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RESEARCH ARTICLE

Effects of soil properties on the remediation of diesel-contaminated soil by Triton X-100-aided washing

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Abstract
Although nonionic surfactant is widely used for petroleum-contaminated soil washing, there is no definite conclusion on the main soil factors which determine the removal of petroleum hydrocarbons from the soil. In this study, the influences of soil properties on Triton X-100-aided soil washing were investigated using 12 soils in China. The sorption characteristic of Triton X-100 on soils was described as well. The sorption isotherms of Triton X-100 on 12 typical soils were fitted to the Langmuir adsorption model, and the maximum sorption amount of Triton X-100 (Q_{max}) varied from 1.54 to 15.15 mg/g. The removal rates of diesel for 12 soils were well fitted to the modified Michaelis-Menten equation, and the maximum removal rate of diesel (φ_{max}) ranged from 62.92 to 90.36%. The correlation analysis indicated that the φ_{max} is significantly correlated with the Q_{max}. The soil factors affecting diesel removal from soils followed the order of sand content > cation exchange capacity (CEC) > organic matter (OM) content > silt and clay content > SSA >> pH. The prediction model based on CEC, silt content, and pH explained 83.1% of variance of diesel removal from soils. This study will have important implication for successfully remediating organic-contaminated soil using nonionic surfactant-based soil washing.

Keywords Soil properties · Diesel · Triton X-100 · Sorption isotherms · Main factors · Prediction model

Introduction

Petroleum hydrocarbons, as highly hydrophobic organic pollutants, have been found the subsurface of soil as a result of the leakage of traffic accidents, damaged pipelines, and storage tanks (Pasha et al. 2011). These organic pollutants are readily adsorbed onto soil particles, representing a long-term pollution source of soil and groundwater, which threaten the ecological environment and human health (Huguenot et al. 2015; Guarino et al. 2017). Recently, a variety of physical, chemical, and biological approaches have been developed to clean up petroleum-contaminated soil (Li et al. 2015; Robert et al. 2017; Lominchar et al. 2018; Bajagain et al. 2018; Song et al. 2017). As for high concentrated hydrocarbons in soil, surfactant-aided washing is an efficient and extensive treatment technique because of its ability to lower interfacial tension and to improve the water solubility of petroleum hydrocarbons (Lai et al. 2009; Hernández-Espriú et al. 2013; Mao et al. 2015; Cecotti et al. 2018).

Nonionic surfactant such as Triton X-100 is widely used in soil washing for its relatively low critical micelle concentrations (110 mg/L) and low toxicity (Chatterjee et al. 2010; Luo et al. 2010; Cheng et al. 2017). However, nonionic surfactants can also sorb onto contaminated soils, thus reducing its concentration in washing solution, which is unfavorable for petroleum hydrocarbon removal in washing process (Zhang et al. 2012). More importantly, the surfactants sorbed onto soils can be used as an effective distribution medium for

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petroleum hydrocarbons, which further complicates the sorption and desorption mechanism of petroleum hydrocarbons with water-soil system (Ussawarujikulchai et al. 2008; Yang et al. 2011; Mao et al. 2015). To fully understand the removal mechanism of petroleum hydrocarbon from soils by nonionic surfactant, it is critical to investigate the sorption behavior of nonionic surfactant onto soils.

Meanwhile, it is increasingly recognized that soil properties, such as soil particle size and organic matter (OM), significantly influence the removal of petroleum hydrocarbon by surfactant-aided soil washing (Zhou and Zhu 2007; Befkadu and Chen 2018). However, single factor was often studied for a certain contaminated soil washing in previous works, which is difficult to get the main soil factors for determining the removal of petroleum hydrocarbons. Petroleum-contaminated soils are widely distributed in China, and the soil properties vary greatly in different regions (Liang et al. 2011, 2012). Therefore, it is interesting to study the combination effects of soil properties which affect the removal of petroleum hydrocarbons from different types of soils by surfactant-aided washing.

In this study, diesel was chosen as the typical pollutant of petroleum hydrocarbons because it is widely used in the society (Serrano et al. 2008; Ramírez-Camacho et al. 2017). The objectives were (1) to investigate the effects of soil properties on Triton X-100 sorption on soil and diesel removal from soil and (2) to develop empirical models based on soil properties for predicting diesel removal by surfactant-aided washing. The results are expected to provide important information for removing diesel from contaminated soils by surfactant-aided soil washing.

Materials and methods

Soil sampling and analysis

The 12 tested soils (depth, 0–20 cm) were collected from Qinghai, Zhejiang, Chongqing, Shaanxi, Hainan, Henan, Hebei, Jiangsu, Jiangxi, Beijing, Jilin, and Heilongjiang, respectively. These soils generally represent typical soils in China and cover a wide range in soil types and properties. The soil samples were naturally air dried at room temperature in the laboratory and sieved through a 2-mm mesh sieve. Then, the soil samples were stored at room temperature in polyethylene bottles.

Soil properties were analyzed following standard procedures proposed by Lu (1999). The soil pH was measured in a 1:2.5 (w/v) soil/water suspension after 1-h equilibration using a SevenCompact™ S210 pH Meter (Mettler-Toledo). The soil OM was measured by the potassium dichromate volumetric method. The particle size of the soils was analyzed by the wet sieving and the pipette method. The ammonium acetate method and the nitrogen adsorption method were used to measure the cation exchange capacity (CEC) and specific surface area (SSA) of soil, respectively. The soil classifications and soil properties are shown in Table 1.

Preparation of diesel-contaminated soil

The 12 contaminated soils were artificially prepared by diesel (dissolved in n-hexane solvent) at the same condition. Five hundred milliliter of n-hexane solution containing 25 mL of diesel was added into a round-bottom flask containing 200.00 g of soil. Then, the round-bottom flask containing soil and diesel solution was shaken for 48 h in a thermostatic oscillator. After the sorption balance, the n-hexane solvent from the round-bottom flask was removed using a rotary evaporator. The diesel-contaminated soils were aged in a fume hood for 30 days, then kept in a closed vessel, and stored in a refrigerator at 4 °C.

Sorption experiments of Triton X-100

Sorption experiments of Triton X-100 were carried out at 25 ± 1 °C in the dark in 40 mL centrifuge tubes. Ten milliliter of Triton X-100 with different concentrations (200–2000 mg/L) dissolved in deionized water were added into the centrifuge tubes, and then 1.00 g soil samples were added to the centrifuge tubes at an unadjusted pH. All centrifuge tubes were sealed. The mixed soil solution was shaken by thermostatic oscillator at 200 rpm for 24 h. Preliminary experiments showed that the adsorption equilibrium of surfactants onto soils has been reached at 24 h. The centrifuge tubes were then centrifuged at 4000 g for 10 min at 25 ± 1 °C. After centrifugation, 1.0 mL of the supernatant was filtered immediately through a 0.2-μm nylon filter for concentration analysis of Triton X-100 by HPLC with a UV detector (Shimadzu). All experiments were executed in triplicate.

Removal experiments of diesel in the presence Triton X-100

The experimental condition of diesel removal from soils by Triton X-100-aided soil washing was same as the sorption experiments of Triton X-100. 1.00 g of the diesel-contaminated soil sample and 10 mL of Triton X-100 solution with different concentrations (0–5000 mg/L) were added to a centrifuge tube. All centrifuge tubes were sealed. The mixed soil solution was shaken by thermostatic oscillator at 200 rpm for 24 h and then centrifuged at 4000 g for 10 min at 25 ± 1 °C. The supernatants were used to determine the concentrations of Triton X-100 and diesel. All experiments were executed in triplicate.

Table 1 Soil properties, the maximum sorption amount of Triton X-100, and the maximum removal rate of diesel for all tested soils

Soil no.	Classification (location)[a]	pH	SSA (m^2/g)	OM (g/kg)	CEC (cmol/kg)	Sand (%)	Silt (%)	Clay (%)	C_{10}-C_{26} (mg/kg)	Q_{max} (mg/g)	φ_{max} (%)
1	Black soil (Heilongjiang)	8.0	1.40	47.90	34.90	40.60	16.10	43.30	2889.59 ± 105.85	15.15	62.92
2	Black soil (Jilin)	6.9	1.53	31.30	26.00	33.06	26.71	40.23	3243.94 ± 216.02	13.14	65.59
3	Fluvo-aquic soil (Beijing)	7.3	1.02	10.58	7.20	73.25	15.12	11.63	2809.73 ± 186.41	7.72	72.63
4	Fluvo-aquic soil (Hebei)	8.0	1.15	11.50	12.20	60.47	17.02	22.51	2867.25 ± 153.46	7.72	72.66
5	Paddy soil (Zhejiang)	5.1	1.35	23.40	9.24	59.99	26.62	13.39	2578.75 ± 128.74	9.44	73.21
6	Fluvo-aquic soil (Henan)	8.0	0.99	13.60	9.35	85.40	3.86	10.74	2902.98 ± 155.34	5.11	74.44
7	Red earth (Jiangxi)	5.8	1.67	14.60	10.50	63.41	13.08	23.51	2938.05 ± 424.30	7.59	75.64
8	Paddy soil (Jiangsu)	7.8	1.35	20.20	15.70	64.34	10.33	25.33	2924.82 ± 57.67	9.03	77.70
9	Purple soil (Chongqing)	7.4	1.66	8.38	18.20	66.69	5.65	27.66	2779.97 ± 94.28	10.85	78.06
10	Gray desert soil (Qinghai)	7.9	1.03	23.10	5.81	73.38	7.36	19.26	2844.87 ± 435.36	4.95	79.89
11	Loessal soil (Shaanxi)	8.8	0.85	1.35	2.57	79.07	4.55	16.38	2315.38 ± 388.42	4.85	79.98
12	Sandy soil (Hainan)	5.7	0.39	3.26	1.92	94.30	0.80	4.90	2205.79 ± 12.33	1.54	90.36

[a] Soil classification according to the "Classification and codes for Chinese soil" (GB/T 17296-2000)

Extraction and analysis

For analyzing the diesel concentration in aged soil, 1.00 g of the aged soil sample and 5 mL of dichloromethane were added into a centrifugal tube, performed by ultrasound for 30 min, and the soil solution was centrifuged at 4000 rpm for 10 min. These procedures were performed by three repetitions; then, the supernatant of dichloromethane was concentrated to 1 mL, and 1 μL sample was injected into the GC-MS.

For analyzing the diesel concentration in supernatant, 5 mL of liquid sample and 5 mL of dichloromethane were transferred into a glass centrifugal tube. To avoid the formation of a trouble solution (supposed to be an emulsion), 200 μL of sulfuric acid (1:1) was added to the centrifugal tube. Then, the glass centrifugal tube was stirred for 2 min and centrifuged at 6000 rpm for 20 min to separate the organic phase. The organic phase was evaporated to 1 mL, and 1 μL sample was injected into the GC-MS.

In this study, n-alkane compounds (C_{10}-C_{26}) are selected as representative components because of their high proportion in diesel (Khalladi et al. 2009). The concentrations of n-alkanes were analyzed by GC-MS (7890A-5975C, Agilent, USA). A DB-5 capillary column (30 m × 0.25 mm internal diameter, 0.25 μm film thickness; Agilent, USA) was used, and the carrier gas was helium (purity, 99.999%). The flow rate was 1.5 mL/min. The oven temperature of GC was programmed from 50 (2 min) to 250 °C at 8 °C/min (3 min). The temperatures of the injector, ion source, and transfer line were set to 250 °C, 230 °C, and 280 °C, respectively.

Aqueous Triton X-100 concentrations were quantified by HPLC-UV detector (LC-20A, Shimadzu, Japan). A Syncronis aQ C18 column (240 mm × 4.6 mm, 5 μm; Thermo, USA) was used. The mobile phase was methanol and water (85:15), and the flow rate was 1 mL/min. Column temperature was maintained at 25 °C. The UV wavelength was set at 224 nm.

Statistical analyses

The Langmuir adsorption equation was used to fit the sorption data of Triton X-100, and the linearized form is as follow: (Hu et al. 2017)

$$\frac{Q_{\max}}{Q} = \frac{1}{C_e} + K \quad (1)$$

where Q is the sorption amount of Triton X-100 onto soils (mg/g), C_e is the concentration of Triton X-100 in the solution (mg/L) at equilibrium, Q_{max} is the maximum sorption amount of Triton X-100 (mg/g), and K is the sorption equilibrium constant (L/mg).

The practical model was used to predict the removal behavior of diesel by surfactant-aided soil washing. The modified Michaelis-Menten equation was shown below: (Chu et al. 2006)

$$[\mathrm{Diesel}] = \frac{[\mathrm{Triton}] \times [\mathrm{Diesel}]_{\max}}{a + [\mathrm{Triton}]} \quad (2)$$

The maximum removal rate of diesel (φ_{max}, %) and the removal rate of diesel (φ, %) obtained from the experiment were calculated using the following equations:

$$\varphi_{max} = \frac{[\text{Diesel}]_{max} \times v}{[\text{Diesel}]_{soil} \times m} \times 100 \quad (3)$$

$$\varphi = \frac{[\text{Diesel}] \times v}{[\text{Diesel}]_{soil} \times m} \times 100 \quad (4)$$

where [Diesel] is the measured concentration of diesel extracted to the supernatant (mg/L), $[\text{Diesel}]_{max}$ is the maximum removal concentration of diesel (mg/L), $[\text{Diesel}]_{soil}$ is the initial concentration of C_{10}-C_{26} for spiked soils, [Triton] is the aqueous concentration of Triton X-100 (mg/L), m and v are the soil weight (g) and the liquid volume (mL), and the a is a characteristic constant.

Results and discussion

Analysis of the soil properties

The initial concentration of diesel (C_{10}-C_{26}) and soil properties were measured, and the results are stated in Table 1. For all soils, the initial concentration of diesel ranged from 2315.38 for loessal soil (Shaanxi) to 3243.94 mg/kg for black soil (Jilin). The soil pH ranged from 5.1 (Zhejiang paddy soil) to 8.8 (Shaanxi loessal soil). The SSA values ranged from 0.39 (Hainan sandy soil) to 1.53 m^2/g (Jilin black soil). The highest content of OM, CEC, and clay in Heilongjiang black soil and the values were 47.90 g/kg, 34.90 cmol/kg, and 43.30%, while 35.48, 18.18, and 8.84-fold were the lowest values, respectively. Correlation analysis showed the strong autocorrelation between soil properties, such as SSA, OM, CEC, sand content, and clay content (Table 2), which was consistent with previous studies (Klement et al. 2017; Yan et al. 2011; Kodešová et al. 2015).

Triton X-100 sorption isotherms

The sorption curves of Triton X-100 onto all soils are presented in Fig. 1. Triton X-100 sorption onto all soils exhibited similar sorption behavior, with the exception of Heilongjiang and Jilin black soil, with sorption first increased with the increase of Triton X-100 concentrations in aqueous until a saturation sorption capacity was reached. Due to the strong sorption capacity of Heilongjiang and Jilin black soils, the sorption saturation of Triton X-100 onto these two soils was not reached in the experimental concentration. The isotherms obtained of Triton X-100 were well fitted to the Langmuir model ($R^2 \geq 0.91$, $p < 0.01$), and the Q_{max} were determined to be 1.54–15.15 mg/g (Table 1). The highest and the lowest Q_{max} values among 12 Chinese soils represented 9.84-fold variations, suggesting a significant effect of soil properties on Triton X-100 sorption.

Pearson correlation coefficients were generated for describing the relationship between the Q_{max} values and soil properties. As shown in Table 3, the best correlation was found between CEC and Q_{max} with a positive correlation coefficient of 0.928, suggesting that CEC in soil was the dominant phase for Triton X-100 sorption. It is speculated that a patchy bilayer of the sorbed Trion X-100 is formed, with the base layer consisting of the "head-on" sorbed Trion X-100 held on the hydrophilic (i.e., charged) patches of the soil surface (Edward et al. 1994); On the other hand, a relatively large amount of organic colloids or minerals in soils with high content of CEC, which sorb TritonX-100 most likely through hydrogen bonding. This speculation was supported by the study of Zhu et al., who reported that montmorillonite and illite in soils have strong sorption power for Triton X-100 (Zhu et al. 2003). Since there existed strong autocorrelation between soil properties (Table 2), the Q_{max} was also highly correlated to SSA, OM, and clay content with a correlation coefficient of 0.784, 0.769, and 0.881, respectively.

These high correlations have been reported by previous studies, but the results were contradictory. For example,

Table 2 The correlation coefficients describing relationship between soil properties

	pH	SSA (m^2/g)	OM (g/kg)	CEC (cmol/kg)	Sand (%)	Silt (%)	Clay (%)
pH	1						
SSA	−0.082	1					
OM	0.014	0.473	1				
CEC	0.156	0.643*	0.823**	1			
Sand	0.001	−0.738**	−0.788**	−0.854**	1		
Silt	−0.345	0536	0.577*	0.474	−0.804**	1	
Clay	0.252	0.706*	0.749**	0.923*	−0.899**	0.462	1

* Significant correlation at 0.05 level

** Extremely significant correlation at 0.01 level

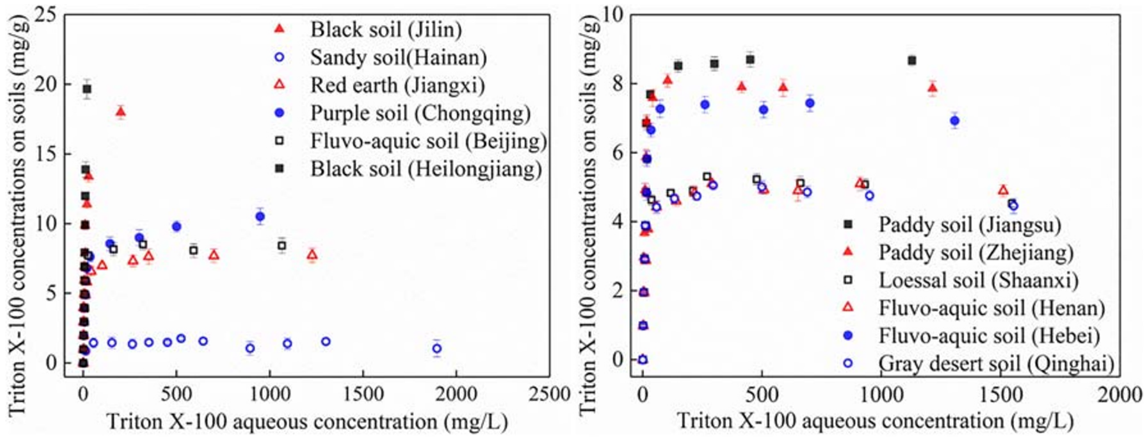

Fig. 1 Sorption isotherms of Triton X-100 onto all soils

Mata-Sandoval et al. showed that the Q_{max} did not correlate with OM content but was controlled by clay content in soils (Mata-Sandoval et al. 2002). The study of Wang and Keller revealed that Triton X-100 sorption capacity was highly dependent on the CEC and soil fractions (Wang and Keller 2008). However, Ussawarujikulchai et al. indicated that the amount of Triton X-100 sorbed onto soil increased with the increase of soil organic content (Ussawarujikulchai et al. 2008). This may be due to the fact that only one or two soil properties were investigated in previous studies when studying Triton X-100 sorption onto soils. The soil factors affecting Triton X-100 sorption onto soils were investigated using 12 typical soils in China and followed the order of CEC > sand content > clay content > SSA > OM content > silt content >> pH.

Diesel removal in the presence of Triton X-100

Diesel removal from 12 soils by Triton X-100-aided soil washing at different Triton X-100 concentrations (0–5000 mg/L) was investigated. As shown in Fig. 2, the removal rate of diesel for all soils showed a similar trend: the removal rate of diesel decreased first and then increased until the maximum removal rate was reached, with the increase of Triton X-100 initial concentration. For example, when the initial concentration of Triton X-100 increased from 0 to 200 mg/L, the removal rates of diesel for loessal soil (Shaanxi), fluvo-aquic soil (Hebei), black soil (Jilin), purple soil (Chongqing), and fluvo-aquic soil (Beijing) were decreased by 5.51%, 4.10%, 6.98%, 5.30%, and 4.43%, respectively. The reason was probably due to the sorption of Triton X-100 onto the soils and subsequent partitioning of the diesel into the sorbed surfactant before the critical micelle concentration was reached (Wang and Keller 2008). Therefore, compared with the removal of diesel from contaminated soils by deionized water, low concentration of Triton X-100 exhibits a lower removal rate of diesel. At higher initial concentration of Triton X-100 (> 1000 mg/L), the removal rate of diesel rapidly increased with the increase of the Triton X-100 concentration due to the presence of surfactant micelles. At 5000 mg/L concentration of Triton X-100, the removal rates of diesel for all soils were over 60%, with the exception of Heilongjiang and Jilin black soils.

Table 3 The correlation coefficients describing relationship between soil properties and C_{10}-C_{26}, Q_{max} and φ_{max}

	C_{10}-C_{26} (%)	Q_{max} (mg/g)	φ_{max} (%)
pH	0.091	0.064	− 0.181
SSA	0.643*	0.784**	− 0.625*
OM	0.572	0.769**	− 0.764**
CEC	0.636*	0.928**	− 0.793**
Sand	− 0.663*	− 0.920**	0.854**
Silt	0.472	0.667*	− 0.733**
clay	0.641*	0.881**	− 0.733**

* Significant correlation at 0.05 level

** Extremely significant correlation at 0.01 level

Previous study proposed a model by modifying Michaelis-Menten equation for the prediction of partitioning behavior of organic pollutants in soil-water system (Chu et al. 2006). Therefore, this model was used to fit the removal process of diesel by Triton X-100-aided soil washing. The removal data of diesel for all soils obtained from experiments were well fitted to the model ($R^2 \geq 0.92$, $p < 0.01$). The maximum removal rates of diesel (φ_{max}) were calculated by Eq. (3). The φ_{max} ranged from 62.92 (Heilongjiang black soil) to 90.36% (Hainan sand soil) and highly correlated with the removal rate of diesel obtained from the experiments (Fig. 3a).

Influence of soil properties on diesel removal by Triton X-100-aided washing

Relationships between the φ_{max} and soil properties (pH, SSA, CEC, OM, sand, silt, and clay contents) were analyzed and shown in Table 3. The φ_{max} was highly correlated to sand

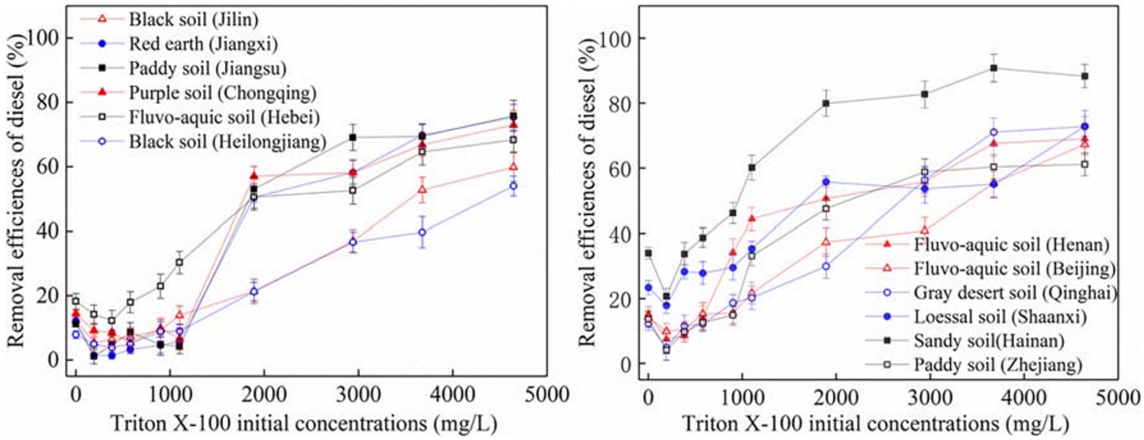

Fig. 2 The removal rates of diesel for 12 soils by Triton X-100-aided soil washing

content with a positive correlation coefficient of 0.854 ($p < 0.01$), suggesting that the diesel in contaminated soils was easier to be removed by Triton X-100-aided soil washing with the increase of sand content in soils. The negative correlations between the initial concentration of C_{10}-C_{26} and sand content ($p < 0.05$) indicated that the soil with high sand

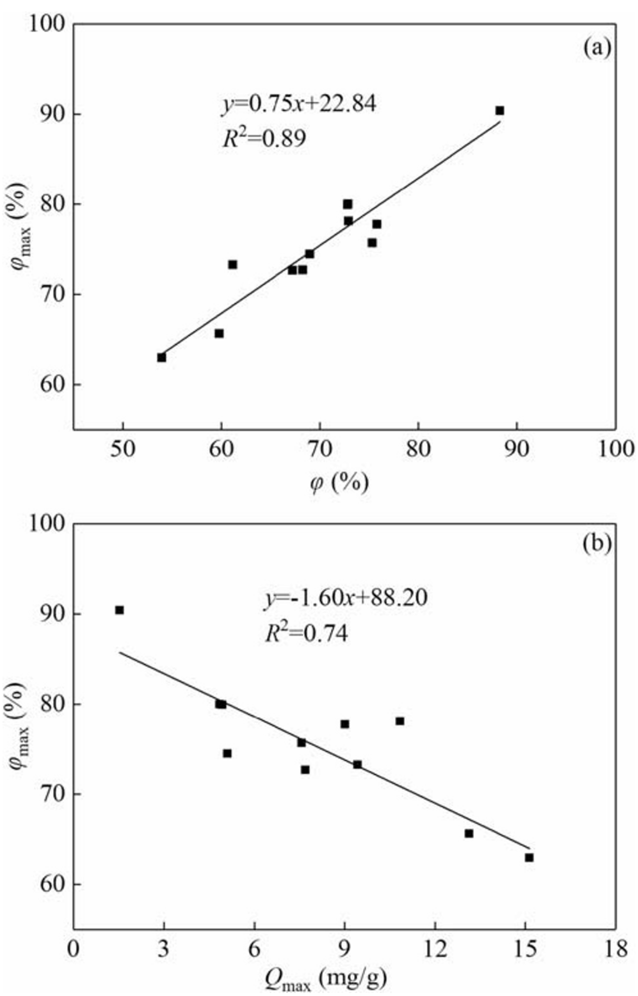

Fig. 3 Relationships between the φ_{max} and the φ (**a**) and the Q_{max} (**b**)

content have a low sorption capacity for diesel, which contribute to the removal of diesel by surfactant-aided soil washing. Falciglia et al. also found that the sorption capacity of diesel on soil showed a logarithmic trend with a variation of soil texture (Falciglia et al. 2011). Moreover, a significant negative correlation ($p < 0.01$) was also obtained between the φ_{max} value and SSA, OM content, CEC, silt content, and clay content, respectively. Recently, studies have shown that SSA, OM content, and soil texture (e.g., sand content and clay content) have a great influence on the removal or partitioning behavior of organic contaminants (Zhou and Zhu 2007; Wang and Keller 2008; Wu et al. 2015); however, the effect of CEC on diesel removal from soils by Triton X-100-aided soil washing has not been reported so far.

To clarify the effect of CEC on the diesel removal by Triton X100-aided soil washing, the relationship between the Q_{max} and the φ_{max} was quantified by linear regression. As shown in Fig. 3b, the φ_{max} negatively correlated with the Q_{max} ($R^2 =$ 0.74), suggesting that the removal of diesel from contaminated soil by surfactant-aided soil washing mainly depends on the sorption loss of surfactants in water-soil system. Due to the strong sorption of Triton X-100 on soils with high CEC content, the concentration of Triton X-100 used for removing the diesel from the soil was decreased.

Prediction for the removal rate of diesel based on soil properties

The empirical relationships based on soil properties were established by regression analysis. In this study, regression equations were developed based on SSA, OM content, CEC, sand content, silt content, and clay content (Table 4). Table 4 shows that the φ_{max} obtained from the modified Michaelis-Menten equation correlated well ($p < 0.05$) with the SSA, clay content, and silt content; the regression models with these parameters as predictors explained 33.0%, 49.1%, and 49.1% of the variance of

Table 4 Multiple linear regression between φ_{max} and soil properties

	Regression equation	R^2	adR^2	F values	signif F
φ_{max}	$\varphi_{max} = -11.917\text{SSA} + 89.547$	0.391	0.330	6.410	0.030
	$\varphi_{max} = -0.449\text{clay} + 84.933$	0.538	0.491	11.629	0.007
	$\varphi_{max} = -0.610\text{silt} + 82.743$	0.538	0.491	11.632	0.007
	$\varphi_{max} = -0.417\text{OM} + 82.533$	0.584	0.542	14.022	0.004
	$\varphi_{max} = 0.351\text{sand} + 52.055$	0.729	0.702	26.938	0.000
	$\varphi_{max} = -0.578\text{CEC} + 82.656$	0.628	0.591	16.887	0.002
	$\varphi_{max} = -0.419\text{CEC-}0.384\text{silt} + 85.325$	0.793	0.747	17.257	0.001
	$\varphi_{max} = -0.318\text{CEC-}0.534\text{silt-}2.077\text{pH} + 100.843$	0.877	0.831	18.999	0.001

diesel removal from soils, respectively. However, these predictors only explained less than 50% of variance of diesel removal from soils, suggesting that these models were less applicable to predict the removal of diesel from soils by surfactant-aided soil washing.

The clay content, CEC, and sand content are the soil parameters that highly correlated with the φ_{max}. These results indicated that the regression equation with clay content, CEC, and sand content as predictors could explain 54.2%, 59.1%, and 70.2% of variance of diesel removal from soils. Subsequently, backward stepwise regression analysis between soil properties and the φ_{max} was performed by a multicomponent linear regression procedure. In comparison with the univariate equation based on CEC, an additional 24.0% of the variation in diesel removal from soils could be explained by adding the parameter pH and silt content. The regression result is as follows: $\varphi_{max} = -0.318\text{CEC-}0.534\text{silt-}2.077\text{pH} + 100.843$ (ad$R^2 = 0.831$, $n = 12$). It is suggested that CEC, silt content, and pH-based multiparameter equations did explain a higher percentage of the observed variation, which contributes to predicting the removal rate of diesel for soils at regional scale by surfactant-aided soil washing.

Conclusions

In this study, the influences of soil properties on Triton X-100-aided soils washing were investigated using 12 soils in China. The sorption isotherms of Triton X-100 were fitted to the Langmuir adsorption model ($R^2 \geq 0.91$, $p < 0.01$), and the Q_{max} varied from 1.54 to 15.15 mg/g. In a surfactant-aided washing process, the removal rates of diesel in 12 soils were well fitted to the modified Michaelis-Menten equation, and the φ_{max} ranged from 62.92 to 90.36%. The soil factors affecting diesel removal from soils followed the order of sand content > CEC > OM content > silt and clay content > SSA >> pH. The prediction model based on CEC, silt content, and pH explained 83.1% of variance of diesel removal from soils.

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