Lindane sorption and desorption behaviour on sediment organic matter

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Abstract: The work is concerned with the sorption and desorption behaviours of lindane on four humic acid fractions (HAs) and two humin fractions, sequentially extracted from Ludas Lake sediment. All sorption isotherms fitted to the Freundlich model were nonlinear. The isotherm linearity increased from 0.757 for the first extracted HA to 0.944 for the ninth HA, showing a positive correlation with the atomic H/C ratio, while a negative correlation between the sorption coefficient and aliphaticity of the isolated HAs was observed. It was shown that the sorption processes may be strongly influenced by the physical conformation of and accessibility to sediment organic matter (SOM), as demonstrated by the high K_{oc} and low n values of the humin samples. Despite exhibiting the most nonlinear sorption isotherms, humin samples did not show a pronounced sorption–desorption hysteresis, while the most significant hysteresis was observed for the three HA samples. These results support the hypothesis that the aromatic domains in SOM influence strongly the sorption and desorption behaviour of lindane. The findings obtained in this study may be helpful in understanding the distribution, transport and fate of lindane in soils and sediments.

Keywords: sediments; humic acid; humin; hydrophobic organic compounds; hysteresis.

INTRODUCTION

Sorption is a major process determining the fate and behaviour of hydrophobic organic compounds (HOCs) in sediments and soils. It is widely recognized that soil and sedimentary organic matter (SOM) is the dominant cons-

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tituent for sorption, sequestration and attenuation of HOCs.[1,2] Since the humic substances (HSs) represent a significant portion of the SOM,[3,4] knowledge of the physical and chemical properties of these substances and the nature of their interactions with HOCs represent aspects relevant to risk assessment and remediation of contaminated sediments. Hence, the identification and comparison of the sorption and desorption behaviour of HOCs by different humic matter fractions are essential to predict the fate and bioavailability of HOCs in soils and sediments.

Many previous papers emphasized the importance of SOM heterogeneity in establishing the nature of the sorption–desorption behaviour and the equilibrium isotherm character of HOCs.[1,5] The concept of amorphous (flexible, rubbery-like) and condensed (rigid, glassy-like) domains of SOM were employed to operationally describe the chemical heterogeneity of SOM having two domains with distinctly different degrees of physicochemical condensation and markedly different HOC sorption behaviour.[6,7] The sorption process is presumed to occur by dissolution of HOCs within the amorphous domains, generating linear, low capacity, non-competitive, and rapid behaviour in the sorption and desorption phases. On the other hand, nonlinear isotherms were observed for the sorption to the condensed domains due to hole-filling (adsorption) process. A number of studies showed the differences of the sorption behaviour of HOCs on HSs.[8–12] The inconsistency of observations may also be attributed to the fact that the HA structural function associated with HOC binding may be more affected by HA sources than by the apparent physicochemical properties.[13] In an earlier paper,[14] which investigated the sorption of pentachlorobenzene on sequentially extracted humic substances from a single sediment sample, it was shown that sorption affinity and mode of sorption to aliphatic and aromatic structures within the SOM differed.

Despite the fact that bioavailability is mostly affected by the desorption process, considerable less information is available in the literature about the effects of structural variations of SOM on the desorption behaviour of HOCs. Therefore, sorption and desorption studies on chemically and structurally different HAs extracted from a single sediment sample could provide more detailed information on the importance of certain structural characteristics of HSs in the sorption mechanism.

Therefore, the objectives of the present study were: *i*) to examine both the sorption and desorption of lindane as a model HOC on four sequentially extracted HA fractions and two humin fractions and *ii*) to find relationships between the structural descriptors of these HSs, lindane sorption and desorption parameters, and sorption–desorption hysteresis.

Hexachlorocyclohexanes (HCHs) were applied globally as pest control from the 1940s.[15] Technical HCH, a mixture of α-, β- and γ-isomer, was banned from

use in North America in the 1970s, but was still used in China until the 1980s and in India and the former Soviet Union until the 1990s.[15] Lindane, purified γ-isomer, was in use in Serbia up to 2006. Due to its persistence in the environment for longer periods, lindane has been detected worldwide.[15,16]

The results of the present study may contribute to a better understanding the effects of structural variations of SOM on the fate of lindane in sediments and soils.

EXPERIMENTAL

Isolation and characterisation of humic acids and humins

The sediment sample was collected from the Ludas Lake, one of the protected areas in the northern province of Serbia, Vojvodina. Ten fractions of HAs and two of humins were isolated by progressive sequential extraction, which involved eight successive extractions with 0.1 M $Na_4P_2O_7$ followed by two extractions with 0.1 M NaOH. Details of the employed extraction procedure and the results of elemental analysis and diffuse reflectance Fourier transform infrared spectroscopy (FTIR) characterization were given in a previous work.[14] The four HA fractions (depicted as HA1, HA3, HA6 and HA9) and two humin samples (depicted as LOHu and HOHu), employed in this study to perform sorption and desorption experiments of lindane, were chemically and structurally different (Table I).

TABLE I. Elemental compositions, atomic *H*/*C* ratios, aliphatic to aromatic peak height ratio and ash content of the four sequentially extracted HA fractions and the two humin fractions used as sorbents in this study[14]

Sample[a]	Composition[b], %				H/C	Aliphatic to aromatic peak height ratio	Ash, %
	C	H	N	S			
HA1	52.3	6.44	5.89	3.07	1.47	1.27	15.0
HA3	52.6	6.71	5.66	3.02	1.52	1.28	16.2
HA6	52.8	7.21	5.54	2.38	1.63	1.43	27.3
HA9	55.3	7.93	5.37	2.87	1.71	1.68	18.3
HOHu	54.0	8.46	4.79	6.03	1.87	1.87	65.4
LOHu	23.6	9.38	1.47	4.69	4.74	–	92.5

[a]Number represents the extraction sequence; [b]Values are expressed on an ash-free and moisture-free basis. H/C: atomic ratio of hydrogen to carbon

The atomic H/C ratio, as a descriptor for the degree of aromaticity,[17] increased gradually from 1.47 for HA1 to 1.71 for HA9, showing that the later-extracted HAs had higher contents of aliphatic carbons. Similar conclusions were derived from the results of FTIR analysis. The aliphatic to aromatic peak height ratios increased from 1.27 for HA1 to 1.68 for HA9, showing that aliphaticity increased with increasing sequence of the extraction. HOHu also showed a high degree of aliphaticity, with an *H*/*C* value of 1.87, while LOHu had an extremely high *H*/*C* value of 4.74, probably due to the high ash content (92.5 %), which could have resulted in strong adsorption of water molecules or hydroxyl groups on the edges of broken minerals. This effect, in combination with the relatively low carbon content (23.6 %), led to uncertainties in the *H/C* determination for the LOHu sample.

The mild purification procedure of the sequentially alkali-extracted HAs resulted in an expected higher ash content, which ranged from 15 % for HA1 to 27 % for HA6. The results

of a previous study showed that the higher ash contents did not cause differences in the sorption behaviour of pentachlorobenzene on the set of humic acids isolated from the same sediment sample.[14]

Sorption and desorption experiments

All sorption and desorption isotherms were run in duplicate at room temperature in 40 mL glass vials with a screw cap having a Teflon-lined silicon septum covered with aluminium foil. The background solution was 0.01 M $CaCl_2$ in double-distilled water with 200 mg L^{-1} $HgCl_2$ as a biocide. The pH of the background solution was adjusted to 3.90±0.05 for all sorption and desorption experiments, to prevent any potential dissolution of the HAs.[11] The volume of background solution in the sorption and desorption experiments was 35 mL in order to keep the volume of head-space in the vials to a minimal and avoid losses of sorbate during experiments due to volatilisation. The initial volume of background solution in each vial was determined by weighing each vial before and after filling. Lindane (99.8 %) was obtained from Sigma-Aldrich. Due to the low water solubility, before spiking the background solution, stock solutions of lindane were prepared in MeOH. The initial lindane concentrations ranged from 0.030 to 2.7 mg L^{-1}. The volume of lindane stock solution used for background solution spiking was < 0.1 %, which was shown to have no measurable influence on the sorption behaviour of HOCs.[5] The amount of HA and humin samples in each experiment corresponded to a sample/solution ratio that resulted in 20–80 % uptake of lindane. The equilibration period of 24 h was based on a preliminary kinetics experiment performed over 168 h. The solids were separated from the aqueous solutions by centrifugation at 6000 rpm for 20 min. Then, 25 mL of supernatant was removed using a glass pipette and replaced with the same volume of fresh solute-free background solution to start the desorption step by the conventional decant-refill method. The weights of each vial were determined before and after refilling. The vials were further agitated under the same conditions. At the end of the desorption step, the solids were removed by centrifugation under the same conditions and an aliquot of supernatant was withdrawn for lindane determination. Solid-phase solute concentrations before and after desorption were calculated from the mass balance of solute between the solid and aqueous phases.

Supernatants collected after each of the sorption and desorption steps were analyzed after liquid–liquid extraction with hexane, using gas chromatography-electron capture detection (GC/ECD; Agilent Technologies 6890 with [63]Ni ECD) on a DB-608 column (J & W Scientific) and quantified according to external standard calibration. Recovery from the liquid–liquid extraction and GC/ECD determination of lindane was 84.9 %, giving an *RSD* of 3.32 % for seven measurements at the 100 μg L^{-1} level. Accordingly, corrections were made for the analytically determined lindane concentrations. To determine the initial concentration of lindane for each isotherm point and to account for lindane losses other than sorption to the sorbent, two control flasks without any sorbent were prepared and treated in the same way. The recoveries of the initial concentrations of lindane from control flasks ranged from 82.5 to 85.2 % and were in the range of recoveries of lindane from solutions without the shaking procedure, indicating no losses of lindane due to processes other than sorption to the sorbents (*e.g.*, volatilisation, degradation).

Data analysis

All sets of equilibrium sorption and desorption data were fitted using the Freundlich model:

$$q_e = K_F c_e^n \qquad (1)$$

where q_e and c_e are the solid phase and aqueous phase equilibrium concentrations (in $\mu g\ g^{-1}$ and $mg\ L^{-1}$, respectively); K_F and the exponent n are the Freundlich sorption capacity coefficient (expressed as $(\mu g\ g^{-1})/(mg\ L^{-1})^n$) and the site energy heterogeneity factor indicating isotherm nonlinearity (dimensionless), respectively. K_F and n were obtained from direct nonlinear curve fitting of the sorption and desorption data using Origin version 6.1. Statistical analysis was performed using One-Way Analysis of Variance (One-Way ANOVA) at the 0.05 significance level. This analysis is appropriate when making a single test to determine whether two or more populations have the same mean.

Sorption–desorption hysteresis was explored using the Hysteresis Index (*HI*) as proposed by Huang *et al.*[18]:

$$HI = \left.\frac{q_e^d - q_e^s}{q_e^s}\right|_{T,c_e} \qquad (2)$$

where q_e^s and q_e^d are the solid-phase solute concentrations for the single cycle sorption and desorption experiments, respectively, and the subscripts T and c_e specify constant temperature and residual aqueous phase concentration, respectively.

RESULTS AND DISCUSSION

Sorption and desorption isotherms

All sorbents exhibited nonlinear isotherms (Figure 1, Table II), meaning that the sorption affinity of the HA fractions and both humin samples decreased as lindane concentration increased. For the HA fractions, *n* increased in the order of HA1 (0.757) < HA3 (0.806) < HA6 (0.852) < HA9 (0.944), while both humin samples exhibited greater nonlinearity compared to HAs (0.619 for HOHu and 0.638 for LOHu). One-Way ANOVA at the 0.05 significance level was employed to explore whether the obtained variation of *n* between different samples was statistically significant or not. This analysis was applied separately for HA fractions and humin samples because of their different structural characteristics and sorption behaviour. The statistical analysis was applied to the following pairs of HAs: HA1/HA3, HA3/HA6 and HA6/HA9. The results showed that the variations of the *n* values were significantly different for all pairs of HAs, as well as for the two humin samples.

The *n* values for sorption isotherms for HAs increased proportionally with increasing atomic *H/C* ratio (Fig. 2, open circles), indicating that the isotherm nonlinearity of HAs increased with aromaticity. The same order of nonlinearity was obtained for the *n* values obtained from the desorption data (Fig. 2, solid circles). The results for lindane sorption are in good agreement with the results obtained for the sorption of pentachlorobenzene,[14] and also with other sorption studies.[8,11,19–22] These studies concluded that HOC sorption in soil is strongly influenced by the aromatic moieties of the SOM. Furthermore, a recent spectroscopic study showed that the condensed domain is mainly attributed to aromatic
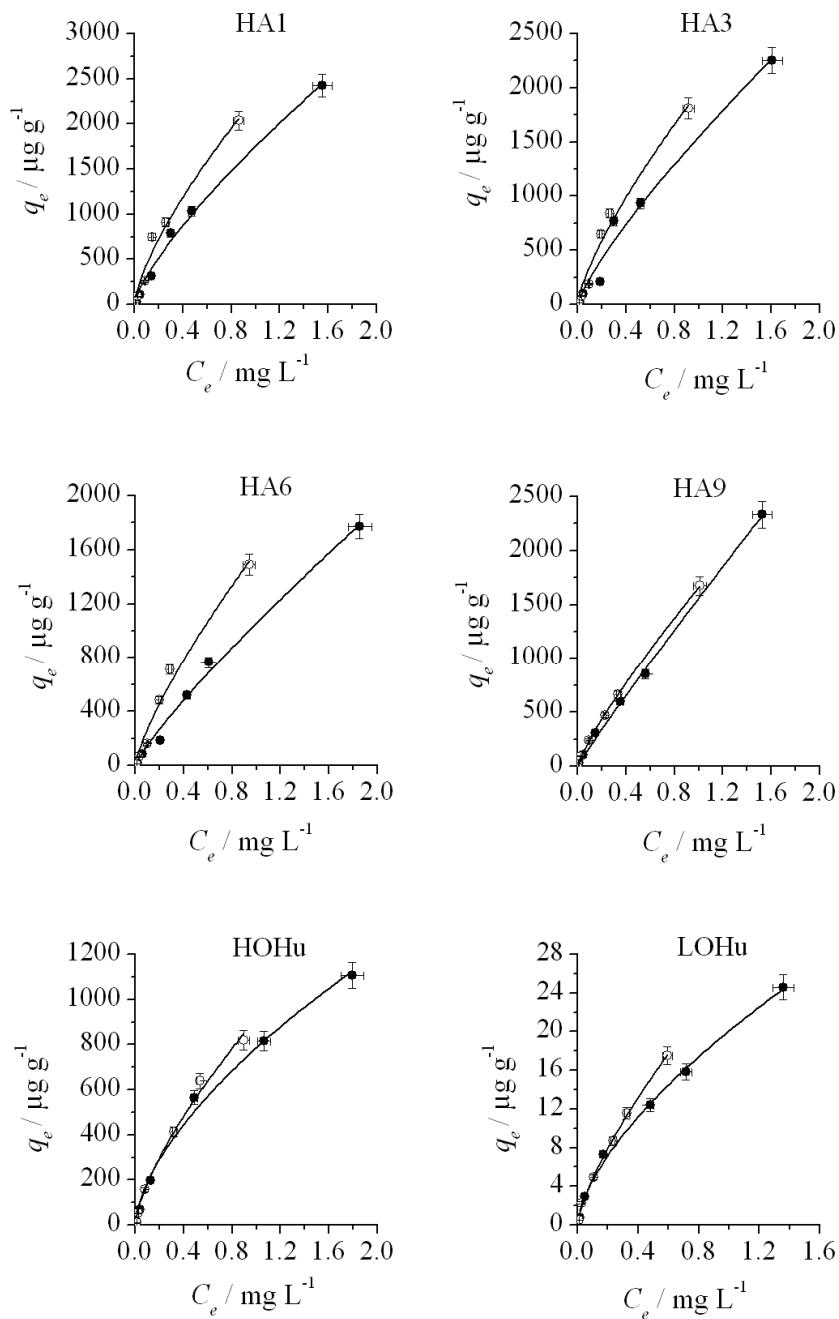
Fig. 1. Sorption and desorption isotherms for lindane by four HA fractions and two humin fractions. Solid line (——) represents the best nonlinear model fit to the Freundlich model. The error bars represent the standard deviation for two measurements.

TABLE II. Freundlich sorption and desorption model parameters and hysteresis indices (*HI*) for four HA fractions and two humin fractions; K_FOC = K_F/F_{OC}. K_{OC} = $(q_e/C_e)/F_{OC}$. F_{OC} represents organic carbon fraction

Sample	Process	R^2	n	K_F / (μg/g)/(mg/L)^n	K_FOC	log K_{OC}			*HI* c_e / mg L^{-1}		
						0.05	0.5	5	0.05	0.5	5
HA1	Sorption	0.994	0.757 (±0.004[a])	1752 (±51.2[a])	3941	3.91	3.67	3.43	0.47	0.34	0.23
	Desorption	0.980	0.718 (±0.007)	2293 (±146)	5157	4.08	3.80	3.52			
HA3	Sorption	0.989	0.806 (±0.008)	1548 (±84.6)	3512	3.80	3.60	3.41	0.49	0.32	0.16
	Desorption	0.979	0.752 (±0.008)	1967 (±123)	4462	3.97	3.72	3.48			
HA6	Sorption	0.994	0.852 (±0.005)	1057 (±36.1)	2753	3.63	3.48	3.34	0.89	0.58	0.33
	Desorption	0.982	0.776 (±0.008)	1589 (±90.5)	4139	3.91	3.68	3.46			
HA9	Sorption	0.998	0.944 (±0.003)	1560 (±25.4)	3453	3.61	3.56	3.50	0.47	0.15	–[b]
	Desorption	1.00	0.835 (±0.001)	1658 (±11.7)	3670	3.78	3.61	3.45			
LOHu	Sorption	0.996	0.638 (±0.003)	20.07 (±0.37)	1140	3.53	3.17	2.80	–	0.20	0.50
	Desorption	0.998	0.733 (±0.002)	25.79 (±0.72)	1465	3.51	3.25	2.98			
HOHu	Sorption	0.991	0.619 (±0.005)	784.7 (±25.4)	4192	4.12	3.74	3.36	–	0.10	0.33
	Desorption	0.992	0.699 (±0.005)	915.2 (±35.2)	4889	4.08	3.78	3.48			

[a]Standard deviation; [b]negative value
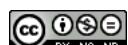
structures.[23] Therefore, the obtained order of nonlinearity is in line with the degree of condensed character of the organic matter, as suggested by Weber *et al.*,[6,24] who hypothesized that the SOM is comprised of two principal domain types: amorphous (flexible, rubbery-like) and condensed (rigid, glassy-like) domains. The linear and nonlinear sorption behaviours of different SOM domains are attributed respectively to non-specific partitioning in an amorphous domain and to site-specific and capacity-limited adsorption at the surface of a condensed domain. In a previous study, the results of elemental analysis and FTIR characterisation showed that the aliphatic character of HA fractions increased with increasing number of extractions.[14] Consequently, the later-extracted HAs, with relatively higher aliphatic carbon content, should exhibit more linear isotherms than the earlier-extracted ones. Although the number of data points is limited, it is evident that the *n* values for HAs increased proportionally with increasing atomic *H/C* ratio, suggesting that sorption becomes more of a partitioning process with increasing aliphaticity. Thus, the obtained order of nonlinearity among HAs supports the role of aromatic moieties in the sorption of HOCs.
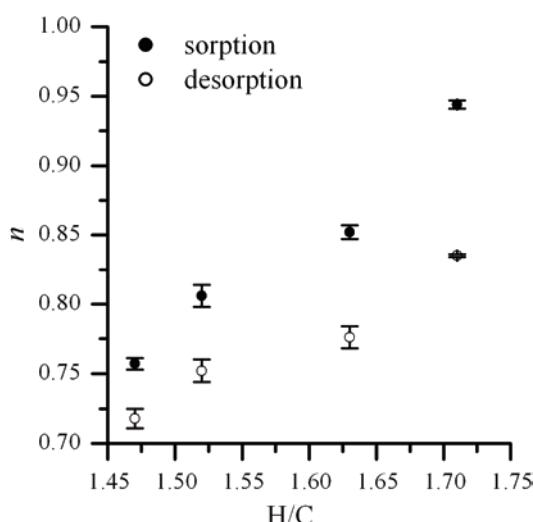

Fig. 2. Relationship between the *n* values for lindane sorption (●) and desorption (○) and atomic *H/C* ratios of four HA fractions and HOHu. The error bars represent the standard deviation for two measurements.

Although both the elemental data and FTIR analysis showed an increased content of amorphous aliphatic domains in HOHu, this sample, as well as LOHu, exhibited greater nonlinearity than the HAs (Table II). Considering the significantly higher mineral phase content in these samples compared to the HAs (LOHu 92.5 %, HOHu 65.4 %), it might be that the mineral matter plays an important indirect role in HOCs sorption in these samples. This is in line with the mechanism suggested by Gunasekara and Xing,[25] who proposed that in the interaction of the crystalline–amorphous complex with mineral surfaces, the first few

molecular layers of the amorphous aliphatic region rearrange to a more condensed form, which enhances nonlinear sorption. However, the higher content of mineral matter in LOHu (92.5 %, $n = 0.638$) did not cause greater nonlinearity in comparison with HOHu (65.4 %, $n = 0.619$), implying that other factors might affect the sorption behaviour of the humin samples, *e.g*., the presence of small amounts of carbonaceous materials. The presence of high-surface area carbonaceous materials in sediments and soils cause nonlinearity of the isotherms due to physical adsorption into the microporous domains, especially at low concentrations.[26,27]

The organic carbon-normalized sorption coefficient (K_FOC) ranged from 1140 for LOHu to 4192 for HOHu, while K_FOC values for HAs varied from 2753 for HA6 to 3941 for HA1 (Table II). However, a direct comparison of the K_FOC values could not be made because of their different units as a result of the nonlinearity of the sorption isotherms obtained for all sorbents. To enable a direct comparison of the sorption affinities among the HA fractions and humin samples, organic carbon-normalized single point distribution coefficients (K_{oc}) at three selected concentrations ($c_e = 0.05$, 0.5 and 5 mg L^{-1}) were calculated. This was realized by calculating the q_e values corresponding to these three c_e values from the respective best fit Freundlich isotherms, the parameters for which are given in Table II. Lindane sorption (K_{oc}) decreased from HA1 to HA6 at each c_e, showing a slightly increase for HA9, except in the low concentration range. Humic acid fraction HA9 was isolated from the sediment by NaOH extraction, which could have caused alkaline oxidation and slightly different sorption behaviour compared to Na$_4$P$_2$O$_7$ isolates.[28] The highest K_{oc} values were obtained for the humin sample HOHu, while the organic matter in the low-organic carbon humin, LOHu, showed the lowest affinity towards lindane.

In the present study, the atomic *H/C* ratios correlated with the sorption affinity of lindane, showing a positive trend between aromaticity of the HAs and log K_{oc} (Fig. 3), thus supporting the role of aromatic moieties in HOC sorption. Due to uncertainties linked to the *H/C* determination for LOHu, this sample was excluded from the correlation. It can be noticed that the changes of log K_{oc} with changes in the atomic *H/C* ratio were especially pronounced in the range of low equilibrium concentrations, which could be expected because the overall sorption under these conditions was dominated by an adsorption mechanism. With increasing equilibrium concentrations, the sorption mechanism shifted towards the distribution and, at concentrations close to solubility of lindane, it became the dominant mechanism in the overall sorption. These results are in line with the observations of several researchers who found a significant positive correlation between the sorption affinity of polycyclic aromatic hydrocarbons and aromaticity.[8,22,29–31] However, the results of a previous study of the sorption of pentachlorobenzene onto a set of HAs isolated from the same sediment sample showed

that the sorption affinity correlated positively with aliphaticity, indicating that the non-polar poly(methylene) domains in the SOM were appropriate sorption domains for the more hydrophobic compound pentachlorobenzene.[14] These results suggest that the properties of both the SOM and the HOCs have to be taken into consideration when explaining the sorption behaviour of HOCs onto the SOM.
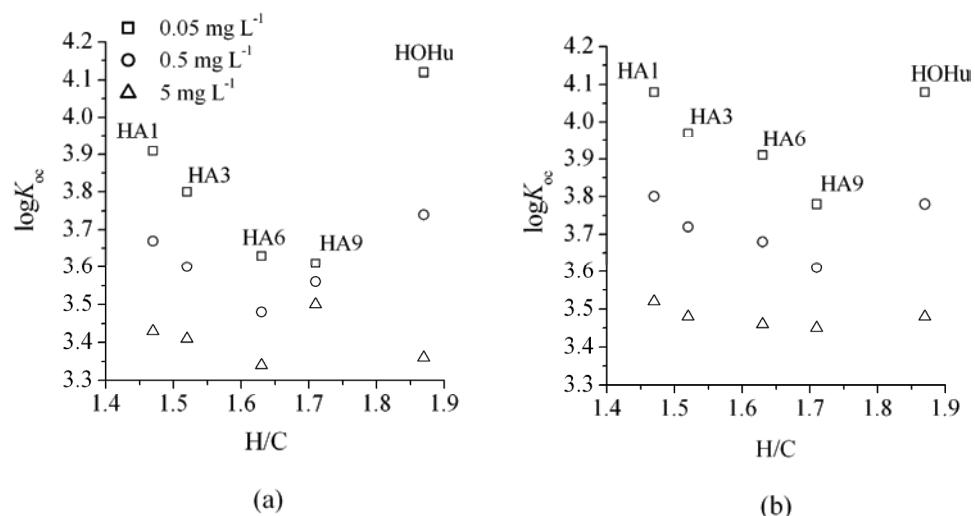

Fig. 3. Relationship between log K_{oc} values for lindane sorption (a) and desorption (b), and the atomic *H/C* ratiosof four HA fractions and HOHu.

Humin has been reported to be an important sink for organic contaminants.[32,33] This was supported by the present study, which showed higher K_{oc} values for HOHu than for HAs (Fig. 3). The increased capacities of humin samples for HOCs could be explained by special physical properties of humin caused by the increased contents of mineral matter. Although mineral surfaces do not contribute to HOC sorption directly, their interaction with organic matter may play an indirect role in the sorption behaviour of humins.[25,34] In addition, the removal of smaller organic fractions could decreased the surface roughness and increased the surface area and porosity of the humin, exposing additional binding sites on its surface.[35] These reports, and the data presented here, demonstrate the increased affinity of HOCs for humin and suggest that the sorption process may be strongly influenced by the changes in the physical conformation of the organic matter, making it more accessible for participation in the sorption.

Sorption–desorption hysteresis

Sorption reversibility provides an additional insight into the sorption mechanisms, as well as structural properties of the sorbent governing the specific sorptive behaviour of the sorbate.

The apparent sorption–desorption hysteresis was quantified for each of the sorption and desorption isotherms using the hysteresis index (*HI*) (Eq. (2)). Hysteresis indices at three concentration levels, $c_e = 0.05$, 0.5 and 5 mg L^{-1}, were calculated for each sorbent using the sorption and desorption parameters of the Freundlich model. The calculated *HI* values are included in Table II. Sorption––desorption hysteresis exists if *HI* has a positive value and is more pronounced as the value of *HI* increases.

The most significant hysteresis for all HAs was observed at low sorbate concentration, while the desorption increased with increasing lindane loading resulting in lower *HI* values at high sorbate concentration. At high solute concentrations, the sorbed lindane molecules were more readily desorbed compared to molecules sorbed at lower concentrations. It is proposed that at low solute concentrations, sorption sites within the condensed domain are occupied more readily than the sorption sites within the amorphous aliphatic domains, causing a greater extent of sorption–desorption hysteresis in the low concentration range. This mechanism cannot explain the desorption from the two aliphatic-rich humin samples, where the opposite trend was observed: lindane molecules were readily desorbed at low sorbate concentrations, while desorption decreased with increasing lindane loading, resulting in an increase in the *HI* values at high sorbate concentration. It is assumed that at high solute concentrations, the sorbed molecules are forced by a concentration gradient to partition in the amorphous aliphatic domains, causing the increased hysteresis.

In addition, lindane exhibited pronounced desorption hysteresis for three HA fractions, which was significantly greater than for the humin samples and HA9. This is suggested to be caused by a more condensed structure of the SOM in the former samples attributed to aromatic domains.

It is interesting to note that the humin samples, despite exhibiting the most nonlinear sorption isotherms, showed a desorption hysteresis for lindane that was less pronounced than expected based on the results found in the literature.[36] Similar observations on nonlinear sorption and low desorption hysteresis were observed by Ran *et al*.[37] for phenathrene with peat. This observation suggests that the nonlinear sorption obtained with the humin samples does not necessarily result from a hole-filling mechanism, especially in the lower concentration ranges, and could result from a surface interaction. The surface-sorbed molecules probably desorb more readily. However, as the lindane concentration increases, the increased concentration gradient will cause molecules to penetrate deeper into the SOM matrix generating "tenant" pores in which they then reside,[38] resulting in increased hysteresis.

CONCLUSIONS

Sorption/desorption behaviour should be seriously considered as an essential tool in evaluating compound behaviour in sediment risk assessment analysis. Positive correlations of log K_{oc} values at three lindane concentrations and the *H/C* ratio in HAs extracted from a single sediment sample, a positive correlation between *n* values and aromatic carbon and greater sorption–desorption hysteresis for three HA fractions compared to humin samples were found, indicating the dominance of aromatic domains in sorption nonlinearity, sorption affinity and irreversibility of lindane sorption on SOM. The above results will help to understand the sorption behaviour of lindane in SOM and provide a theoretical basis for risk assessment and remediation of contaminated sediments.

И З В О Д

СТРУКТУРНЕ ОБЛАСТИ ОРГАНСКЕ МАТЕРИЈЕ СЕДИМЕНТА КОЈЕ УТИЧУ НА СОРПЦИОНО И ДЕСОРПЦИОНО ПОНАШАЊЕ ЛИНДАНА

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У раду је испитивано сорпционо и десорпционо понашање линдана на четири хуминске киселине (ХК) и два хумина секвенцијално екстрахованих из седимента језера Лудаш. Све сорпционе изотерме, фитоване према Фројндлиховом моделу, су биле нелинеарне. Линеарност изотерми је расла од 0,757 за прву екстраховану ХК до 0,944 за девету ХК показујући позитивну корелацију са H/C атомским односом, док је између коефицијента сорпције и алифатичности изолованих ХК уочена негативна корелација. Показано је да сорпциони процес може бити снажно условљен физичком конформацијом и доступношћу органске материје седимента (COM) на шта указују високе K_{oc} и ниске *n* вредности добијене за узорке хумина. Упркос томе што су узорци хумина дали сорпционе изотерме највеће нелинеарности, они нису показали изражену сорпционо–десорпциону хистерезу, док је најизраженија хистереза уочена за три узорка ХК. Ови резултати подржавају претпоставку да ароматичне области COM снажно утичу на сорпционо и десорпционо понашање линдана. Наша запажања могу бити корисна за разумевање расподеле, транспорта и судбине линдана у земљиштима и седиментима.

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