

Article

Addition of Carbonaceous Material to Aquatic Sediments for Sorption of Lindane and *p,p'*-Dichlorodiphenyldichloroethylene

Zhiyong Guo ¹, Tianyi Chen ¹, Xinzhou Wang ², Liwen Zhang ¹, Liting Wang ¹, Deming Dong ¹ and Xiuyi Hua ^{1,*}

¹ Key Laboratory of Groundwater Resources and Environment, Ministry of Education, Jilin Provincial Key Laboratory of Water Resources and Environment, College of New Energy and Environment, Jilin University, Changchun 130012, China; zyguo@jlu.edu.cn (Z.G.); chenty18@mails.jlu.edu.cn (T.C.); zhangliwen@jlu.edu.cn (L.Z.); wanglt17@mails.jlu.edu.cn (L.W.); dmdong@jlu.edu.cn (D.D.)

² Hebei Key Laboratory of Geological Resources and Environment Monitoring and Protection, Shijiazhuang 050021, China; wangxinzhou76@126.com

* Correspondence: huaxy@jlu.edu.cn; Tel./Fax: +86-0431-85168429

Received: 22 March 2019; Accepted: 22 April 2019; Published: 26 April 2019



Abstract: Isomers of hexachlorocyclohexanes (HCHs) and metabolites of dichlorodiphenyltrichloroethanes (DDTs) are still frequently detected worldwide in considerable amounts, even decades after their prohibition. Carbonaceous materials (CMs) have been shown to significantly reduce risks of propagation to humans by binding the hydrophobic organochlorine pesticides (OCPs) present in aquatic sediments. In the present study, black carbons extracted from natural sediments, and artificially produced black carbons, including black carbons by burning rice straw at 450 and 850 °C, and a commercial activated carbon were compared to investigate the factors affecting the sorption of γ -HCH (lindane) and *p,p'*-dichlorodiphenyldichloroethylene (*p,p'*-DDE) on CMs. The results indicated that when the proportion of CMs to total organic carbon (f_{CM}/f_{OC}) was greater than 0.35, CMs played a leading role in the sorption of lindane and *p,p'*-DDE by the sediments. The sorption contribution rate of CMs could reach up to 64.7%. When the ratio of f_{CM}/f_{OC} was less than 0.10, CMs played a minor role in the sorption. In addition, the nonlinearity of the sorption isotherms was strengthened with the increasing the proportion of CMs to total organic carbon. Our findings show that f_{CM}/f_{OC} value is a principal parameter for assessing the sorption capacity of sediments added by CMs for OCPs.

Keywords: organochlorine pesticide; hydrophobic organic compound; persistent organic pollutant; black carbon; activated carbon; rice straw

1. Introduction

Organochlorine pesticides (OCPs) are a class of persistent organic pollutants (POPs) used extensively from the 1940s through the 1960s in agriculture and mosquito control. Although they have been prohibited for over 40 years, they and their metabolites still persist, propagate in food chains and have adverse effects on aquatic organisms and human beings [1,2]. Hexachlorocyclohexanes (HCHs) and dichlorodiphenyltrichloroethanes (DDTs) are two classic OCPs that are frequently used as insecticides. Although they were banned in 1983 for agricultural use in China, they still pose a serious threat to human health and aquatic environment because of their historical use and reemissions [3–6]. Gamma-hexachlorocyclohexane (γ -HCH), also well known as lindane, is one typical isomer of HCHs. It has already been a global environmental problem because of historical use and strong persistence [7].

p,p'-dichlorodiphenyldichloroethylene (*p,p'*-DDE), one of the main metabolites of DDT, can exist for decades in soils and aquatic sediments and have adverse effects on humans and the environment [8–11].

Sorption is an important mechanism for the interaction between OCPs and natural solids in aquatic environments [12], and it is closely related to the physicochemical properties of solids. Sediment is one of the common natural solids in aquatic environment that can sorb OCPs. The sorption of OCPs by the sediments has already caused great concern because of its importance in the migration and transformation of OCPs [13–15]. Although many factors affect the distribution and sorption of OCPs, total organic matter content is one of the most important in this regard in the sediments [16].

Carbonaceous materials (CMs) are one of the main sources of total organic matter in aquatic sediments. Studies over the past two decades have shown that CMs have a key influence on the migration and transformation of organic pollutants in water [17,18]. Black carbon (BC), usually defined as a CM formed during the incomplete combustion of biomass, is one of the CMs typically found in natural sediments [19]. The possible sources of BC in the sediments (SC) are the burning of nearby agricultural waste, vehicle exhaust emissions, and the burning of fossil fuel [1], which cause the BC to have a more complicated composition. Comparatively speaking, artificially prepared CMs, such as activated carbon (AC) and the BC produced by burning rice straw at 450 (BC450) and 850 °C (BC850) have relatively simple composition. The differences of physicochemical properties between the four CMs make their sorption characteristics more different. However, studies on the factors affecting the sorption of OCPs on CMs by comparing CMs in natural sediments with artificially prepared CMs are relatively scarce.

The aims of this study were to investigate the effects of CMs on the sorption of lindane and *p,p'*-DDE by the sediments. Lindane and *p,p'*-DDE were selected as model OCPs; BC450, BC850, AC, and BC extracted from sediments were selected as model CMs. The physicochemical properties of CMs can have important effects on the sorption of sediments, therefore, these four CMs were compared to select the most suitable and typical one to investigate the effect of CMs on the sorption of lindane and *p,p'*-DDE by the sediments.

2. Materials and Methods

2.1. Materials

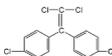
Surface sediments (5 cm in depth) were collected from the Songhua River in Northeastern China. A part of the sediments was freeze-dried and ground to pass through a 0.15 mm sieve for BC extraction. The extraction procedure of BC from sediments was referred by Lim et al. [20]. In brief, the procedure was as follows: (1) added 15 mL of 3 mol·L⁻¹ HCl to 3 g sediments, reacted for 24 h to remove carbonates; (2) added 20 mL of mixed solution of 10 mol·L⁻¹ HF and 1 mol·L⁻¹ HCl, reacted for 12 h to remove silicates; (3) added 15 mL of 10 mol·L⁻¹ HCl and reacted for 24 h to remove CaF₂; (4) added 20 mL of mixed solution of 0.1 mol·L⁻¹ K₂Cr₂O₇ and 2 mol·L⁻¹ H₂SO₄, reacted at 55 °C for 60 h to remove the active organic carbon; (5) dried at 60 °C in a drying oven to attain constant weight. The obtained residue comprised the BC samples, which was recorded as SC. The extracted samples were placed in a crucible and fired in a muffle furnace at 375 °C for 4 h. The BC contents recorded as f_{CM} were measured through determining the total organic carbon (TOC) contents of the residue.

Rice straws were collected from the riverine farmland of the Songhua River. The BC preparation from the rice straws was referred by Hsieh et al. [21]. The burning temperatures were 450 and 850 °C, and the BC produced under the two temperatures were recorded as BC450 and BC850, respectively. AC was purchased from Guangfu Technology Co. Ltd. (Tianjin, China, 2010). Lindane (99% purity) and *p,p'*-DDE (98% purity) were purchased from Dr. Ehrenstorfer GmbH (Augsburg, Germany, 2010). The basic physicochemical properties of lindane and *p,p'*-DDE are listed in Table 1. Methanol was used in the preparation of standards of lindane and *p,p'*-DDE. All of the other reagents and chemicals used were of analytical grade and purchased from Sinopharm Chemical Reagent Co., Ltd., Shanghai, China,

2010. The water used in the experiment was Milli-Q water. Chromosulfuric acid was used to clean the laboratory glassware.

The specific surface area (SSA), pore size, and TOC contents of the sediments and the four CMs were characterized by SSA and pore size distribution analyzer (NOVA-2000E, Quantachrome Instruments, Boynton Beach, FL, USA, 2005), and TOC analyzer (TOC-VCPH, Shimadzu, Tokyo, Japan, 2006), respectively, as described in our previous studies [14,22]. The values of SSA were calculated using the BET multipoint method.

Table 1. The physicochemical properties of lindane and *p,p'*-dichlorodiphenyldichloroethylene (*p,p'*-DDE).

Organochlorine Pesticide	Structural Formula	Molecular Formula	Melting Point (°C)	Solubility (mg·L ⁻¹)	Vapor Pressure (mmHg)	Octanol-Water Partition Coefficient (LogKow)	Bioconcentration Factor
Lindane		C ₆ H ₆ Cl ₆	112.5	7.30	4.2 × 10 ⁻⁵ (20 °C)	3.72	1.4 × 10 ⁴
<i>p,p'</i> -DDE		C ₁₄ H ₈ Cl ₄	89.0	0.12	6.0 × 10 ⁻⁶ (25 °C)	6.51	9.8 × 10 ⁵

2.2. Batch Sorption Experiments of Lindane and *p,p'*-DDE by the Sediments

All sorption experiments were conducted in triplicate following a batch equilibration method at 25 ± 1 °C. Sorption of lindane and *p,p'*-DDE, with the concentration levels ranging from 0.5 to 4.0 µg·L⁻¹, were conducted by mixing 10 mg dry weight of the sediments in 250 mL stoppered conical flasks. These flasks were rotated continuously for 24 h at 120 r·min⁻¹ in a thermostatic oscillator. The pre-experiment indicated that the apparent equilibrium was reached within 24 h. The initial pH value of the solution system was about 7.1. The contents of lindane and *p,p'*-DDE in equilibrium sorption solution were determined by gas chromatography. The sorption amount of the two sorbates on the sediments was calculated by the subtraction method. Blank experiments containing sorbents without sorbates and containing sorbates without sorbents were carried out. Both the losses of lindane and *p,p'*-DDE by degradation and volatilization, as well as the effects of dissolving matters from the solids on the determination results were negligible.

2.3. Effects of CMs on the Sorption of Lindane and *p,p'*-DDE

Sorption of lindane and *p,p'*-DDE, with the concentration levels ranging from 0.5 to 4.0 µg·L⁻¹, were conducted by mixing 10 mg dry weight of separate SC, BC450, BC850, and AC in a group of 250 mL stoppered conical flasks. The effects of SC content on the sorption of lindane and *p,p'*-DDE by the sediments were investigated in the same way as in the aforementioned sorption experiment in addition to the sorption systems added by 10 mg sediments containing 0.5% SC, 1.5% SC, 3.0% SC, 5.0% SC, and 9.0% SC.

2.4. Determination of Lindane and *p,p'*-DDE

The lindane and *p,p'*-DDE in the equilibrium solution were extracted using C18 solid-phase extraction columns. Each column was sequentially conditioned with 6.0 mL of n-hexane and 6.0 mL of methanol prior to use, and the water samples were loaded at a flow rate of 10 mL·min⁻¹. After drying, the columns were eluted with 6 mL of n-hexane. The extract was concentrated to 1 mL by nitrogen blowing. Their determination was performed using a gas chromatograph equipped with an electron capture detector (GC-ECD, GC-14C, Shimadzu, Tokyo, Japan, 2006). The carrier gas was high-purity nitrogen (99.999% purity), and the flow rate was 1.6 mL·min⁻¹. The GC was equipped with a capillary column (Rtx-1, 30 m × 0.25 mm × 0.25 µm). During analysis, the column was initially maintained at a temperature of 100 °C, which was then increased at a rate of 20 °C·min⁻¹ to 210 °C, increased further at a rate of 3 °C·min⁻¹ to 230 °C, and held for 5 min. The temperature of the injector and detector was

maintained at 250 and 280 °C, respectively. Splitting injection was taken and the injection volume was 1 µL. The recoveries of determination for lindane and *p,p'*-DDE were 95.3% and 96.8%, respectively.

2.5. Data Analysis

Linear and Freundlich models were used to fit the equilibrium sorption data. These models are expressed as follows:

$$\text{Linear model : } Q_e = K_H C_e \quad (1)$$

$$\text{Freundlich model : } Q_e = K_F C_e^n \quad (2)$$

where K_H ($L \cdot g^{-1}$) and K_F [$(\mu g \cdot g^{-1}) \cdot (\mu g \cdot L^{-1})^{-n}$] are the linear and Freundlich model sorption coefficients, respectively. Q_e ($\mu g \cdot g^{-1}$) is the amount of sorbate sorbed onto solid materials; C_e ($\mu g \cdot L^{-1}$) is the sorbate equilibrium concentration; and n is the Freundlich nonlinear coefficient.

The single-point distribution coefficient K_d ($L \cdot g^{-1}$) was used to compare the sorption capacities of sorbents at a certain equilibrium concentration. It was calculated by Equation (3):

$$K_d = \frac{Q_e}{C_e} \quad (3)$$

The adjusted coefficient of determination R^2_{adj} was used to compare the performance of the two models and calculated by Equation (4):

$$R^2_{adj} = 1 - \frac{(1 - R^2)(N - 1)}{N - M - 1} \quad (4)$$

where N and M are the numbers of experimental data points and parameters in the model, respectively.

The organic carbon standard partition coefficient K_{OC} [$(\mu g \cdot g^{-1}) \cdot (\mu g \cdot L^{-1})^{-n}$] reflects the sorption capacity of sediments on organic pollutants to some extent. It was calculated by Equation (5):

$$K_{OC} = \frac{K_F}{f_{OC}} \quad (5)$$

where K_F is the Freundlich model sorption coefficients and f_{OC} is the quality percentage of TOC.

3. Results

The measured SSA and f_{CM} of SC, BC450, BC850, and AC are listed in Table 2. The order of SSA was AC ($525.1 \text{ m}^2 \cdot \text{g}^{-1}$) > BC850 ($79.6 \text{ m}^2 \cdot \text{g}^{-1}$) > BC450 ($26.5 \text{ m}^2 \cdot \text{g}^{-1}$) > SC ($21.4 \text{ m}^2 \cdot \text{g}^{-1}$). The order of f_{CM} was AC (56.93%) > BC850 (37.29%) > SC (14.49%) > BC450 (12.47%). The order of f_{CM} and SSA of the four CMs showed that AC and BC850 had better SSA and f_{CM} than SC and BC450, which could be related to their structures, given that BC850 was mainly consisted of an aromatic lamellar structure and had many irregular holes; compared with BC850, AC had smaller grain size, more pores, and less inorganic minerals [23]. While compared with AC and BC850, SC and BC450 had lower organic matter content and contained fewer pores [24]. The f_{CM} value of sediments was calculated by the f_{CM} value of SC shown in Table 2. The value was only 0.17%, because the sediments had a low content of organic matter which was mainly composed of nonliving organic matter such as humic substances [22].

Table 2. The specific surface area (SSA) and black carbon content (f_{CM}) of different kinds of carbonaceous materials.

	SD	SC	AC	BC450	BC850
f_{CM} (%)	0.17 ^a	14.49	56.93	12.47	37.29
SSA ($\text{m}^2 \cdot \text{g}^{-1}$)	-	21.4	525.1	26.5	79.6

^a The f_{CM} value of SD = (mass of SC / mass of SD) × the f_{CM} value of SC.

3.1. Sorption Isotherms of Lindane and *p,p'*-DDE on the Sediments

The parameters of the lindane and *p,p'*-DDE sorption isotherms for the sediments fitted by the linear and Freundlich models are presented in Table S1. According to the values of R^2_{adj} , the linear model gave a better fit for the sorption isotherms of lindane and *p,p'*-DDE on the sediments ($R^2_{adj} > 0.983$). The sorption isotherms are shown in Figure 1. The isotherms of lindane and *p,p'*-DDE on the sediments appeared to be highly linear, suggesting that the linear partition could be involved in the sorption. Previous studies showed that the hydrophobic partition was the most important mechanism in the sorption of OCPs by natural solids [12,25].

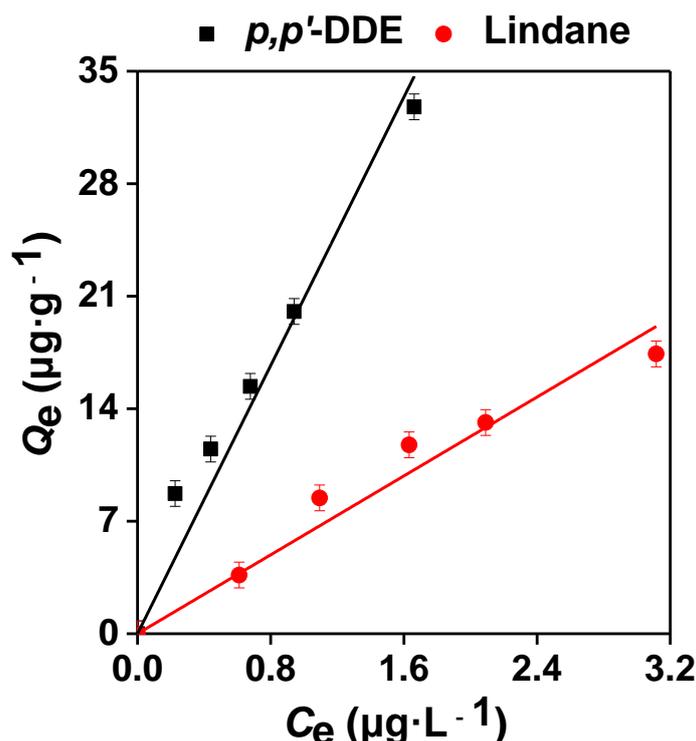


Figure 1. Sorption isotherms of lindane and *p,p'*-DDE fitted by linear model on the sediments.

3.2. Sorption Isotherms of Lindane and *p,p'*-DDE on CMs

The parameters of the lindane and *p,p'*-DDE sorption isotherms for SC, BC450, BC850, and AC, fitted by the linear and Freundlich models, are presented in Table S2. Both the lindane and *p,p'*-DDE sorption isotherms for the four CMs were fitted better by the Freundlich model based on the R^2_{adj} values. The sorption isotherms are shown in Figure 2. The Freundlich nonlinear coefficient n values for lindane sorbed by SC, BC450, BC850, and AC were 0.718, 0.818, 0.517, and 0.518, respectively, and the n values for *p,p'*-DDE were 0.478, 0.632, 0.385, and 0.770, respectively. The sorption of lindane and *p,p'*-DDE on CMs appeared to be highly nonlinear. The order of K_d values for lindane sorption on the four CMs was AC ($1443.0 \text{ L}\cdot\text{g}^{-1}$) > BC850 ($77.0 \text{ L}\cdot\text{g}^{-1}$) > BC450 ($40.8 \text{ L}\cdot\text{g}^{-1}$) > SC ($38.0 \text{ L}\cdot\text{g}^{-1}$); the order of *p,p'*-DDE was AC ($2926.2 \text{ L}\cdot\text{g}^{-1}$) > BC850 ($565.2 \text{ L}\cdot\text{g}^{-1}$) > SC ($318.1 \text{ L}\cdot\text{g}^{-1}$) > BC450 ($122.3 \text{ L}\cdot\text{g}^{-1}$).

3.3. Effects of SC with Different Contents on the Sorption of Lindane and *p,p'*-DDE by the Sediments

The sorption isotherm parameters of lindane and *p,p'*-DDE on the sediments added by SC with different contents fitted by the linear and Freundlich models are presented in Table S3. Both the lindane and *p,p'*-DDE sorption isotherms were fitted better by the Freundlich model based on the R^2_{adj} values. The sorption isotherms are shown in Figure 3. The Freundlich nonlinear coefficient n values for lindane sorbed on the sediments with 0.5% SC, 1.5% SC, 3.0% SC, 5.0% SC, and 9.0% SC

were 0.778, 0.889, 0.785, 0.709, 0.585, and 0.492, respectively; and the n values for p,p' -DDE were 0.763, 0.907, 0.734, 0.743, 0.558, and 0.476, respectively. The K_d values for lindane sorption on the sediments with different contents of SC increased in the following order: sediments ($6.6 \text{ L}\cdot\text{g}^{-1}$) < sediments with 0.5% SC ($11.9 \text{ L}\cdot\text{g}^{-1}$) < sediments with 1.5% SC ($14.4 \text{ L}\cdot\text{g}^{-1}$) < sediments with 3.0% SC ($23.5 \text{ L}\cdot\text{g}^{-1}$) < sediments with 5.0% SC ($33.1 \text{ L}\cdot\text{g}^{-1}$) < sediments with 9.0% SC ($49.4 \text{ L}\cdot\text{g}^{-1}$). The order of p,p' -DDE was sediments ($25.7 \text{ L}\cdot\text{g}^{-1}$) < sediments with 0.5% SC ($49.7 \text{ L}\cdot\text{g}^{-1}$) < sediments with 1.5% SC ($65.0 \text{ L}\cdot\text{g}^{-1}$) < sediments with 3.0% SC ($92.7 \text{ L}\cdot\text{g}^{-1}$) < sediments with 5.0% SC ($145.8 \text{ L}\cdot\text{g}^{-1}$) < sediments with 9.0% SC ($241.4 \text{ L}\cdot\text{g}^{-1}$), respectively. The K_d values increased with the increase of SC contents in the sediments.

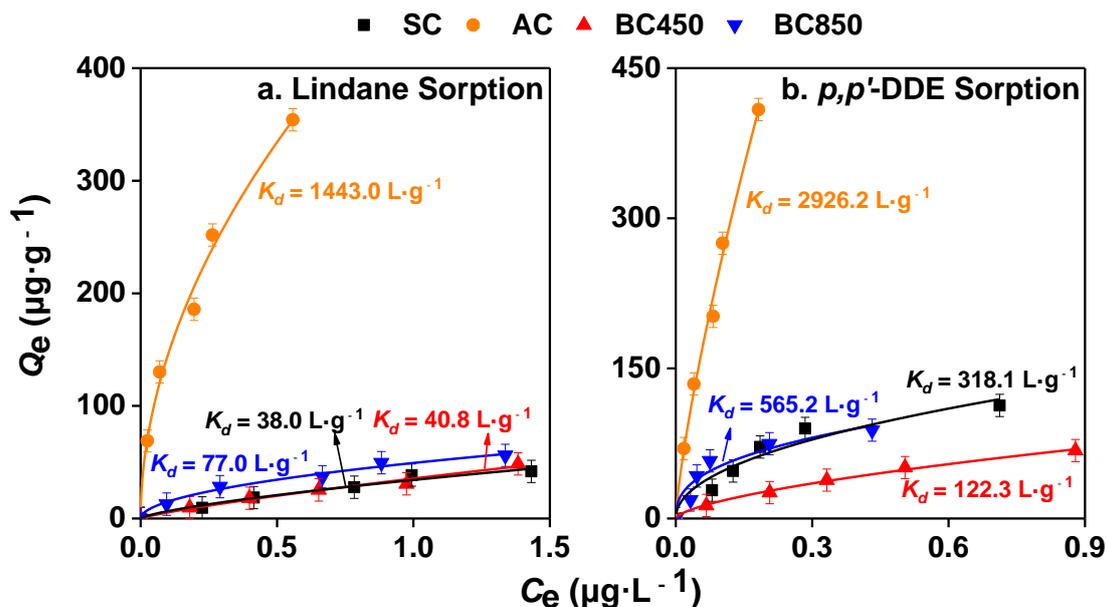


Figure 2. Sorption isotherms of lindane (a) and p,p' -DDE (b) fitted by Freundlich model on different kinds of CMs.

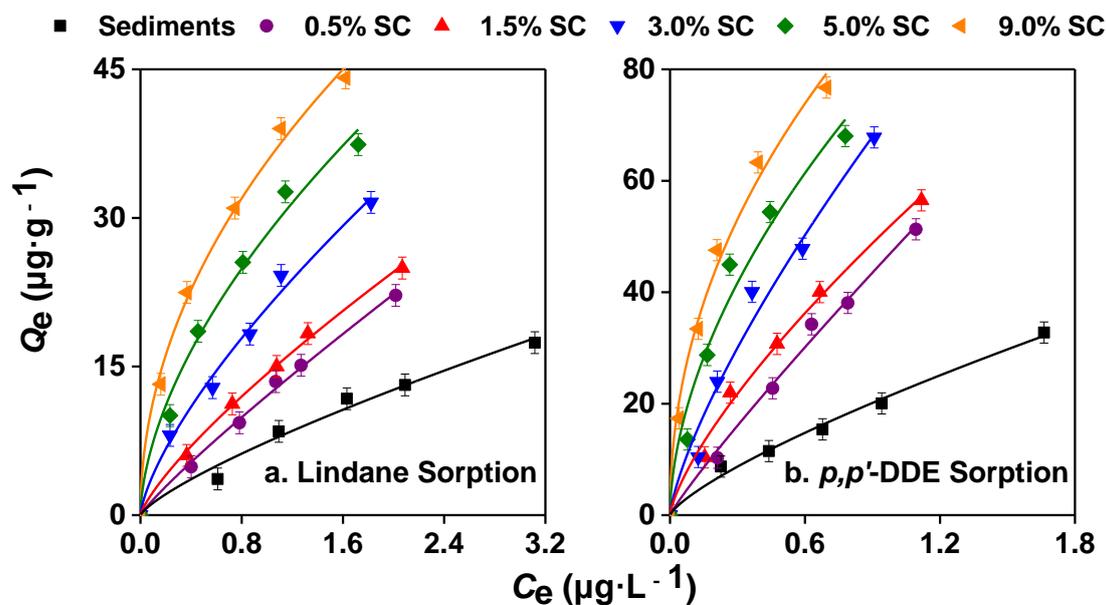


Figure 3. Sorption isotherms of lindane (a) and p,p' -DDE (b) fitted by Freundlich model on the sediments with different contents of SC.

4. Discussion

The sorption characteristics of CMs were closely related to their physicochemical properties. According to the n values, the sorption isotherms of BC850 and AC almost had good nonlinearity, because they had more micro-pores and higher BC content, but the sorption isotherms of p,p' -DDE on AC appeared to be slightly linear, suggesting that the linear partition was involved in the sorption of p,p' -DDE on AC [26]. Comparing the n values of SC with BC450, the nonlinearity of lindane and p,p' -DDE sorption isotherms on SC was much stronger than that of BC450. Pore-filling was found to account for a significant proportion of the nonlinearity sorption process of HCHs and DDTs by CMs [27–31]. As such, the explanation for why the sorption of SC had a better nonlinearity could be related to its porosity, because BC450 had a very low level of porosity due to its incomplete pyrolysis, while SC contained more microporous structures [24,32]. The porosity could be an important factor affecting the nonlinearity of CMs.

The K_d values showed that the sorption capacity of lindane and p,p' -DDE by AC and BC850 was 1.8–38.0 times larger than that of SC. Comparing the sorption capacity of BC450 and SC, they were similar, though the SC sorption was slightly superior to that of BC450. The sorption capacities of CMs were closely related to their content of BC [33,34]. Previous studies showed that BC had a strong sorption capacity and could play a leading role in the entire sorption of natural solids despite its content being very low; when the proportion of BC in TOC was only 23%, the contribution rate to the entire sorption could reach 52% [35–37]. Furthermore, the correlation analysis between f_{CM} and K_d in this study showed that the two had good correlation ($r > 0.85$). Thus, it was speculated that the difference of f_{CM} could be the reason why the sorption capacity of SC was stronger than that of BC450. This shows that f_{CM} is an important factor affecting the sorption capacity of CMs.

The sorption capacity of BC850 and AC was at least 11–21 times higher than that of natural sediments, while SC and BC450 were only 4–11 times higher than that of natural sediments. Adding a small amount of BC850 or AC to natural sediments could significantly increase the proportion of BC in TOC; by contrast, adding SC and BC450 could gradually increase said proportion of BC in TOC, meaning that they were more suitable to investigate the effects of CMs content on the sorption of lindane and p,p' -DDE by the sediments. Comparing SC with BC450, SC had higher f_{CM} and more pores, therefore, it was chosen to investigate the effects of CMs on the sorption of lindane and p,p' -DDE by the sediments.

As the contents of SC increased in the sediments, the n values of lindane sorption on the latter decreased from 0.889 to 0.492, and the n values of p,p' -DDE decreased from 0.907 to 0.476, suggesting that the nonlinearity of the sorption became stronger. The same situation was observed in previous studies [35,36], indicating that the content of SC was an important factor affecting the nonlinearity of the sorption of lindane and p,p' -DDE by the sediments. By comparing the K_d values of the sediments with different contents of SC, the sorption capacity of lindane sorption on the sediments with 0.5–9.0% SC was 1.8–7.5 times larger than that of natural sediments, and the sorption capacity of p,p' -DDE sorption on the sediments with 0.5–9% SC was 1.9–9.4 times larger than that of natural sediments, respectively. The correlation analysis between f_{CM} and K_d showed that the two had good correlation ($r > 0.99$), and combined what was shown in Figure 3, the conclusion could be drawn that the sorption capacity of sediments was closely related to the content of SC [36–39]. The values of K_F reflected the sorption capacity of natural solids to some extent [40], when the proportion of CMs in TOC increased from 0 to 60%, the K_F values of lindane sorption increased from 7.38 to 35.69, increased by 3.8 times, and the K_F values of p,p' -DDE sorption increased from 21.83 to 94.19, increased by 3.3 times, which also confirmed the importance of SC content in the sorption of lindane and p,p' -DDE by the sediments.

The contribution of SC to the sorption of the sediments was calculated as follows: the difference between the amount of pesticides sorbed by the sediments with different contents of SC and natural sediments was taken as the amount of pesticides sorbed by SC; the ratio of the amount of pesticide sorbed by SC and the amount of pesticide sorbed by the sediments with different contents of SC was recorded as the contribution of SC to the sorption of lindane and p,p' -DDE by the sediments. Figure 4

shows the relationship between the ratio of CMs and TOC (f_{CM}/f_{OC}) and the sorption contribution rate of SC. When the ratios of f_{CM}/f_{OC} were 0.10, 0.22, 0.35, 0.46, and 0.60, the contribution rates of SC to the sorption of lindane were 16.4%, 28.9%, 43.1%, 57.1%, and 64.7%, respectively; the contribution rates of SC to the sorption of p,p' -DDE were 40.7%, 41.1%, 50.0%, 55.3%, and 61.7%, respectively, which was similar to the results reported by Xia et al. and Liu et al. [35,41], indicating that the ratio of f_{CM}/f_{OC} was an important factor affecting the sorption of lindane and p,p' -DDE by the sediments.

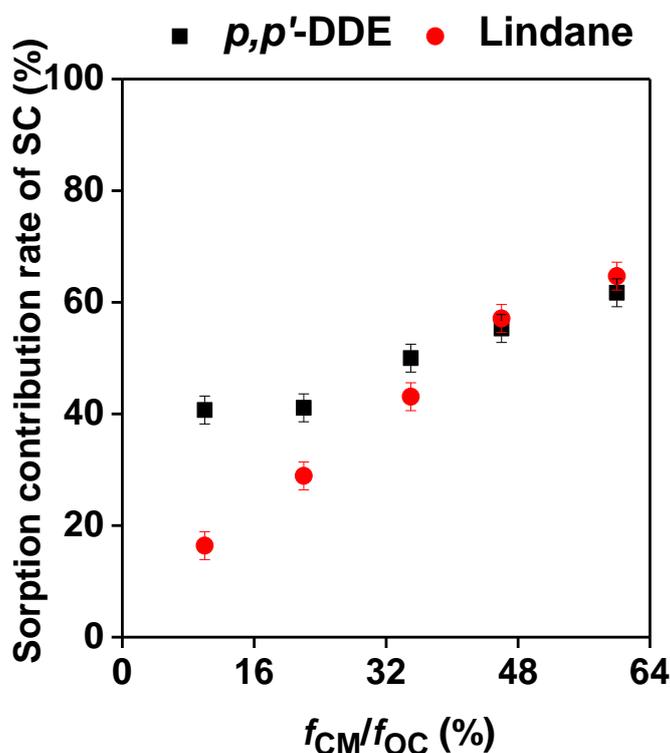


Figure 4. The relationship between the ratio of f_{CM}/f_{OC} and sorption contribution rate of SC.

The organic carbon standardized partition coefficient (K_{OC}) reflects the sorption capacity of the sediments for organic pollutants [12]. The values of K_{OC} and the ratios of f_{CM}/f_{OC} are listed in Table 3. When the ratio of f_{CM}/f_{OC} in the sediments was low, as in 0.10–0.22, the change of f_{CM} had little effect on the value of K_{OC} , and the contribution rate of SC was below 50%. At this time, CMs played a minor role in the sorption of lindane and p,p' -DDE by the sediments; when f_{CM}/f_{OC} was higher, as in 0.35–0.60, CMs gradually played a leading role in the sorption, the contribution rate of SC even went up to 64.7%, and the higher the f_{CM} , the greater the effect on the values of K_{OC} . This indicates that f_{CM}/f_{OC} could be a principal parameter for assessing the sorption capacity of sediments and CMs for the hydrophobic OCPs.

Table 3. The values of f_{CM} , f_{OC} , f_{CM}/f_{OC} , and K_{OC} of the sediments with different contents of SC.

	Sediments	0.5% SC	1.5% SC	3.0% SC	5.0% SC	9.0% SC
f_{CM} (%)	0.17	0.67	1.67	3.17	5.17	9.17
f_{OC} (%)	6.16	6.66	7.66	9.16	11.16	15.16
f_{CM}/f_{OC}	0.03	0.10	0.22	0.35	0.46	0.60
K_{OC} -lindane [($\mu\text{g}\cdot\text{g}^{-1}$)-($\mu\text{g}\cdot\text{L}^{-1}$) ⁻ⁿ]	119.82	180.81	186.17	228.41	253.94	235.44
K_{OC} - p,p' -DDE [($\mu\text{g}\cdot\text{g}^{-1}$)-($\mu\text{g}\cdot\text{L}^{-1}$) ⁻ⁿ]	346.23	718.90	688.12	801.81	731.11	621.31

5. Conclusions

In this study, the factors affecting the sorption of lindane and *p,p'*-DDE by CMs were explored by comparing the four CMs including SC, BC450, BC850, and AC. The results indicated that when the ratio of f_{CM}/f_{OC} was greater than 0.35, CMs played a leading role in the sorption of lindane and *p,p'*-DDE on the sediments. The sorption contribution rate of CMs could reach up to 64.7%. When the ratio of f_{CM}/f_{OC} was less than 0.10, BC played a minor role in the sorption. The nonlinearity of sorption isotherms was strengthened with the increasing f_{CM} and porosity. Our findings show that the porosity of CMs was an important factor affecting the nonlinearity of sorption isotherms and f_{CM}/f_{OC} is a principal parameter for assessing the sorption capacity of sediments and CMs for the hydrophobic OCPs.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2076-3417/9/9/1722/s1>, Table S1. Isotherm parameters for lindane and *p,p'*-DDE sorption by the sediments; Table S2. Isotherm parameters for lindane and *p,p'*-DDE sorption by different kinds of CMs; Table S3. Isotherm parameters for lindane and *p,p'*-DDE sorption by the sediments with different contents of SC.

Author Contributions: Conceptualization: Z.G.; data curation: L.Z.; formal analysis: L.Z.; funding acquisition: Z.G. and X.H.; investigation: T.C. and L.W.; methodology, Z.G.; software: T.C.; supervision: D.D. and X.H.; writing—original draft: Z.G. and T.C.; writing—review and editing: X.W.

Funding: This study was supported by the National Natural Science Foundation of China (no. 21307041 and 21277056), and the 111 Project (no. B16020).

Conflicts of Interest: The authors declare no conflict of interest.

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