Sorption kinetics of 1,3,5-trinitrobenzene to biochars produced at various temperatures

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Abstract

Sorption kinetics of organic compounds on biochars is important for understanding the retardation of mobility and bioavailability of organic compounds. Herein, sorption kinetics of 1,3,5-trinitrobenzene on biochars prepared from 200 to 700 °C was investigated to explore the sorption process. Loose partition matrix and condensed partition matrix were formed at relatively low and moderate temperatures, respectively. However, biochars produced at relatively high temperatures formed rich pore structures. Therefore, sorption equilibrium time of 1,3,5-trinitrobenzene increased with increasing preparation temperature from 200 to 350 °C due to the slower diffusion rate in the more condensed matrix, and then decreased when preparation temperature was higher than 400 °C because of the faster adsorption rate in the greater number of pores. Linear positive relationship between matrix diffusion rates of 1,3,5-trinitrobenzene on biochars prepared at 200, 250, 300, 350 °C and H/C ratios of biochars was observed, suggesting that the inhibition of partition process was caused by the condensed matrix in biochars. Linear positive relationships between adsorption rates (i.e., fast outer diffusion rate and slow pore diffusion rate) of 1,3,5-trinitrobenzene on biochars prepared at 400, 450, 550, 700 °C and graphite defects of biochars were observed, because the increase of graphite defects of biochars could promote the adsorption by increasing the quantity of fast diffusion channels and sorption sites. This study reveals the underlying mechanisms of sorption kinetics for organic compounds with relatively large size on biochars, which has potential guidance for the application of biochars and prediction of the environmental risks of organic compounds.

Graphical Abstract

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1 Introduction

Biochars are carbon-rich materials produced by heating crop wastes, wood, or other biomass in oxygen-limited conditions (Jaffe et al. 2013; Keiluweit et al. 2010). In recent years, biochars have received increasing attention for use in soil improvement, carbon sequestration, and waste management (Lehmann 2007; Thompson et al. 2016; Yang et al. 2018). Biochars are potential sorbents for mitigating the plant uptake and removal of organic compounds from wastewater due to their large surface area and high microporosity (Chun et al. 2004; Ni et al. 2011; Pignatello and Xing 1996; Yang et al. 2016, 2018; Yu et al. 2010; Zhu et al. 2021). For organic compounds, the sorption rate, rather than the sorption capacity, dominates the uptake from the environmentally contaminated natural waters at the relatively low concentrations. An improved understanding of the sorption kinetics of organic compounds on biochars is thus critical for the selection of biochars as potential environmental sorbents and the evaluation of the environmental risks of organic compounds in the soil environment (David et al. 2009; Chen et al. 2008, 2012; Pignatello and Xing 1996).

In the previous study (Zhu et al. 2021), desorption hysteresis from biochars produced at 700 °C (BC700) was observed for 1,3,5-trinitrobenzene with a 2-day adsorption–desorption time. Once the adsorption–desorption time was extended to 5 days and 15 days, the desorption hysteresis of 1,3,5-trinitrobenzene on BC700 almost disappeared (Zhu et al. 2021). Therefore, the adsorption–desorption behavior of 1,3,5-trinitrobenzene on BC700 largely depends on the biochar adsorption kinetics. In addition to the biochars produced at high temperatures (i.e., 700 °C), biochars produced at relatively low temperatures are also widely used in soil improvement and waste management (Chen et al. 2008, 2012; Chun et al. 2004; Ni et al. 2011; Thompson et al. 2016; Yu et al. 2010). With increasing preparation temperature, biomass polymers (e.g., hemicellulose, cellulose, and lignin) evolve through several pyrolysis stages, (i.e., dehydration, depolymerization, fragmentation, and condensation) (Keiluweit et al. 2010; Lehmann 2007; Yu et al. 2010), resulting in a condensed matrix with almost no pore structure at relatively low temperatures and porous particles at relatively high temperatures (Keiluweit et al. 2010; Yu et al. 2010). Accordingly, the sorption mechanism of organic compounds on biochars undergoes a transition from partition (matrix diffusion) to adsorption/pore filling (pore diffusion) as the heat treatment temperature increases (Chen et al. 2008, 2012; David et al. 2009). Therefore, the influence of biochar properties on the sorption kinetics of organic compounds on biochars produced at relatively high temperatures (700 °C) cannot be directly employed to interpret the sorption kinetics of organic compounds on biochars produced at relatively low temperatures with almost no pore structure.

The sorption kinetics of a solute (e.g., an organic compound) by a sorbent should be described in two aspects, i.e., sorption equilibrium time and sorption rates. In general, the sorption equilibrium time of contaminants by biochars depends on the composition and the porosity of the biochars, which are affected by the pyrolytic temperature (Chun et al. 2004; Chen et al. 2012, 2017). Earlier studies suggested (Zheng et al. 2010) that the biochar produced at 450 °C with smaller particle size needed less time to reach sorption equilibrium for atrazine and simazine. Sorption equilibrium of naphthalene on biochars produced at 150 °C and 700 °C was reached quickly because the sorption rate was accelerated by the loose structure of biochar produced at 150 °C and abundant the pore structures of biochar produced at 700 °C (Chen et al. 2012). However, the sorption equilibrium time of naphthalene on biochar produced at 350 °C was longer than 30 days because the diffusion rate in the condensed partition phase of biochar produced at 350 °C was slow (Chen et al. 2012). On the other hand, the sorption rate of carbamazepine on amorphous carbon in biochar produced at 200 °C was faster than that on aromatic carbon in biochar produced at 300 °C (Chen et al. 2017). In addition to the carbon forms of biochars, other physicochemical and structural properties, such as the degree of pyrolysis, graphitization, and pore structure of biochars may play crucial roles in the sorption kinetics. It is hypothesized that the sorption rates of 1,3,5-trinitrobenzene on biochars with a loose matrix (produced at relatively low temperatures) or rich pore structure.
(produced at relatively high temperatures) would be higher than those on biochars with condensed matrix and poor pore structure (produced at moderate temperatures). Biochars prepared at different temperatures commonly have varying physicochemical and structural properties (Chen et al. 2012, 2017) and thus have various underlying mechanisms for sorption kinetics. Therefore, it is critical to examine the sorption kinetics on biochars produced at different temperatures to establish the correlations of sorption kinetics with the physicochemical and structural properties of biochars to predict the sorption process of organic compounds on biochars and explore the underlying mechanisms.

The main objective of this study was to illustrate the influence of adsorbent properties on the sorption kinetics of organic compounds on wood-derived biochars produced at a series of temperatures to gain more insights into the nature of kinetic processes for organic contaminants. 1,3,5-Trinitrobenzene has been widely used in explosives, munitions, and vulcanization of rubber (Reddy et al. 1997). 1,3,5-Trinitrobenzene or its derivatives formed from the reduction of nitro groups are well absorbed in living organisms (e.g., humans, algae, plants, and microorganisms) (Kraeling et al. 1998; Maeda et al. 2010), and detected as environmental contaminants of surface water and soil (Reddy et al. 1997). Pine wood, an inexpensive material and the most commonly used precursor of biochars (Keiluweit et al. 2010; Zhu et al. 2021), was chosen to prepare a series of biochars from 200 to 700 °C to assess the ability of the biochars to retard the mobility and bioavailability of organic compounds.

2 Materials and methods

2.1 Biochars and chemical

Pine wood chips were collected from Zhejiang, China, ground to pass through a 0.154 mm sieve and stacked tightly in porcelain crucibles with lids before heating. Biochars were produced by heating the pine wood under oxygen-limited conditions in a muffle furnace at 200, 250, 300, 350, 400, 450, 550, or 700 °C for 6 h (Chen et al. 2008; Chun et al. 2004). The preparation temperature of biochars is determined by the pyrolysis temperature of biomass polymer and the carbonization degree of wood biomass (Table S1). Meanwhile, these temperatures cover the range over which most biochars are made (Yang et al. 2021). The pristine biochars were demineralized using 1 mol/L HCl solution (m/v=0.1 g/mL) for 12 h, washed with deionized distilled water (Milli-Q, Millipore) to neutral, and dried at 80 °C before use (Chen et al. 2008; Chun et al. 2004). The demineralized biochars were labeled as W200, W250, W300, W350, W400, W450, W550, and W700 according to pyrolysis temperatures.

1,3,5-Trinitrobenzene (wetted with 40% water) was purchased from Tokyo Chemical Industry Co. and used as received. The maximum absorption wavelength of 1,3,5-trinitrobenzene measured by UV spectrophotometer is 228 nm.

2.2 Biochar characterization

Thermogravimetric (TG) and derivative thermogravimetric (DTG) analyses of the pine wood chips and biochars (Fig. S1) were conducted with a thermal analyzer (TGA/DSC3+) under nitrogen atmosphere by heating the samples from room temperature to 900 °C (10 °C/min). Elemental (C, N, H) analyses were conducted using an EA1112 CHN elemental analyzer (Thermo Finnigan) (Table 1). The ash content was measured by heating biochars at 800 °C for 1 h (Table 1) (Yang et al. 2016). The O content was calculated by mass difference (Table 1) (Yang et al. 2018). The pore size distributions and surface characteristics of biochars were calculated with a physisorption analyzer (Quantachrome, AUTOSORB AS-1) using the N2 adsorption method at 77 K (Lillo-Rodenas et al. 2005; Yang et al. 2018) (Fig. S2). The specific surface area, micropore surface area ($A_{\text{mic}}$), total pore volume ($V_{\text{total}}$) and the micropore volume ($V_{\text{mic}}$) were measured based on N2 adsorption isotherms (Table 2) (Zhu et al. 2021). The degree of graphitization of biochars was evaluated by Raman spectroscopy (Zhu et al. 2021). Raman measurements of biochars were conducted in the range of 400–2400 cm$^{-1}$ using a laser confocal Raman spectrometer (LabRAM HR evolution) with a Nd-YAG laser beam at 532 nm. Before the N2 adsorption and Raman spectroscopy tests, all samples were dried at 105 °C for 24 h. Solid-state $^{13}$C direct polarization/magic angle spinning (DP/MAS) nuclear magnetic resonance (NMR) spectra of biochars (Fig. S3) were obtained at a frequency of 75 MHz using a Bruker Avance 400 MHz NMR spectrometer (Karlsruhe, Germany) and used to determine the aromaticity of biochars (Cao et al. 2012; McBeath et al. 2011). Biochars were embedded in spur resin and heated at 70 °C for 10 h for the cross-sectional transmission electron microscopy (TEM, JEM1230) observation. Before TEM observation, biochars were cut into sections with a thickness of approximately 90 nm by ultramicrotome (Leica, EMUC7) (Zhu et al. 2021).

2.3 Kinetic sorption experiments

1,3,5-Trinitrobenzene (wetted with 40% water), purchased from Tokyo Chemical Industry Co. and used as received, was selected as the sorbate. Kinetic sorption experiments of 1,3,5-trinitrobenzene by biochars were conducted at 25 ± 1 °C using 8 mL vials. 1,3,5-Trinitrobenzene was dissolved in a background solution containing 0.01 mol/L CaCl2 and 200 mg/L NaN3 (as a bioinhibitor) in deionized water. The initial concentration of 1,3,5-trinitrobenzene was 132 mg/L. The vials were sealed with screw caps and placed on a shaker
at 150 rpm for 15 min to 120 days. Then, the mixtures were filtered to obtain the supernatants for measuring the concentrations of 1,3,5-trinitrobenzene by a UV spectrophotometer (Shimadzu, UV-2450, Tokyo, Japan) at 228 nm. Controls consisting of 1,3,5-trinitrobenzene solutions without biochars and of background solutions with biochars were prepared. The concentration loss of 1,3,5-nitrobenzene during the experiment was less than 4%. Therefore, the adsorbed solute concentration of 1,3,5-trinitrobenzene was directly calculated by sorbate mass difference.

2.4 Data analysis

The sorption kinetic curves were fitted by pseudo-first-order (PFO) (Eq. 1) and pseudo-second-order (PSO) (Eq. 2) models to quantify the adsorption behavior (Jiang et al. 2020).

\[
\ln(q_e - q_t) = \ln q_e - k_1 t
\]

(1)

\[
\frac{t}{q_t} = \frac{1}{k_2(q_e)^2} + \frac{t}{q_e}
\]

(2)

where \(q_e\) (mg/g) is the equilibrium sorption amount, and \(q_t\) (mg/g) is the amount of adsorbed 1,3,5-trinitrobenzene at given time (day). The \(k_1\) (day\(^{-1}\)) and \(k_2\) (g/(mg day)) are the PFO and PSO constants, respectively.

Furthermore, the sorption process has been widely reported to correspond to a diffusion process (Cao et al. 2012; Chen et al. 2012, 2017; McBeath et al. 2011) and well fitted by the intraparticle diffusion model (Weber-Morris (W-M) model) to identify the mass transfer process and dynamic sorption mechanism (Jiang et al. 2020; Qu et al. 2021; Zhu et al. 2021). The diffusion process can be divided into different stages to explore the fast and slow sorption processes according to the subsections of the fitting results for the kinetic curves (Jiang et al. 2020; Qu et al. 2021). The time corresponding to the intersection of the last two stages is defined as the equilibrium time (Zhu et al. 2021).

Herein, sorption kinetic curves of 1,3,5-trinitrobenzene on biochars produced from 200 to 700 °C were fitted by the W-M model (Eq. 3).

\[
q_t = k_{ip} \times t^{0.5} + C
\]

(3)

where, \(t\) (day) is the sorption time; \(q_t\) (mg/g) is the sorption amount at the given time; \(k_{ip}\) (mg/(g·day\(^{0.5}\))) is the constant related to the diffusion rate; and \(C\) (mg/g) is the parameter related to the diffusion thickness of the boundary layer.

3 Results and discussion

3.1 Sorption kinetic curves and equilibrium time on biochars

The sorption equilibrium times were 1 day for W200, 14 days for W250, 99 days for W300, 107 days for W350, 45 days for W400, 13 days for W450, 6 days for W550, and 5 days for W700 (Fig. 1, Fig. S4). As such, with increasing pyrolytic temperature, the sorption equilibrium time of 1,3,5-trinitrobenzene increased on biochars produced from 200 to 350 °C, but decreased on biochars produced from 400 to 700 °C. In addition to the sorption equilibrium time, the sorption rate is an important factor for understanding sorption efficiency (Chen et al. 2012; Pignatello and Xing 1996). Sorption kinetic curves of 1,3,5-trinitrobenzene were fitted by PFO and PSO models to quantify the adsorption behavior (Table 3 and Fig. S5). Furthermore, the W-M model was employed to further identify the mass transfer stages and dynamic sorption mechanism (Table 3 and Fig. 1). The sorption process of 1,3,5-trinitrobenzene on biochars produced from different biomasses at 700 °C can be divided into three stages.

### Table 1 Selected physical–chemical properties of biochars

| Biochars | C (%) | N (%) | H (%) | O (%) | Ash (%) | H/C | O/C | (N + O)/C | \(I_d/I_G\) | \(F_{aco}\) |
|----------|-------|-------|-------|-------|---------|-----|-----|-----------|----------|--------|
| W200     | 49.93 | 0.02  | 6.28  | 43.48 | 0.29    | 1.51| 0.65| 0.65      | –        | 0.38   |
| W250     | 56.62 | 0.02  | 5.53  | 36.81 | 1.02    | 1.17| 0.49| 0.49      | –        | 0.60   |
| W300     | 68.32 | 0.05  | 4.24  | 26.88 | 0.51    | 0.74| 0.30| 0.30      | 0.51     | 0.74   |
| W350     | 67.72 | 0.07  | 4.09  | 26.45 | 1.67    | 0.72| 0.29| 0.29      | 0.61     | 0.81   |
| W400     | 73.09 | 0.06  | 3.20  | 23.05 | 0.60    | 0.52| 0.24| 0.24      | 0.68     | 0.89   |
| W450     | 72.92 | 0.09  | 3.47  | 21.82 | 1.71    | 0.57| 0.22| 0.23      | 0.72     | 0.90   |
| W550     | 84.56 | 0.10  | 2.70  | 11.95 | 0.69    | 0.38| 0.11| 0.11      | 0.79     | 0.92   |
| W700\(^a\) | 84.70 | 0.32  | 1.46  | 12.07 | 1.45    | 0.21| 0.11| 0.11      | 0.96     | 0.84   |

\(^a\)W700: data of elemental analysis obtained from Yang et al. 2018. H/C: atomic ratio of hydrogen to carbon; O/C: atomic ratio of oxygen to carbon; (N + O)/C: atomic ratio of the sum of nitrogen and oxygen to carbon; \(I_d/I_G\): fraction of D band to G band in Raman spectroscopy; \(F_{aco}\): detection of Raman spectra was failed on W200 and W250 due to the low degree of graphitization; total carbon in solid state \(^{13}\)C DP/MAS NMR analysis

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Fig. 2 and Table 3. The sorption kinetics parameters are shown in Table 1, and W300 and W350 could be separated into only two stages for W400 and W450, with the complete decomposition and carbonization of hemicellulose and cellulose (Fig. S1), the fraction of aromatic carbon was more than 80% (Table 1). Therefore, pore diffusion rather than slow matrix diffusion dictated the adsorption on W400 and W450. With increasing preparation temperature, the number of functional groups on biochar decreases sharply (Table 1 and Fig. S3), eventually leading to the formation of a stable graphitized biochar structure (Keiluweit et al. 2010). Therefore, for W550 and W700, the fast adsorption of organic compounds was attributed to the strong adsorption in pores (Yang and Xing 2010), which is in conformity with other porous materials (Chen et al. 2012; Yang and Xing 2010). Similar to naphthalene and carbamazepine (Chen et al. 2012, 2017), the sorption equilibrium time of 1,3,5-trinitrobenzene on biochars produced from 200 to 700 °C increased with increasing condensation degree of biochars and then decreased with increasing porosity of biochars. Therefore, the sorption efficiency of organic compounds on biochars produced at moderate temperatures (e.g., 350 °C) was worse than that on biochars produced at relatively low (e.g., 250 °C) and relatively high temperatures (e.g., 550 °C) because of the lower sorption amount or longer sorption equilibrium time (Fig. 1).

### 3.2 Influence of biochar properties on sorption equilibrium time

The TG curves of W200 and wood chips were almost overlapped (Fig. S1a), indicating that the pyrolysis degree of W200 was very low. Therefore, W200 was almost completely composed of uncarbonized biopolymers (hemicellulose, cellulose, and lignin). The oxygen-containing groups of uncarbonized biopolymers are hydrophilic and can interact with water to loosen the partition matrix (Greenberg et al. 2005; Hunter et al. 1996; Pignatello and Xing 1996; Sander and Pignatello 2009). The sorption equilibrium time of naphthalene on biochar produced at 350 °C was 36 days. The longer equilibrium time of 1,3,5-trinitrobenzene might be attributed to the stronger diffusion hindrance caused by its larger molecular size than naphthalene (Yang et al. 2018). On the other hand, a long-term diffusion process for organic compounds was observed in soil adsorbents (Greenberg et al. 2005; Hunter et al. 1996; Pignatello and Xing 1996; Sander and Pignatello 2009) due to the slow diffusion in condensed soil organic matter (SOM) structures. The sorption equilibrium time of 1,4-dichlorobenzene in soil was 107 days (Sander and Pignatello 2009). The sorption equilibrium time of pyrene in lake sediments was 183 days (Pignatello and Xing 1996). SOM has been described as having two phases of rubbery and glassy polymers, where diffusion is fast through the rubbery (loose) stage and slow through the glassy (condensed) stage (Hunter et al. 1996; Pignatello and Xing 1996). The long-term diffusion of organic compounds in soil can also be attributed to the slow matrix deformation.

| Biochars | $SA$ (m$^2$·g$^{-1}$) | $A_{micro}$ (m$^2$·g$^{-1}$) | $V_{total}$ (cm$^3$·g$^{-1}$) | $V_{micro}$ (cm$^3$·g$^{-1}$) | $R_{micro}$ (%) |
|----------|-----------------|------------------|-------------------|-----------------|----------------|
| W200     | 0.877           | 0.0460           | 0.006             | 0.0004          | 5.0            |
| W250     | 0.649           | 0.132            | 0.002             | 0.0003          | 20             |
| W300     | 0.911           | 0.743            | 0.005             | 0.0004          | 82             |
| W350     | 0.478           | 0.467            | 0.003             | 0.0001          | 98             |
| W400     | 65.9            | 43.0             | 0.045             | 0.0280          | 65             |
| W450     | 106             | 85.0             | 0.058             | 0.0440          | 80             |
| W550     | 388             | 319              | 0.193             | 0.1600          | 82             |
| W700     | 562             | 459              | 0.286             | 0.2270          | 82             |

$SA$: specific surface area of biochars probed by N$_2$ adsorption; $A_{micro}$: micropore surface area probing by N$_2$ adsorption; $V_{total}$: total pore volume probed by N$_2$ adsorption; $V_{micro}$: micropore volume probed by N$_2$ adsorption; $R_{micro}$: the ratio of micropore surface area to specific surface area.

(i.e., fast adsorption, slow diffusion, and adsorption equilibrium) (Zhu et al. 2021). Herein, the sorption kinetic curves of 1,3,5-trinitrobenzene on W400, W450, W550, and W700 could be divided into three stages and well fitted by the W-M model (Fig. 1). However, the sorption kinetics of 1,3,5-trinitrobenzene on W200, W250, W300, and W350 could be separated into only two stages (Fig. 1). The sorption kinetics parameters are shown in Fig. 2 and Table 3.
The pyrolysis degree of biochars produced at relatively low temperatures is not high enough to form an aromatic structure. Some humus-like substances were observed on biochars produced at relatively low temperatures (e.g., 300 °C) (Hameed et al. 2019). The components of biochar-derived dissolved organic matter (DOM) gradually changed from hydrophilic humic acid-like substances to highly aromatic hydrophobic substances as the pyrolysis temperature increased from 200 to 700 °C (Hameed et al. 2019). Therefore, similar to the diffusion mechanism of organic compounds in soils, the long-term diffusion process of organic compounds on biochars produced at relatively low temperatures (e.g., 300 °C and 350 °C) could be attributed to slow diffusion in condensed (e.g., matrix swelling) (Sander and Pignatello 2009). The pyrolysis degree of biochars produced at relatively low temperatures is not high enough to form an aromatic structure. Some humus-like substances were observed on biochars produced at relatively low temperatures (e.g., 300 °C) (Hameed et al. 2019). The components of biochar-derived dissolved organic matter (DOM) gradually changed from hydrophilic humic acid-like substances to highly aromatic hydrophobic substances as the pyrolysis temperature increased from 200 to 700 °C (Hameed et al. 2019). Therefore, similar to the diffusion mechanism of organic compounds in soils, the long-term diffusion process of organic compounds on biochars produced at relatively low temperatures (e.g., 300 °C and 350 °C) could be attributed to slow diffusion in condensed
humic acid-like substances and slow matrix deformation, too (Hunter et al. 1996; Pignatello and Xing 1996; Sander and Pignatello 2009).

### 3.3 Influence of biochar properties on the sorption process

In addition to the pyrolysis conditions affecting the features of wood polymers (e.g., hemicellulose, cellulose, and lignin), the fraction of aromatic carbon (F\text{aro}, aromaticity) sharply increased from 38% for W200 to 81% for W350, while it increased slowly from 89% for W400 to 92% for W550 (Fig. S6a). The decrease of F\text{aro} in W700 (Fig. S6a) might be caused by the broadening of the aromatic band, part of which is attributed to “oxygen-containing” functional groups (Cao et al. 2012; David et al. 2009). Furthermore, the surface area was almost undetectable on biochars produced from 200 to 350 °C, but increased rapidly on biochars produced from 400 to 700 °C (Table 2). In addition, no pore structure was observed on W300 and W350 from the TEM images (Fig. 3). However, similar to W700 (Yang et al. 2018; Zhu et al. 2021), abundant slit-shaped pores were observed on W550 (Fig. 3). With increasing preparation temperature, the content of C elements on biochars increased, while the contents of O and H elements gradually decreased (Table 1). The decreased H/C, O/C, and (O + N)/C ratios implied that the amorphous carbon was gradually transformed into aromatic carbon with increasing pyrolytic temperature (Keiluweit et al. 2010). A highly aromatic structure was formed as indicated by the low H/C ratio (i.e., 0.21 in W700). Similarly, in previous studies (Chen et al. 2008, 2012; David et al. 2009), the sorption mechanism of organic compounds on biochars transferred from partition (matrix diffusion) to adsorption/pore filling (pore diffusion) as the heat treatment temperature increased. Therefore, a multilevel pore structure was formed on biochars produced from 400 to 700 °C. That is, the sorption behavior of organic compounds on biochars produced from 200 to 350 °C is dominated by partition while that on biochars produced from 400 to 700 °C is dominated by adsorption/pore filling. The adsorption process in porous adsorbents is generally separated into film diffusion, intraparticle diffusion, and adsorption on active sites (Jiang et al. 2020). Accordingly, the sorption process in matrix sorbents should be separated into film diffusion, matrix diffusion, and sorption on active sites.

The PFO and PSO model were employed to quantify the adsorption behavior of 1,3,5-trinitrobenzene on biochars. The PSO model gives better fitting to adsorption data than PFO model with much higher correlation coefficients (Table 3). The sorption rates of 1,3,5-trinitrobenzene obtained by PFO and PSO fits on biochars produced at moderate temperatures were slower than biochars produced at relatively low and relatively high temperatures (Table 3). The slow sorption rate can be attributed to the condensed structures of biochar. To further identify dynamic sorption mechanism, the W-M model was employed to evaluate the influence of mass transfer process and rate-limiting stage (Fig. 1). The uptake of 1,3,5-trinitrobenzene on biochars produced from 200 to 350 °C was dominated by matrix diffusion only. Since the multilevel pore structure was formed on biochars produced from 400 to 700 °C as shown by the pore structure analysis (Table 2), the diffusion of 1,3,5-trinitrobenzene from liquid film to pore walls was separated into two stages (fast outer diffusion and slow intraparticle diffusion) on W400, W450, W550, and W700. The PFO and PSO models were fitted well for the sorption in which only one step was dominated for the whole process as shown by the better fitting results for biochars produced at relatively low temperatures than that on biochars produced at relatively high temperatures (Table 3). However, the W-M model was fitted well for the sorption in which one step or several steps were dominated for the whole process both (Table 3).

The adsorption of 1,3,5-trinitrobenzene onto adsorbent exterior surface of biochars (outer diffusion) was fast and represented by the $k_{ip1}$ from W-M model. The transport of 1,3,5-trinitrobenzene from the biochars exterior surface to the pores of biochars internal structure (intraparticle diffusion) was slow and represented by the $k_{ip2}$ from W-M model. Accordingly, the sorption stages corresponding to the sorption kinetic curves of 1,3,5-trinitrobenzene on W200, W250, W300, and W350 suggest matrix diffusion (matrix partition) and diffusion equilibrium, while on W400, W450, W550, and W700 suggest fast outer diffusion (fast adsorption), slow intraparticle diffusion (slow pore diffusion), and diffusion equilibrium (Fig. 1) (Zhu et al. 2021). Surface oxygen-containing functional groups were observed on biochars (Table 1 and Fig. S3). However, in previous studies (Sander and Pignatello 2007; Zhu et al. 2021), no desorption hysteresis of aromatic organic compounds with nitro groups on biochars was observed, suggesting that the uptake of aromatic organic compounds with nitro groups on biochars was dominated by physisorption rather than chemisorption.
The sorption kinetics results for biochars produced from 200 to 350 °C and 400 to 700 °C were considered to explain the effects of partition and adsorption on the sorption process, respectively. In addition to the porosity, the condensation is an important feature determining the sorption rate of organic compounds (Chen et al. 2012, 2017; Zhu et al. 2021) because the sorption of organic compounds on condensed carbon is slower than that on loose carbon (Chen et al. 2017). The aromatic condensation degree and the aromaticity of biochars can be directly explored using NMR methodology or Raman spectroscopy (Brewer et al. 2009; Cao et al. 2012; McBeath et al. 2011; Takahashi et al. 2002; Xiao and Chen 2017; Yang et al. 2021; Zhu et al. 2021). As shown in the Table 1, the fraction of aromatic carbon (F_{arom}, aromaticity) increased with increasing temperature in the range of 200–700 °C. An increase in the aromaticity of biochars can promote adsorption by enhancing the adsorption affinity for hydrophobic organic compounds, especially by enhancing π-π interactions for aromatic organic compounds (Yang et al. 2021). The integrated intensity ratio of the D-band (1350 cm⁻¹) to the G-band (1580 cm⁻¹) (I_D/I_G) of Raman spectra usually reflects the degree of defects and disorder of carbon materials (Zhu et al. 2021). Detection of Raman spectra failed on W200 and W250 due to the low degree of graphitization. However, a good relationship between

![Cross-sectional TEM images of W300 (a, b), W350 (c, d), and W550 (e, f)](image_url)

Fig. 3 Cross-sectional TEM images of W300 (a, b), W350 (c, d), and W550 (e, f)
the $I_D/I_G$ values of biochars and preparation temperature was observed (Fig. S6b), indicating gradually increasing defects on biochars with preparation temperature. Therefore, the fast diffusion dominated by graphite defects was more significant on biochars produced at higher temperatures (Zhu et al. 2021). Based on the variation trend in $I_D/I_G$ values with increasing preparation temperature, biochars produced at higher temperatures had more graphite defects, which may explain the pore formation and the gradually increasing surface area (Keiluweit et al. 2021). Therefore, an increase in defects can provide fast diffusion channels for the diffusion of organic compounds in the pores of biochars to enhance adsorption.

### 3.4 Influence of biochar properties on sorption rates

The sorption equilibrium time of 1,3,5-trinitrobenzene on W300 (99 days), W350 (107 days) and W400 (45 days) was more than 30 days. The mechanism of long-term diffusion of organic compounds on biochars was further explored by the analysis of rate-limiting stages and diffusion rates. It was observed that the plots of W-M model fitted kinetic curves did not pass through the origin, suggesting that the intraparticle diffusion is not the sole rate-limiting stage. However, the intraparticle diffusion rate ($k_{ip1}$) of 1,3,5-trinitrobenzene was significantly slower than the outer diffusion rate ($k_{ip2}$) on W400, W450, W550, and W700 (Table 3), suggesting that the intraparticle diffusion stage played a predominant role in controlling the adsorption process. Therefore, the matrix diffusion rate ($k_{mp}$) on biochars produced from 200 to 350 °C and the intraparticle diffusion rate ($k_{ip2}$) on biochars produced from 400 to 700 °C of 1,3,5-trinitrobenzene were used to explore the long-term kinetics mechanism. The decrease of biochars H/C ratios was caused by the dehydration and polycondensation of biomass polymers (Keiluweit et al. 2010). A linear positive relationship between the matrix diffusion rate of 1,3,5-trinitrobenzene on biochars produced from 200 to 350 °C and the H/C ratios of biochars was observed (Fig. 4a), suggesting that the inhibition of partition caused by the condensed biochar matrix on biochars could be attributed to the dehydration and polycondensation. The adsorption rate of organic compounds on BC700 increased with increasing $I_D/I_G$ value because graphite defects can provide fast diffusion channels for the diffusion of organic compounds in the pores of biochars to enhance adsorption (Zhu et al. 2021). Herein, due to the absence of $I_D/I_G$ values for of W200 and W250, the sorption rates of 1,3,5-trinitrobenzene were not analyzed in conjunction with the $I_D/I_G$ values of biochars produced from 200 to 350 °C. Similarly, a linear positive relationship between the diffusion rates (outer diffusion rate and intraparticle diffusion rate) of 1,3,5-trinitrobenzene on biochars produced from 400 to 700 °C and the $I_D/I_G$ values of biochars was observed (Fig. 4b, c), suggesting that an increase in graphite defects of biochars could promote the sorption of organic compounds by increasing the number of fast diffusion channels in biochars with pore structures. Therefore, sorption process of 1,3,5-trinitrobenzene on biochars produced from 200 to 350 °C was dominated by the condensation of biochar matrix, and on biochars produced from 400 to 700 °C was dominated by graphite defects in the biochars.

The increasing of surface area of biochars produced from 400 to 700 °C could provide more sorption sites to improve the adsorption efficiency, as shown by the higher sorption capacity of 1,3,5-trinitrobenzene on the biochars with larger surface areas on W400, W450, W550, and W700 (Table 2 and Fig. 1). Furthermore, the pyrolysis of pine wood under 350 °C mainly involves biomass depolymerization and fragmentation reactions (Keiluweit et al. 2021). The graphitization and aromatic condensation of biochars mainly occur on biomass fragments. Partition in the uncarbonized organic matter of biochars, rather than the aromatic fragments of biochars, dominated the sorption process. Therefore, although the aromaticity of biochars produced from 200 to 350 °C increased according to $F_{aro}$, it was not suitable for sorption kinetics analysis of biochars produced from 200 to 350 °C.

In previous study (Yang et al. 2021), π–π interactions, one of the main adsorption affinities for the adsorption of aromatic compounds on biochars, could be significantly enhanced by increasing the aromaticity of biochars or the polarizability of organic compounds. Herein, for biochars produced from 400 to 700 °C, on which adsorption/pore filling dominates the uptake of organic compounds on biochars, the increase in aromaticity could promote the adsorption of aromatic compounds by the enhancement of π–π interactions.

Porous structures could facilitate the adsorption of organic compounds on adsorbents by increasing the adsorption affinity (Farrell and Reinhard 1994; Lian et al. 2020; Nguyen et al. 2007; Xiao and Pignatello 2015, 2016; Yang and Xing 2010; Zhu et al. 2021). However, the molecular sieving effect plays an important role in the pore filling process (Lattao et al. 2014; Takahashi et al. 2002; Xiao and Pignatello 2016; Zhu and Pignatello 2005; Zhu et al. 2005). Steric hindrance increases with decreasing pore size and becomes stronger as pore size approaches molecular dimensions (Farrell and Reinhard 1994). For example, steric hindrance for naphthalene increases exponentially with the small micropores fraction on biochars (Lattao et al. 2014). The pore diffusion rate of triazine herbicides on a temperature series (300–700 °C) of hardwood biochars increased with the fraction of mesopores (Nguyen et al. 2007). The pore diffusion rate of 1,3,5-trinitrobenzene on BC700 increased with increasing pore size (Zhu et al. 2021). Herein, the surface area was almost undetectable on biochars produced from 200 to 350 °C but increased rapidly on biochars.
produced from 400 to 700 °C (Table 2). Therefore, the sorption equilibrium of 1,3,5-trinitrobenzene on W200, W250, W300, and W350 was dominated by only matrix diffusion. The variation in the equilibrium time of 1,3,5-trinitrobenzene on biochars caused by partition matrix condensation from W200 (1 day) to W350 (107 day) (a difference of 106 days) was more significant than that caused by biochar porosity from W400 (45 day) to W700 (5 day) (a difference of 40 days) because pore structure can promote the sorption of organic compounds on biochars but micropores can reduce the adsorption rate because of the steric hindrance effect (Zhu et al. 2021). In previous studies (Yang et al. 2018; Zhu et al. 2021), the molecular sieving effect of micropores was significant for 1,3,5-trinitrobenzene and other organic compounds with large molecular sizes (phenanthrene and pyrene). Herein, the fraction of micropores of W400, W450, W550, and W700 did not change significantly (Table 2). Therefore, the variation in sorption equilibrium time for 1,3,5-trinitrobenzene on biochars was dominated by the condensation and porosity of biochars, but not the steric hindrance. As such, the sorption equilibrium time of 1,3,5-trinitrobenzene increased on W200, W250, W300, and W350 with a surface area of almost zero, but decreased on W400, W450, W550, and W700 with the gradual increase in the surface area of biochars (Tables 2 and 3). The sorption rates of 1,3,5-trinitrobenzene decreased on W200, W250, W300, and W350 and then increased on W400, W450, W550, and W700 with increasing biochar preparation temperature regularly (Fig. 2). The sorption efficiency of 1,3,5-trinitrobenzene on biochars produced at moderate temperatures (i.e., 300 and 350 °C) was worse than that on biochars produced at relatively low (i.e., 200 and 250 °C) and relatively high temperatures (i.e., 550 and 700 °C) because of the lower sorption capacity and slower sorption rate (Figs. 1 and 5). Therefore, biochars produced at relatively low temperatures, with a high sorption rate but low sorption capacity (Figs. 1 and 5), could be used to rapidly remove 1,3,5-trinitrobenzene at low concentrations from wastewater. Biochars produced at relatively high temperatures, with a high adsorption capacity and adsorption rate (Figs. 1 and 5), could be used to rapidly remove the 1,3,5-trinitrobenzene at high concentrations from wastewater.

**4 Conclusion**

This study reveals the diffusion behavior of 1,3,5-trinitrobenzene on biochars produced at different temperatures. As the heat treatment temperature increased, the sorption equilibrium time of 1,3,5-trinitrobenzene increased on biochars produced from 200 to 350 °C due to slow diffusion in the condensed matrix and then decreased on biochars.
produced from 400 to 700 °C because of fast adsorption in pores. Long-term diffusion, the rate-limiting step in the biodegradation and transport of organic contaminants, was observed on W300 (99 days), W350 (107 days) and W400 (45 days) for 1,3,5-trinitrobenzene. The sorption rates of 1,3,5-trinitrobenzene decreased on biochars produced from 200 to 350 °C with the decrease in the H/C ratios of biochars, suggesting that the diffusion hindrance of organic compounds in the partition matrix could be explored in terms of H/C ratios for biochars. The adsorption rates of 1,3,5-trinitrobenzene increased on biochars produced from 400 to 700 °C with increasing I_D/I_G values of biochars, because graphite defects on biochars can promote the adsorption of organic compounds by increasing the number of fast diffusion channels. Thus, the sorption efficiency of organic compounds with relatively large molecular sizes on biochars produced at moderate temperatures was worse than that on biochars produced at relatively low and relatively high temperatures because of the lower sorption capacity and slower sorption rate. While biochars are potential sorbents for mitigating the plant uptake of contaminants or removing contaminants from wastewater, the findings of this work indicate that synthesizing biochars at different temperatures with desirable structures and properties could further alter their properties and performance for these potential application scenarios.

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Availability of data and materials The authors declare that the data supporting the findings of this study are available within the article and its additional information files.

Declarations

Competing interests The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Brewer CE, Schmidt-Rohr K, Satrio JA, Brown RC (2009) Characterization of biochar from fast pyrolysis and gasification systems. Environ Prog Sustain 28:386–396. https://doi.org/10.1002/ep.10378

Cao XY, Piglatello JJ, Li Y, Lattao C, Chappell MA, Chen N, Miller LF, Mao JD (2012) Characterization of wood chars produced at different temperatures using advanced solid-State 13C NMR spectroscopic techniques. Energy Fuel 26:5983–5991. https://doi.org/10.1021/ef300947s

Chen BL, Zhou DD, Zhu LZ (2008) Transitional adsorption and partition of nonpolar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures. Environ Sci Technol 42:5137–5143. https://doi.org/10.1021/es8002684

Chen ZM, Chen BL, Chiu CT (2012) Fast and slow rates of naphthalene sorption to biochars produced at different temperatures. Environ Sci Technol 46:11104–11111. https://doi.org/10.1021/es302345e

Chen J, Zhang D, Zhang H, Ghosh S, Pan B (2017) Fast and slow adsorption of carbamazepine on biochar as affected by carbon structure and mineral composition. Sci Total Environ 579:598–605. https://doi.org/10.1016/j.scitotenv.2016.11.052

Chun Y, Sheng GY, Chiu CT, Xing BS (2004) Compositions and sorptive properties of crop residue-derived chars. Environ Sci Technol 38:4649–4655. https://doi.org/10.1021/es035034w

David K, Pu YQ, Foston M, Muzzy J, Ragauskas A (2009) Cross-polarization/magic angle spinning (CP/MAS) 13C nuclear magnetic resonance (NMR) analysis of chars from alkaline-treated pyrolyzed softwood. Energ Fuel 23:498–501. https://doi.org/10.1021/ef8004527

Fig. 5 Sorption isotherms of 1,3,5-trinitrobenzene on biochars
Farrell J, Reinhard M (1994) Desorption of halogenated organics from model solids, sediments, and soil under unsaturated conditions. 2. kinetics. Environ Sci Technol 28:63–72. https://doi.org/10.1021/es00050a010

Greenberg MS, Burton GA, Landrum PF, Leppänen MT, Kukkonen JVK (2005) Desorption kinetics of fluoroanthene and trifluralin from lake Huron and lake Erie, USA, sediments. Environ Toxicol Chem 24:31–39. https://doi.org/10.1002/etc.059R.1

Hameed R, Cheng LL, Yang K, Fang J, Lin DH (2019) Endogenous release of metals with dissolved organic carbon from biochar: effects of pyrolysis temperature, particle size, and solution chemistry. Environ Pollut 255:113253. https://doi.org/10.1016/j.envpol.2019.113253

Hunter MA, Kan AT, Tomson MB (1996) Development of a surrogate sediment to study the mechanisms responsible for adsorption/desorption hysteresis. Environ Sci Technol 30:2278–2285. https://doi.org/10.1021/es950639g

Jaffe R, Ding Y, Niggemann J, Vahatalo AV, Stubbins A, Spencer Hunter MA, Kan AT, Tomson MB (1996) Development of a surrogate sediment to study the mechanisms responsible for adsorption/desorption hysteresis. Environ Sci Technol 30:2278–2285. https://doi.org/10.1021/es950639g

Jiang D, Yang J, Wang DH (2020) Green carbon material for organic contaminants adsorption. Langmuir 36:3141–3148. https://doi.org/10.1021/acs.langmuir.9b03811

Keiluweit M, Nico PS, Johnson MG, Kleber M (2010) Dynamic molecular structure of plant biomass-derived black carbon (biochar). Environ Sci Technol 44:1247–1253. https://doi.org/10.1021/es9031449

Kraeling MEK, Reddy G, Bronaugh RL (1998) Pervious adsorption of trinitrobenzene: animal models for human skin. J Appl Toxicol 18:387–392. https://doi.org/10.1002/(SICI)1099-1263(199811/12)12:6<387::AID-JAT526>3.0.CO;2-W

Lattao C, Cao XY, Mao JD, Schmidt-Rohr K, Pignatello JJ (2014) Influence of molecular structure and adsorbent properties on sorption of organic compounds to a temperature series of wood chars. Environ Sci Technol 48:4790–4798. https://doi.org/10.1021/es400909q

Lehmann J (2007) A handful of carbon. Nature 447:143–144. https://doi.org/10.1038/447143a

Liao F, Yu WC, Zhou QX, Gu SG, Wang ZY, Xing BS (2020) Size matters: nano-biochar triggers decomposition and transformation inhibition of antibiotic resistance genes in aqueous environments. Environ Sci Technol 54:8821–8829. https://doi.org/10.1021/acs.est.0c02227

Lillo-Rodenas MA, Cazorla-Amoros D, Linares-Solano A (2005) Behaviour of activated carbons with different pore size distributions and surface oxygen groups for benzene and tolune adsorption at low concentrations. Carbon 43:1758–1767. https://doi.org/10.1016/j.carbon.2005.02.023

Liu XD, Yu WY, Zhang Y, Xue WM, Yu WT, Xiong Y, Ma XJ, Chen Y, Yuan Q (2002) Characterization of structure and diffusion behaviour of Ca-alginate beads prepared with external or internal calcium sources. J Microencapsulation 19:775–782. https://doi.org/10.1080/0265204021000022743

Maeda T, Nakamura R, Kadokami K, Ogawa HI (2010) Relationship between mutagenicity and reactivity or biodegradability for nitroaromatic compounds. Environ Toxicol Chem 26:237–241. https://doi.org/10.1002/etc.0198R.1.1

McBeath AV, Smernik RJ, Schneider MPW, Schmidt MWI, Plant EL. (2011) Determination of the aromaticity and the degree of aromatic condensation of a thermosquence of wood charcoal using NMR. Org Geochem 42:1194–1202. https://doi.org/10.1016/j.orggeochem.2010.08.008

Nguyen TH, Cho HH, Poster DL, Ball WP (2007) Evidence for a pore-filling mechanism in the adsorption of aromatic hydrocarbons to a natural wood char. Environ Sci Technol 41:1212–1217. https://doi.org/10.1021/es0617845

Ni JZ, Pignatello JJ, Xing BS (2011) Adsorption of aromatic carboxylate ions to black carbon (biochar) is accompanied by proton exchange with water. Environ Sci Technol 45:9240–9248. https://doi.org/10.1021/es201859J

Pignatello JJ, Xing BS (1996) Mechanisms of slow sorption of organic chemicals to natural particles. Environ Sci Technol 30:1–11. https://doi.org/10.1021/es940683g

Qu JH, Liu Y, Cheng L, Jiang Z, Zhang GS, Deng FX, Wang L, Han W, Zhang Y (2021) Green synthesis of hydrophilic activated carbon supported sulfide nZVI for enhanced Pb(II) scavenging from water: characterization, kinetics, isotherms and mechanisms. J Hazard Mater 403:123607. https://doi.org/10.1016/j.jhazmat.2020.123607

Reddy G, Reddy TV, Choudhury H, Bernard DF, Leach GJ (1997) Assessment of environmental hazards of 1,3,5-trinitrobenzene. J Toxicol Environ Health 52:447–460. https://doi.org/10.1080/00984109708940705

Sander M, Pignatello JJ (2007) On the reversibility of sorption to black carbon: distinguishing true hysteresis from artificial hysteresis caused by dilution of a competing adsorbate. Environ Sci Technol 41:843–849. https://doi.org/10.1021/es061346y

Sander M, Pignatello JJ (2009) Sorption irreversibility of 1,4-dichlorobenzene in two natural organic matter-rich geosorbents. Environ Toxicol Chem 28:447–457. https://doi.org/10.1897/08-128.1

Takahashi R, Sato S, Sodesawa T, Nishida H (2002) Effect of pore size on the liquid-phase pore diffusion of nickel nitrate. Phys Chem Chem Phys 4:3800–3805. https://doi.org/10.1039/B202024F

Thompson KA, Shimabuku KK, Kearns JP, Knappe DRU, Summers RS, Cook SM (2016) Environmental comparison of biochar and activated carbon for tertiary wastewater treatment. Environ Sci Technol 50:11253–11262. https://doi.org/10.1021/acs.est.6b03239

Wu WH, Chen W, Lin DH, Yang K (2012) Influence of surface oxidation of multiwalled carbon nanotubes on the adsorption affinity and capacity of polar and nonpolar organic compounds in aqueous phase. Environ Sci Technol 46:5446–5454. https://doi.org/10.1021/es3004848

Xiao X, Chen BL (2017) A direct observation of the fine aromatic clusters and molecular structures of biochars. Environ Sci Technol 51:5473–5482. https://doi.org/10.1021/acs.est.6b06030

Xiao F, Pignatello JJ (2015) Interactions of triazine herbicides with biochar: steric and electronic effects. Water Res 80:179–188. https://doi.org/10.1016/j.watres.2015.04.040

Xiao F, Pignatello JJ (2016) Effects of post-pyrolysis air oxidation of biomass chars on adsorption of neutral and ionizable compounds. Environ Sci Technol 50:6276–6283. https://doi.org/10.1021/acs.est.6b00362

Yang K, Xing BS (2010) Adsorption of organic compounds by carbon nanomaterials in aqueous phase: Polanyi theory and its application. Chem Rev 110:5989–6008. https://doi.org/10.1021/cr100059s

Yang K, Yang JJ, Jiang Y, Wu WH, Lin DH (2016) Correlations and adsorption mechanisms of aromatic compounds on a high heat temperature treated bamboo biochar. Environ Pollut 210:57–64. https://doi.org/10.1016/j.envpol.2015.12.004

Yang K, Jiang Y, Yang JJ, Lin DH (2018) Correlations and adsorption mechanisms of aromatic compounds on biochars produced from various biomass at 700 °C. Environ Pollut 233:64–70. https://doi.org/10.1016/j.envpol.2017.10.035

Yang JG, Pignatello JJ, Yang K, Wu WH, Lu GL, Zhang LJ, Yang C, Dang Z (2021) Adsorption of organic compounds by biomass chars: direct role of aromatic condensation (ring cluster size)
revealed by experimental and theoretical studies. Environ Sci Technol 55:1594–1603. https://doi.org/10.1021/acs.est.0c04852
Yu X, Pan L, Ying G, Kookana RS (2010) Enhanced and irreversible sorption of pesticide pyrimethanil by soil amended with biochars. J Environ Sci (china) 22:615–620. https://doi.org/10.1016/S1001-0742(09)60153-4
Zheng W, Guo MX, Chow T, Bennett DN, Rajagopalan N (2010) Sorption properties of greenwaste biochar for two triazine pesticides. J Hazard Mater 181:121–126. https://doi.org/10.1016/j.jhazmat.2010.04.103
Zhu DQ, Pignatello JJ (2005) Characterization of aromatic compound sorptive interactions with black carbon (charcoal) assisted by graphite as a model. Environ Sci Technol 39:2033–2041. https://doi.org/10.1021/es0491376
Zhu DQ, Kwon S, Pignatello JJ (2005) Adsorption of single-ring organic compounds to wood charcoals prepared under different thermochemical conditions. Environ Sci Technol 39:3990–3998. https://doi.org/10.1021/es050129e
Zhu HX, Liu XY, Jiang Y, Zhang M, Lin DH, Yang K (2021) Time-dependent desorption of anilines, phenols, and nitrobenzenes from biochar produced at 700 °C: insight into desorption hysteresis. Chem Eng J 422:130584. https://doi.org/10.1016/j.cej.2021.130584

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