was determined by Raman spectroscopy with an In Via Raman spectrometer (Renishaw, UK).

**Effects of oxalic acid on the sorption of phenanthrene to biochar**

Batch sorption equilibrium experiments were conducted to investigate the effects of oxalic acid on the contaminant sorption capacity of biochar. In brief, biochar (50 mg) was added to phenanthrene solution (20 mL) in brown glass flasks and the glass bottles were tightly sealed with polytetrafluoroethylene bottle caps during the experiment. The initial concentrations of phenanthrene were 0.5, 1.0, 2.0, 5.0 and 10.0 mg L⁻¹ and acetone, whose amount is less than 1% of solution volume, was used as a cosolvent [15]. The background solution was 0.01 M CaCl₂ with 0.1% HgCl₂ for sterilization. Meanwhile, five different concentrations of oxalic acid (0, 1, 20, 50, 100 mg L⁻¹) were used to evaluate the effects of oxalic acid on the sorption of phenanthrene onto biochar.

| Table 1. Physicochemical properties of the maize straw biochar pyrolyzed at 500°C. |
|-----------------|-------|---------|----------|--------|-------|---------|---------|
| pH              | DOC a | CEC b   | SSA c    | Pore size | Ash content | Micropore volume | Median pore width |
| 9.66            | 1.77  | 35.08   | 36.38    | 2.80    | 4.89   | 3.26    | 0.83    |

**Notes:**

a) DOC is the amount of dissolved organic matter;

b) CEC is the cation exchange capacity of the soil;

SSA is the specific surface area of biochar determined by the Brunauer-Emmett-Teller method.
biochar. 20 mL of oxalic acid solution with different concentrations of 0, 1, 20, 50, 100 mg L\(^{-1}\) was conducted synchronously. Each test was carried out in triplicate. After being shaken at 25°C for 72 h, all bottles were centrifuged; the suspensions were then sampled and filtered through a 0.22 μm membrane. The biochar on the films were gently scraped and dried for analysis of elemental composition, SSA, functional groups by FTIR and graphene structure by Raman spectroscopy. The concentration of phenanthrene in solution was analyzed by high-performance liquid chromatography (HPLC). The pH values of the supernatants were measured with a pH meter (Thermo Scientific, China). DOC concentration in solution was determined by TOC-V CPH total carbon analyzer (Shimadzu, Japan). The DOC concentrations released from biochar (DOC\(_{BC}\)) was calculated by DOC\(_{BC}\) = DOC\(_{Total}\) - DOC\(_{Oxalic}\) where DOC\(_{Total}\) is the concentration of DOC in treatments of biochar solution with different concentrations of oxalic acids and DOC\(_{Oxalic}\) is the background concentration of DOC of oxalic acids in solution.

**Effects of oxalic acid on the sorption of pyrene to biochar**

Briefly, biochar (50 mg) was added to pyrene solution (20 mL) in brown glass flasks with initial pyrene concentrations between 0.01 and 0.1 mg L\(^{-1}\). The gradient concentrations of oxalic acid and sampling were the same as those described in the section of ‘Effects of oxalic acid on the sorption of phenanthrene to biochar’. The concentration of pyrene in solution was also analyzed by HPLC. The pH values of the supernatants were measured with a pH meter (Thermo Scientific, China).

**Analysis of phenanthrene and pyrene by HPLC**

The determination methods of phenanthrene and pyrene were the same as in our previous study [16]. Briefly, a Shimadzu Class-VP HPLC system (LC-20A, Japan) equipped with a Supelco Sil\(^\text{TM}\) LC-PAHs chromatographic column (25 cm × 4.6 mm, 5 mm particle diameter) and a fluorescence detector (Shimadzu RF-10AXL) were used. The excitation and emission wavelengths were 245 nm and 365 nm for phenanthrene and 270 nm and 390 nm for pyrene, respectively. During the analysis, the column temperature was maintained at 30°C and the mobile phase consisted of acetonitrile (90%) and water (10%) at a constant flow rate of 1.5 mL min\(^{-1}\). An external standard mixture was used for quantification of the two compounds.

**Quality control and data analysis**

The recoveries of phenanthrene and pyrene in solution were 90.63 ± 4.7% and 93.71 ± 8.4%, respectively.

The sorption isotherms of phenanthrene and pyrene onto biochar were characterized with the Freundlich model (Equation (1)), Langmuir model (Equation (2)), Henry model (Equation (3)) and Dubinin-Radushkevich model (Equation (4)) as follows:

\[
Q_e = K_f C_e^{1/n} \quad (1)
\]

\[
Q_e = \frac{Q_m K_f C_e}{1 + K_f C_e} \quad (2)
\]

\[
Q_e = K_h C_e \quad (3)
\]

\[
\ln Q_e = \ln Q_{D,R} - \beta e^2 \quad (4)
\]

where \(Q_e\) (mg kg\(^{-1}\)) and \(C_e\) (mg L\(^{-1}\)) are the sorption amount and equilibrium concentration at equilibrium, respectively; \(K_f\) (mg/kg) (mg/L\(^{-1}\)) is the adsorption affinity parameter of the Freundlich model; and 1/n is the linear constant in the Freundlich model, referring to sorption intensity [17]. The thermodynamic parameter of Gibbs free energy (\(\Delta G\)) is specified as \(\Delta G = -RT \ln K_h\), where R is the gas constant (8.314 J mol\(^{-1}\)K\(^{-1}\)) and T = 298.15 K [18]; \(K_h\) (L mg\(^{-1}\)) is the sorption binding energy of the sorbent in the Langmuir model; and \(Q_m\) (mg kg\(^{-1}\)) is the maximum sorption capacity of PAHs onto biochar. \(K_h\) (L mg\(^{-1}\)) is the adsorption coefficient (partition coefficient of biochar and water) in the Henry model. \(Q_{D,R}\) (mg kg\(^{-1}\)) is the theoretical saturation sorption capacity in the Dubinin-Radushkevich model; \(\beta\) (mol\(^2\) kj\(^{-2}\)) is the constant for the mean free energy of sorption; \(\varepsilon\) (kJ mol\(^{-1}\)) = \(RT\ln (1 + 1/C_e)\) is the Polanyi potential; and \(E = (-2\beta)^{-0.5}\) represents the free energy required for adsorption per unit mol ion on the biochar surface [19].

The data analysis was performed with the Sigma Plot 12.0 software. The statistical analysis of variance (ANOVA) was conducted with SPSS 19 at the significance level of \(p < 0.05\).

**Results and discussion**

**Effects of oxalic acid on sorption of phenanthrene onto biochar**

Phenanthrene sorption onto biochar can be well fitted by the Freundlich and Langmuir models, with a high \(R^2\) (Figure 1). The \(K_f\) and 1/n constants obtained from the Freundlich model represent the sorption capacity and intensity of biochar to phenanthrene, respectively. As shown in Table 2, the sorption of phenanthrene was inhibited by a low concentration of oxalic acid (1 mg L\(^{-1}\)) but was promoted by high concentrations of oxalic acid (20, 50 and 100 mg L\(^{-1}\)). All of the 1/n values were far less than 1, indicating that surface adsorption dominated phenanthrene sorption onto biochar. Phenanthrene was mainly adsorbed on the amorphous surface of biochar, which contains many available
sorption sites. This behavior is ascribed to the high SSA and abundant functional groups in biochar. Low concentrations of oxalic acid enhanced the sorption intensity of phenanthrene onto biochar, with increased 1/n values; by contrast, high concentrations of oxalic acid caused the opposite result. All the ΔG values were in the range from 0 and -20 kJ mol⁻¹ regardless of treatments, indicating that the adsorption of phenanthrene onto biochar was spontaneous and that physical sorption dominated in this process [20]. The Q_{D-R} values obtained from the Dubinin-Radushkevich model were consistent with the K_f values obtained from the Freundlich model. The Dubinin-Radushkevich model can be used to characterize the sorption process in a porous adsorbent and to distinguish between chemical and physical sorption in the adsorbent [21,22]. The E values were less than 8 kJ mol⁻¹, indicating that phenanthrene sorption onto biochar was dominated by physical adsorption. As fitted by the Langmuir model, the Q_m values notably increased when oxalic acid was added, indicating an increased phenanthrene sorption ability of biochar, except when the oxalic acid concentration was 20 mg L⁻¹.

**Effects of oxalic acid on the sorption of pyrene onto biochar**

The sorption of pyrene to biochar differed from that of phenanthrene and was best fitted by the Henry model, which is a linear model (Figure 2). This behavior suggests that pyrene sorption onto biochar is mainly via hydrophobic partition. In this case, organic carbon in biochar plays an important role in pyrene sorption. As shown in Table 2, the K_H values – the partition coefficients of pyrene between biochar and solution – decreased with oxalic acid addition, indicating that oxalic acid inhibited the sorption of pyrene onto biochar. Regardless of the effects of oxalic acid, all of the ΔG values were less than 0 and in the range from 0 to -20 kJ mol⁻¹, indicating that pyrene sorption onto biochar was spontaneous and that physical sorption predominated in this process. The ΔG values increased with increasing oxalic acid addition, indicating a restraining force to pyrene sorption onto biochar. To better understand the sorption behavior of pyrene onto biochar, the Dubinin-Radushkevich model was applied to assess the interaction forces in pyrene sorption. This model fit the sorption data of pyrene.

| OA (mg L⁻¹) | Q_m × 10^3 (mg kg⁻¹) | K_f (L mg⁻¹) | R² | ΔG (kJ mol⁻¹) | 1/n | E (kJ mol⁻¹) | β (mol² kJ⁻²) | R² |
|-------------|-----------------------|-------------|----|--------------|-----|-------------|-------------|----|
| 0           | 33.21                 | 0.72        | 0.97 | -14.32       | 0.54 | 4.31        | 0.03        | 0.84 |
| 20          | 25.41                 | 5.44        | 0.97 | -16.41       | 0.47 | 4.25        | 0.02        | 0.91 |
| 50          | 85.89                 | 0.45        | 0.96 | -17.43       | 0.36 | 4.25        | 0.03        | 0.58 |
| 100         | 17.20                 | 0.28        | 0.91 | -17.20       | 0.41 | 4.33        | 0.03        | 0.64 |

| OA (mg kg⁻¹) | K_f (mg/kg) | 1/n | ΔG (kJ mol⁻¹) | R² |
|-------------|-------------|-----|--------------|----|
| Control     | 17.43       | 0.59 | -12.81       | 0.94 |
| OA20        | 16.41       | 0.98 | -17.34       | 0.69 |
| OA50        | 14.32       | 0.85 | -15.73       | 0.43 |
| OA100       | 13.85       | 0.98 | -16.41       | 0.98 |

Table 2. Isothermal parameters of phenanthrene sorption onto biochar and the effects of different concentrations of oxalic acid (OA).
Mechanisms of PAHs’ sorption onto biochar, as affected by oxalic acid

Sorption mechanisms of organic compounds onto biochar include hydrophobic partition, surface adsorption and pore-filling [23]. Surface adsorption, by which organic compounds can interact with the functional groups on the biochar surface or be sorbed onto some sorption sites, is an important contribution for the sorption capacity of biochar. Adsorption is a competitive sorption process, and the large SSA of biochar is critical in this process. Hydrophobic partitioning mainly occurs for biochar sorption to nonpolar or weakly polar organic compounds, which is a non-competitive sorption process [24]. Pore-filling is based on the non-homogeneous porous structure of biochar, which is affected by the pore distribution and the molecular weight of organic compounds [25]. Compared to pyrene, phenanthrene has lower molecular weight and higher polarity and is thus more likely to approach and enter the pores of biochar. Phenanthrene sorption onto biochar occurs predominantly through surface adsorption, whereas pyrene sorption onto biochar is mainly a hydrophobic partition interaction, as confirmed by the sorption isotherm results.

Biochar structure and effects of oxalic acid

Elemental analysis shows that the composition of oxygen greatly increased with increasing oxalic acid addition (Table 4), which is indicative of an acid oxidation of biochar by the oxalic acid treatment [26]. In addition, the ratios of H/C, O/C and (N + O)/C increased with increasing concentration of oxalic acid (Table 4), indicating that oxalic acid promoted the polarity and weakened the aromaticity of biochar.

Table 4. Effects of oxalic acid (OA) on elemental compositions of biochar and pH values of solutions in the sorption system.

| OA mg L⁻¹ | C (%) | H/C | O/C | (N + O)/C | pH |
|-----------|-------|-----|-----|-----------|----|
| 0         | 43.76 | 5.13| 25.11| 1.51      | 0.57| 0.61| 6.74 |
| 1         | 38.15 | 5.50| 26.59| 1.29      | 0.14| 0.70| 0.73| 6.68 |
| 20        | 33.51 | 6.52| 30.39| 1.18      | 0.19| 0.91| 0.94| 4.68 |
| 50        | 30.90 | 6.91| 37.51| 1.13      | 0.22| 1.21| 1.25| 3.47 |
| 100       | 31.01 | 6.64| 41.66| 4.41      | 0.21| 1.34| 1.49| 3.02 |
I− (a) Deconvoluted and (b) peak−fitting results related to the stretching disorder and defective structure of biochar), which are subduced from the stretching band (1580 cm−1). The maximum peak areas of the two typical bands in the range from 1100 to 1800 cm−1 were quantified (Figure 3(b)). With increasing concentration of oxalic acid from 0 to 1, 20, 50 and 100 mg L−1, the I_D/I_G ratio increased from 0.92 to 1.66, 1.52, 1.23 and 1.35, respectively. This behavior is indicative of increased disorder and decreased graphite structure of biochar with increasing oxalic acid addition. The changes in the biochar structure can be ascribed to the doping of oxalic acid into the biochar structure [33]. The authors of another study also detected a change in the graphic structure of biochar with acid treatment by electrophilic attack [30]. In addition, the elemental analysis results show changes in the atomic H/C and O/C ratios (Table 4), which are consistent with the Raman spectroscopy results. Together, the elemental analysis and Raman spectra suggest that oxalic acid attacked the carbon structure of biochar, introducing defects and disordered structures and thereby improving the polarity and reducing the aromaticity of the biochar. These structural changes enhanced phenanthrene sorption but subdued pyrene sorption onto the biochar.

**Fourier transform infrared spectroscopy (FTIR) of biochar and the effects of oxalic acid**

To determine the interaction among oxalic acid, PAHs and biochar, FTIR spectra of biochar before and after sorption of PAH with or without oxalic acid addition were collected (Figure 4). The peaks in the range from 500 to 1000 cm−1 are ascribed to the vibration of C–H bonds of aromatic groups [34,35]. The bands at approximately 1094 cm−1 are related to the stretching of cellulosic or non-cellulosic C=O bonds such as C=O–C and C–OH [36]. The bands at approximately 1382, 1429 and 1621 cm−1 are attributed to the stretching of C=O groups such as the carbonyl, aldehyde, ketone, carboxylic and hydroxyl groups [37]. The peaks at approximately 3500 cm−1 arose from the stretching of N–H groups and O–H groups [38,39]. During the sorption process, the adsorption peaks did not obviously shift, indicating that the sorption of phenanthrene and pyrene onto biochar was dominated by physical sorption, consistent with the adsorption isotherm results (Tables 2 and 3). As evident in Figure 4, two peaks appeared at approximately 1385 cm−1 when oxalic acid was added, and the intensities of these peaks were enhanced with increasing concentration of oxalic acid. These peaks are ascribed to C=O deformation vibrations, indicating that high concentrations of oxalic acid may oxidize the biochar and generate new carboxylic acid groups on the biochar carbon structure [30]. This result is attributable to the greatly increased pH values of the solution (Table 4). Therefore, the oxalic acid is reasonably assumed to have affected the sorption of PAHs onto biochar. On the one hand, oxalic acid may compete with phenanthrene for some sorption sites on biochar, thereby inhibiting the adsorption of phenanthrene; on the other hand, high concentrations of oxalic acid can also generate new functional groups on the biochar surface (Figure 4), thereby benefitting the phenanthrene interaction dominated by surface adsorption onto biochar.

**Figure 3.** (a) Deconvoluted and (b) peak fitting of Raman spectra for oxalic-acid-treated biochar. D and G represent the two bands that contributed to the disorder and defective structure and to the graphite structure of biochar, respectively.
Dissolved organic carbon (DOC) content of the aqueous phase and the effects of oxalic acid

DOC is an organic complexing agent that can also affect the availability and fates of organic compounds [40,41]. Oxalic acid, a natural DOC, can certainly influence the sorption behavior of phenanthrene and pyrene in solution. As shown in Figure 5(a), the DOC contents in solution increased from 4.77 to 421 mg L\(^{-1}\) as the oxalic acid concentration was increased from 0 to 100 mg L\(^{-1}\). Therein, oxalic acid promoted the release of DOC from biochar from 4.77 to 8.6 mg L\(^{-1}\) (Figure 5(b)). This behavior is explained by oxalic acid disrupting the bonds of DOC on biochar, resulting in the release of organic carbon into solution. Wu et al. (2018) also found that large amount of DOC could be released from biochar under various acidic or alkaline extracting solutions [42]. An increase of the DOC in solution is well known to favor PAH desorption from adsorbates [43] due to the solubility enhancement of PAHs in solution [44]. In addition, DOC can form a hydrophilic layer around the biochar, repelling the hydrophobic organic compounds in the two-phase system of biochar-water [44]. Therefore, PAHs’ sorption onto biochar should be inhibited by oxalic acid. However, only pyrene sorption onto biochar was inhibited within the investigated oxalic acid concentration range (Tables 2 and 3). This result is ascribed to the different sorption behaviors of the two PAHs. A previous study has shown that the interaction between high-ring PAHs and DOC is dominated by hydrophobic partitioning [45], resulting in a decreased hydrophobic partition of pyrene onto biochar.

Specific surface area of biochar and the effects of oxalic acid

SSA is a critical property of biochar for surface adsorption. Therefore, the changes in the SSA with oxalic acid addition should be considered when investigating the effects of oxalic acid on phenanthrene sorption. As shown in Figure 6(a), the presence of high concentrations of oxalic acid substantially increased the SSA of biochar by 2.2 times compared with the control, and the SSA increased with increasing concentration of oxalic acid. This result is ascribed to the
dissolution of the ash contents by high concentrations of oxalic acid, which increased the quantity of micropore structures in the biochar [46]. Therefore, phenanthrene sorption onto the biochar was greatly promoted by high concentrations of oxalic acid. However, low concentrations of oxalic acid did not cause a substantial increase in the SSA in biochar. Moreover, the SSA was significantly positively correlated with the sorption capacity of biochar for phenanthrene (Figure 6(b)) rather than pyrene, further confirming that an increase in the SSA with increasing addition of oxalic acid played a key role in promoting phenanthrene sorption onto biochar, which is dominated by surface adsorption. However, the increase in the SSA weakly affected the sorption of pyrene onto biochar, which is dominated by hydrophobic partitioning.

Conclusion

The sorption of phenanthrene by wheat-straw biochar was dominated by surface adsorption, which was inhibited by low concentrations of oxalic acid but promoted by high concentrations of oxalic acid. By contrast, pyrene sorption onto biochar occurred predominantly through hydrophobic partitioning, which was inhibited by oxalic acid. The increased polarity and increased SSA of biochar with oxalic acid coexisted are critical to phenanthrene sorption, whereas the increased DOC in solution and decreased aromaticity of biochar with oxalic acid coexisted mainly inhibit pyrene sorption onto biochar. Root exudates can affect the sorption of PAHs onto biochar and thus potentially influence the availability of PAHs in biochar-amended soil.

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Disclosure statement

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