Sorptive affinity of ionic surfactants on silt loamy soil

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ABSTRACT
Due to their broad applications, ionic surfactants have already been released into or utilized in soil and environmental systems. However, current understanding on the sorption behavior of surfactants onto soils is still limited. This work systematically investigated the sorption kinetics and isotherms of one cationic surfactant, cetyltrimethylammonium bromide (CTAB), and one anionic surfactant, sodium dodecyl sulfate (SDS), onto a silt loamy soil to determine the governing sorption mechanisms. The pseudo-second-order rate equation described the sorption kinetics data better than the pseudo-first-order rate equation. Experimental data showed that the sorption equilibrium for CTAB and SDS were reached at 24 and 240 h, respectively. Langmuir equation was better than Freundlich equation in simulating the sorption isotherms of CTAB and SDS on the soil. Soil Langmuir maximum sorption capacity of CTAB was much higher than that to SDS. When the experimental temperature increased, the sorption of CTAB and SDS on the soil decreased. In addition, the sorptive process of the surfactants on the soil was spontaneous and exothermal, as indicated by the absolute values of Gibbs free energy and enthalpy. The results also indicated that physical sorption was the dominant mechanism for the sorption of the two surfactants on the soil. Findings from this work are crucial to understand the environmental behaviors of ionic surfactants.

1. Introduction
The term surfactant encompasses a whole family of compounds that possess both hydrophilic and hydrophobic groups in their structure. Because of this special amphiphilic structure, surfactants can significantly lower the surface tension of a solution.[1] One important property of surfactants is that they generate micelles in the aqueous solution. Micelles can form a hydrophobic microenvironment in the aqueous solution so as to improve the solubility of hydrophobic organic contaminants.[2–5] Due to such property, surfactants are widely used in the detergent industry. At present, almost all the detergents contain surfactants. There is a considerable amount of surfactant in washing discharge, which can't be removed in the conventional process of sewage treatment, so they just enter the natural water bodies. According to Wiel-Shafran et al. [6], concentration of surfactants in the treated greywater ranged from 0.7 to 70 mg L⁻¹. Freshwater resources have always been scarce in North China and there are great demands for the agricultural irrigation water,[7] so it is necessary to irrigate the land with the polluted water containing surfactants.[8,9] Surfactants are also intentionally used in contaminated soils to remove organic pollutants. The surfactant-enhanced remediation, the most potential remediation technology for organic pollutants in soil, has been widely used.[10–12] However, the drawbacks of this technique lie in that, during the remediation, a portion of surfactants are absorbed by the soil, which leads to the secondary pollution in the soil. It has been reported that residual surfactant concentrations in soil and groundwater can be as high as 2750 mg L⁻¹ even 450 days after the remediation event.[13] Moreover, surfactants are added into pesticide to enhance the wetting capability of active ingredients. During the process of spraying, some surfactants may directly drop into soil or adhere to leaves and stems, which may enter soil indirectly during irrigation or rainfall events.

When a surfactant enters the soil, it interacts with the soil components.[6] The sorption of ionic surfactants onto the surface of soil particles can alter the distribution on the surface of soil particles, which influences the stability of soil aggregates[14,15] and the adsorption and desorption of soil nutrient ions.[16] Surfactant micelles can dissolve organic matters from soil, especially the polysaccharide and the humus which are involved in the formation of soil aggregate. Consequently, it leads to an increased risk of the disintegration of soil aggregate.

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The destruction of soil aggregate will further change the condition of soil porosity, which will affect the soil aeration, the infiltration and movement of soil water.\cite{17–19}

Therefore, to study the sorptive affinity of surfactants on soils is of great significance to soil quality and environmental safety.

Some earlier studies are concerning the sorption of surfactants in geo-materials.\cite{20} The main focus were placed on the sorptive roles of soil components, such as soil organic matter and clay minerals, and the structure of surfactants, including the lengths of carbon chain, the position of benzene ring and the numbers of the hydrophilic groups, and environmental factors, such as pH and types of electrolyte. Chlou et al.\cite{21} reported that the partitioning of the soil organic compounds was the primary process for the sorption of nonionic organic compounds from water to soil. Qu et al.\cite{22} found that sorption of linear alkylbenzene (LAS) on a soil significantly depended on clay content of the soil. Shen\cite{23} proposed that soils with larger value of Si: (Al + Fe) ration exhibited higher sorption capacity for Polyethylene Mono-\-nonylphenyl Ether (A9PE10). Rodriguez-Cruz et al.\cite{24} studied the adsorption of sodium dodecyl sulfate (SDS) and octylphenoxypolyethoxyethanol (Triton X-100) on 18 soils and indicated that SDS was adsorbed mainly by the 1:1 mineral kaolinite and Triton X-100 by the 2:1 mineral montmorillonite and illite. Hand and Williams\cite{25} reported sorption affinity increased significantly as LAS chain length increased. For alkylbenzene sulfonates isomers, sorption increased significantly as phenyl position was changed from the 5- or 6- position to the 2-position. Rao and He\cite{26} suggested that, with the increase of pH, adsorption amount of sodium dodecylbenzenesulfonate (SDBS) and alcohol ethoxylates (A_{12}E_{9}) on soils decreased, and the reduction of ionic strength in soils also resulted in the decrease of SDBS and A_{12}E_{9} on soils. Dai et al.\cite{27} found that the adsorptive capacity of SDS and SDBS decreased on soil with the enhancement of temperature.

In the literatures, only a few studies have systematically investigated the sorption dynamics of surfactants on soils. This work investigated the sorption behavior and mechanisms of two typical ionic surfactants, cet- yltrimethylammonium bromide (CTAB) and SDS, on a silt loamy soil under various experimental conditions. Findings of this work not only provide the fundamental evaluation of the influence of surfactants on the physicochemical properties and the soil ecological security, but also support the theoretical basis for the implementation of pollution treatment and soil remediation using surfactants.

### 2. Materials and methods

#### 2.1. Materials

A soil sample was collected from Corn High-tech Park, Huang-Huai-Hai region, Shandong Agricultural University in May 2013. The soil type was Hapli-Ustic Argosols, and the texture was silt loam. After the soil was collected, it was air-dried indoor, and the visible roots and stones were removed. All the soil was ground and passed through 2 mm. A portion was milled and passed through 0.25 mm. The soil pH, CEC, the organic matter content, and texture of the soil was measured by common characterization methods,\cite{28} and the results were shown in Table 1.

CTAB and SDS were purchased from Tianjian Kaitong Chemical Reagent Company. CTAB is a cationic surfactant with purity of ≥99.0%, molecular formula of C_{19}H_{42}BrN, relative molecular mass of 364.45 g mol⁻¹, and the critical micelle concentration of about 400 mg L⁻¹.\cite{29,30} SDS is an anionic surfactant with purity of ≥99.0%, molecular formula of C_{19}H_{42}O_{3}Na, relative molecular mass of 288.4 g mol⁻¹, and the critical micelle concentration of about 1600 mg L⁻¹.\cite{24} The stock solutions at 1000 mg L⁻¹ of CTAB or SDS were prepared using the deionized water and were stored in 4 °C refrigerator for use.

#### 2.2. Sorption kinetics

The sorption kinetics experiments for CATB and SDS on the soil were conducted in batch experiment. The initial concentrations of the CTAB and SDS solutions were 2000 and 1000 mg L⁻¹, respectively. The soil sample that was sieved through the 2 mm was weighed and put into the centrifuge tubes of 35 mL. The ratio of water and soil was 62.5 for CTAB and 25 for SDS, respectively. Twenty-five milliliter of the surfactant (CTAB or SDS) solution was then added into the cube, and the cap of the centrifuge tube was sealed. The mixture was shaken at a speed of 220 r min⁻¹ at a constant temperature of 25 °C. Samples were taken after 0.5, 1, 2, 4, 7, 24, 48, 96, 168 h for CTAB and 1, 3, 5, 7, 12, 24, 48, 96, 168, 240 h for SDS and were centrifuged at 3381 g min⁻¹ for 10 min. The supernatant was collected to measure surfactant concentrations. The CTAB concentration in the supernatant was measured using the titration method,\cite{31} and the SDS concentration in the supernatant was measured using the colorimetry method.\cite{32} Each interval was repeated in triplicate and the sorption amount was calculated as follows:

\[
q_t = \frac{(C_0 - C_t) \times V}{m}
\] (1)
where \( q \) is the sorption quantity of the surfactant on the soil, and the unit is mg g\(^{-1}\); \( C_0 \) (mg L\(^{-1}\)) and \( C \) (mg L\(^{-1}\)) refer to the initial concentration and the concentration at time \( t \) of surfactants in the solution, respectively; \( V \) (L) means the volume of solvent; \( m \) (g) is the weight of soil sample.

### 2.3. Sorption isotherms

Based on sorption kinetic results, sorption equilibrium times for CTAB and SDS were determined as 48 and 240 h, respectively. The equilibrium time of SDS was much higher than the reported values in the literatures,[24,33] probably because the surfactant concentrations used in this work was much higher than that in the previous studies. The deionized water was used to dilute the CTAB (or SDS) stock solution into solutions of different concentrations between 100 and 2000 mg L\(^{-1}\) for use. A defined quantity of the soil samples was weighed and put into the centrifuge tube. CTAB (or SDS) of different concentrations was then added into the corresponding centrifuge tube, and the cap of the centrifuge tube was sealed. The mixture was shaken at a speed of 220 r min\(^{-1}\) at a constant temperature of 15, 25, or 35 °C. The oscillation was stopped after 48 h (or 240 h) and the tubes were centrifuged for 10 min at 3381 g min\(^{-1}\). The concentration of surfactant in the supernatant was measured by the same method as that employed in the kinetic experiment. The sorption amount was calculated using the Equation (1).

### 2.4. Modeling

#### 2.4.1. Simulation of CTAB and SDS sorption kinetics

There were extensive literatures reporting the simulation of solid–liquid sorption kinetic curves using different rate equations.[34–39] The pseudo-first-order (PFO) kinetic equation and the pseudo-second-order (PSO) kinetic equation were chosen for the simulation of the sorption kinetic curves of CTAB and SDS. The PFO kinetic equation was originally proposed by Lagergren in 1913, and had a variety of expression for sorption kinetics. The pseudo-first-order (PFO) rate equations.[34–39] The pseudo-second-order (PSO) kinetic equation were chosen for the simulation of the sorption kinetic curves using different rate equations.[34–39] The pseudo-first-order (PFO) rate equations.

#### 2.4.2. Description of CTAB and SDS sorption isotherms

The sorption isotherm curves of the solid–liquid sorption indicate the relation between adsorbed capacity and the equilibrium concentration. For the sorption isotherm curve, there are many model fitting equilibriums reported in the literature.[43–45] These authors had employed Langmuir and Freundlich equations to fit the sorption isotherm curves of CTAB and SDS on the soil. The general form of Langmuir is as following:

\[
q_e = \frac{q_m k_L C_e}{1 + k_L C_e} \tag{5}
\]

where \( q_e \) and \( q_m \) are the equilibrium sorption amount and the maximum sorption amount, and the unit for both of them is mg g\(^{-1}\); \( k_L \) is the Langmuir equilibrium constant, and the unit of it is L mg\(^{-1}\); \( C_e \) is the equilibrium concentration, and the unit of it is mg L\(^{-1}\); \( k_L \) is derived through the rate equation, and is a constant related to the sorption strength.

Freundlich formula is an empirical equation, and its general form is as followed:

\[
q_e = k_F C_e^{1/n} \tag{6}
\]

where \( k_F \) is Freundlich constant, and its unit is (mg g\(^{-1}\) (mg\(^{-1}\) L\(^{1/n}\)); \( 1/n \) is a dimensionless value, and is denoted the degree sorption intensity. The greater the value is, the easier the surface sorption becomes, and the smaller the non-linearity of sorption happens.

#### 2.4.3. Thermodynamic parameters of CTAB and SDS sorption

According to the thermodynamic principles in the domain of chemistry,[7] when the reaction is equilibrated, the standard Gibbs free energy (\( \Delta G^0 \)) and the standard equilibrium constant have the following relationship:
3. Results

3.1. Sorption kinetics curve of CTAB and SDS on the soil

The sorption kinetics of CTAB and SDS on the soil were processed and simulated with the PFO and PSO equations (Figure 1), and the relevant parameters were shown in Table 2. As shown, the fitting of sorption kinetics curves of CTAB on the soil through the PSO equation was quite good, and all the data points were almost located in the same line. However, the fitting of sorption kinetics curves of CTAB via the PFO equation was rather poor because the correlation coefficient was less than 0.1860. The equilibrium amount of CTAB detected in the experiment was 72.49 mg g⁻¹, and the equilibrium sorption amount fitted using the PSO equation was 72.20 mg g⁻¹ (Table 2), which is almost the same as the data obtained in the experiment. Moreover, the correlation coefficients (0.9997) for the fitting through the PSO equation was significantly higher than that of the PFO equation, suggesting the sorption kinetics of CTAB on the soil were well simulated with the PSO equation.

The sorption kinetic of SDS on the soil were fitted with PFO and PSO equations (Figure 1 (c) and (d)). In terms of the kinetic simulation for SDS on the soil, the correlation

\[ \Delta G_m^0(T) = -RT \ln K^0 \]  

(7)

where \( R \) is the constant of molar gas, and the unit for it is kPa L (mol K)⁻¹; \( T \) is the absolute temperature, the standard equilibrium constant, \( K^0 \) is a dimensionless value; the greater \( K^0 \) indicates the greater extent of the reaction, which is the reciprocal of relative equilibrium concentration.

According to Van’t Hoff equation, the standard enthalpy change of sorption reaction of surfactant can be written as:

\[ \ln \frac{K_2^0}{K_1^0} = \frac{\Delta H_m^0}{R} \left( \frac{T_2 - T_1}{T_1 T_2} \right) \]  

(8)

where \( \Delta H_m^0(T) \) is the enthalpy change, and its unit is kJ mol⁻¹; \( T_1 \) and \( T_2 \) are absolute temperatures; \( K_1^0, K_2^0 \) are corresponding standard equilibrium constants.

According to Gibbs–Helmholtz equation, the standard entropy change can be written as:

\[ \Delta S_m^0(T) = \Delta H_m^0 - T \Delta S_m^0 \]  

(9)

where \( \Delta S_m^0(T) \) is enthalpy and its unit is J (mol K)⁻¹.
concentration was relatively high ($C_e > 100$ mg L$^{-1}$), the fitting curves of Langmuir and Freundlich equations deviated. The Langmuir equation appeared to have a closer fit with the data points than the Freundlich (Figure 2). Consequently, Langmuir equation fitted CTAB and SDS sorption on the soil better. Concerning CTAB sorption isotherms, the correlation coefficients of Langmuir and Freundlich equations were 0.9339 and 0.9252, respectively, and the correlation coefficients of Langmuir and Freundlich equations for SDS sorption isotherms were 0.9568 and 0.8368, respectively (Table 3). Both of them showed that, in terms of the fitting with the sorption of CTAB and SDS on the soil, Langmuir equation significantly outperformed Freundlich equation.

3.3. Sorption mechanisms of CTAB and SDS on the soil

Temperature is one of important environmental factors that affect the surfactant sorption. [4] The authors had measured the sorption isotherm curve of CTAB and SDS on the soil at three different temperatures, 288, 298 and 308 K, respectively (Figure 3). When the equilibrium concentration was relatively high ($C_e > 100$ mg L$^{-1}$), the fitting curves of Langmuir and Freundlich equations deviated. The Langmuir equation appeared to have a closer fit with the data points than the Freundlich (Figure 2). Consequently, Langmuir equation fitted CTAB and SDS sorption on the soil better. Concerning CTAB sorption isotherms, the correlation coefficients of Langmuir and Freundlich equations were 0.9339 and 0.9252, respectively, and the correlation coefficients of Langmuir and Freundlich equations for SDS sorption isotherms were 0.9568 and 0.8368, respectively (Table 3). Both of them showed that, in terms of the fitting with the sorption of CTAB and SDS on the soil, Langmuir equation significantly outperformed Freundlich equation.

3.2. Sorption isotherms of CTAB and SDS on the soil

The sorption isothermal data (298 K) of CTAB and SDS on the soil were fitted with Langmuir and Freundlich equations (Figure 2), and the relevant parameters for the fitting were shown in Table 3. When the equilibrium concentration was very low ($C_e < 50$ mg L$^{-1}$), the data were well fitted with the Langmuir and Freundlich equations; however, when the equilibrium concentration was relatively high ($C_e > 100$ mg L$^{-1}$), the fitting curves of Langmuir and Freundlich equations deviated. The Langmuir equation appeared to have a closer fit with the data points than the Freundlich (Figure 2). Consequently, Langmuir equation fitted CTAB and SDS sorption on the soil better. Concerning CTAB sorption isotherms, the correlation coefficients of Langmuir and Freundlich equations were 0.9339 and 0.9252, respectively, and the correlation coefficients of Langmuir and Freundlich equations for SDS sorption isotherms were 0.9568 and 0.8368, respectively (Table 3). Both of them showed that, in terms of the fitting with the sorption of CTAB and SDS on the soil, Langmuir equation significantly outperformed Freundlich equation.

![Figure 2. Sorption isotherms of CTAB and SDS on soil. Notes: full line: Langmuir equation; dotted line: Freundlich equation.](image)

![Figure 3. Sorption isotherms of CTAB and SDS on soil under different temperatures.](image)

| Equations     | Parameters       | Parameters       | CTAB | SDS |
|---------------|------------------|------------------|------|-----|
| Langmuir      | $A$              | 50.39            | 3.86 |
|               | $R^2$            | 0.9339           | 0.9568|
|               | $q_m$ (mg g$^{-1}$) | 78.85           | 26.13 |
|               | $k_l$ (L mg$^{-1}$) | 0.0622          | 0.2054|
| Freundlich    | $A'$            | 57.00            | 14.60 |
|               | $R^2$            | 0.9252           | 0.8368|
|               | $1/n$            | 0.2378           | 0.1793|
|               | $k_p$ (mg g$^{-1}$) (mg$^{-1}$ L$^{1/3}$) | 18.71 | 8.91 |
The enthalpies of CTAB and SDS on the soils were $-44.50$ and $-60.37$ kJ mol$^{-1}$ (Table 4), respectively, indicating the sorption of CTAB and SDS on the soils spontaneously occurred. According to the size of absolute values of Gibbs free energy, the sorption process can be divided into physical sorption and chemical sorption. The absolute value of Gibbs free energy is generally lower than 20 kJ mol$^{-1}$ for the physical sorption and is generally higher than 80 kJ mol$^{-1}$ for the chemical sorption. Since the absolute values of Gibbs free energy for the sorptions of both of CTAB and SDS on the soils are lower than 20, the mechanism of sorptions of both of them was probably physical.

| Surfactants | Temperature (°C) | $K^0$ | $\Delta H_m^0$ (kJ mol$^{-1}$) | $\Delta S_m^0$ (J (mol k)$^{-1}$) | $\Delta G_m^0$ (kJ mol$^{-1}$) |
|-------------|------------------|-------|-----------------------------|----------------------------------|-------------------------------|
| CTAB        | 288              | 219.09±15.72 | $-12.90 \pm 0.18$ | $-12.90 \pm 0.09$ | $-44.50 \pm 1.20$ | $-60.37 \pm 5.48$ |
|             | 298              | 114.71±3.91  | $-11.75 \pm 0.09$ | $-10.71 \pm 0.07$ | $-109.78 \pm 0.07$ |
|             | 308              | 65.48±1.88   | $-10.26 \pm 0.16$ | $-8.84 \pm 0.12$ | $-167.58 \pm 0.36$ |
| SDS         | 288              | 163.58±5.52  | $-12.20 \pm 0.08$ | $-60.37 \pm 5.48$ | $-167.58 \pm 0.36$ |
|             | 298              | 63.05±4.08   | $-10.71 \pm 0.07$ | $-8.84 \pm 0.12$ | $-167.58 \pm 0.36$ |

The sorption amount of CTAB on the soil was much greater than that of SDS (Langmuir equation). At the temperature of 25 °C, the maximum sorption amounts of CTAB and SDS were 78.85 and 26.13 mg g$^{-1}$, respectively. Zhang and Zeng [48] found that, the maximum sorption amounts of CTAB and SDS on alkaline soil in Beijing were 100.00 and 35.10 mg g$^{-1}$, respectively. The reason is that the number of negative charges is much greater than the number of positive charges in the soil colloid, and the sorption amount of CTAB that carries positive charges is much higher than the sorption amount of SDS which carries negative charges. Xu and Boyd [14] also suggested that the sorption of CTAB on the soil initially occurred by means of exchanges of positive ions.

The enthalpies of CTAB and SDS on the soils were $-44.50$ and $-60.37$ kJ mol$^{-1}$ (Table 4), respectively, which suggested that the sorption occurred spontaneously. The enthalpy changes of both CTAB and SDS were negative, which suggests that the sorption of them on the soils is exothermic processes. It is generally believed that, when the absolute value of Gibbs free energy changes was smaller than 20 kJ mol$^{-1}$, the sorption mechanism was physical. [46] Therefore, the sorption of CTAB and SDS on the soil was mainly controlled by physical sorption. The entropy changes of CTAB and SDS were also negative, because CTAB and SDS were adsorbed to the soil particles in the form of solutions, and the disorder degree of solid–liquid system reduced.

The initial sorption of CTAB and SDS on the soil surface occurred by means of ion pairing and ion exchanges. Because the ion bond energy was relative large, the surfactant molecules were tightly bound to the soil particles, and the temperature had little influence on the sorption. With the saturation of the ion sorption points, the sorption of CTAB and SDS on soil particles occurred mainly through the hydrophobic interaction. Because the bond energy of hydrophobic force was relatively small, it was dependent on the temperature. Therefore, it easily damaged hydrophobic force when the temperature rose, which leads to reduce sorption amount of CTAB and SDS on the soil. Dai and Dong [4] also found that the sorption amount of SDS on the soil decreased as the temperature rose, while the sorption amount of non-ionic type surfactant Tween-80 enhanced as the temperature rose. They provided the explanation from the angle of variation of solubility with the temperature changes. The elevating temperature raised the solubility of ionic-type surfactant in the water solution, and its tendency

### Table 4. Thermodynamic parameters of CTAB and SDS sorption on soil.

| Surfactants | Temperature (°C) | $K^0$ | $\Delta H_m^0$ (kJ mol$^{-1}$) | $\Delta S_m^0$ (J (mol k)$^{-1}$) | $\Delta G_m^0$ (kJ mol$^{-1}$) |
|-------------|------------------|-------|-----------------------------|----------------------------------|-------------------------------|
| CTAB        | 288              | 219.09±15.72 | $-12.90 \pm 0.18$ | $-12.90 \pm 0.09$ | $-44.50 \pm 1.20$ | $-60.37 \pm 5.48$ |
|             | 298              | 114.71±3.91  | $-11.75 \pm 0.09$ | $-10.71 \pm 0.07$ | $-109.78 \pm 0.07$ |
|             | 308              | 65.48±1.88   | $-10.26 \pm 0.16$ | $-8.84 \pm 0.12$ | $-167.58 \pm 0.36$ |
| SDS         | 288              | 163.58±5.52  | $-12.20 \pm 0.08$ | $-60.37 \pm 5.48$ | $-167.58 \pm 0.36$ |
|             | 298              | 63.05±4.08   | $-10.71 \pm 0.07$ | $-8.84 \pm 0.12$ | $-167.58 \pm 0.36$ |

### Discussion

The sorption kinetics of exogenous substance on soil represents the sorption speed, which is closely related to the contact time. In the present studies, the FSO equation fitted the sorption kinetics of CTAB and SDS on the soil very well. By using the sorption kinetics equations, it was confirmed that, under the current experiment conditions, the sorption equilibrium time of CTAB and SDS on the soil were 48 and 240 h, respectively. Paria et al. [47] studied the sorption kinetics curve of CTAB and SDS on cellulose and found that the sorption rate of CTAB was higher than that of SDBS.

In this work, the Langmuir equation modeled the sorption isotherm of CTAB and SDS on the soil better than the Freundlich equation. Similarly, Zhang and Zeng [48] had investigated the sorption isotherm on brown soil in Shandong province, China, and recognized that Langmuir was more suitable in simulating the experimental data. However, for some researchers, they preferred the Freundlich equation to describe the adsorptive isotherms by surfactants. [24,33] The explanations for the difference may be the discrepancy of the concentrations used by us. In their studies, the concentrations were usually much lower than 100 mg L$^{-1}$, the lowest concentration we used. For example, the highest concentration of LAS used by Rubio et al. [33] was 1000 ng L$^{-1}$, with the help of the $^{14}$C-labeled, the concentration of AE ranged from 0.3 to 900 nM in Brownawell et al. study,[49] and the concentrations of SDS and Triton X-100 was not higher than 100 μg L$^{-1}$ in Rodriguez-Cruz et al. [24] research. At such low concentration, the $C_e$ vs. $Q$ was linear and the maximum sorption was not reached far. So it was valid to identically describe the adsorptive isotherms by Freundlich equation.
of escaping from the aqueous solution decreased, which thus resulted in reducing the adsorbed amount on the solid surface.

5. Conclusions

Compared with SDS, there was less time required for the CTAB sorption onto the soil to reach the equilibrium. The PSO rate equation fitted the sorption kinetics curve of CTAB and SDS on the soil well. The sorption amount of CTAB on the soil was much higher than that of SDS; Langmuir equation better simulated the sorption isotherms of CTAB and SDS on the soil at higher equilibrium concentrations. The sorption of CTAB and SDS on the soil was controlled by a spontaneous heat-release process. The governing sorption mechanism was physical, which was dominated by ion exchange and hydrophobic interactions.

Funding

This research was funded by the National Natural Science Foundation of China [No. 21377074]; Specialized Research Fund for the Doctoral Program of Higher Education [2012370212003], Ministry of Education, China and China Postdoctoral Science Foundation on the 54th grant project.

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