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Adsorption and desorption of iodine by various Chinese soils: II. Iodide and iodate

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ABSTRACT

It is important to understand iodine availability in various soils in China to efficiently manage and control environmental iodine. A series of batch experiments was conducted on a variety of Chinese soils in order to determine the adsorption characteristics of iodide and iodate. For five soils, the sorption isotherms of iodide were determined, while for all 17 soils, iodide adsorption was studied under one initial concentration to evaluate its sorption capacity. Furthermore, iodate sorption isotherms on two soils at five different initial concentrations were determined in this study, to complement the earlier work of Dai et al. (2004a). From the sorption isotherm results, five Chinese soils were ranked in terms of their capacity for iodate adsorption: Perudic Ferrisols soil, HN>Orthic Aridisols soil, XJ1>Udic Ferrisols soil, JX2>Udic Luvisols soil, BJ>Udic Isohumisols soil, JL. As a comparison, iodide adsorption was ranked as follows: Udic Ferrisols soil, JX2>Perudic Ferrisols soil, HN>Udic Isohumisols soil, JL>Udic Luvisols soil, BJ>Orthic Aridisols soil, XJ2. It was also found that the desorbed amounts demonstrated a significant positive correlation with the adsorption of the XJ1 and BJ soils for iodate, and also did the HN and JX2 soils for iodide. At an initial iodide concentration of 4 mg L^{-1} , the values of the sorption distribution coefficient, K_d , ranged between 0.78 and 6.59 mg kg^{-1} soil in 17 soils from China, and iodide adsorption was significantly correlated with soil organic matter and cation exchange capacity. K_d exhibited a linear relationship with soil organic matter, a polynomial relationship with free iron oxide content and a logarithmic relationship with cation exchange capacity. Furthermore, results from iodate and iodide adsorption from 17 Chinese soils, except for Fimic Anthrosols soil (GX) showed that the adsorption capacities of iodate were greater than those of iodide, and organic matter in soil environments plays an important role in controlling iodine geochemistry.

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1. Introduction

It is well recognized that environmental iodine deficiency can cause a number of iodine deficiency disorders (IDD), such as goiter, spontaneous abortion, sterility (Longombe and Geelhoed, 1997) and mental retardation (Delange et al., 2001). Environmental iodine deficiency in China is severe, particularly in the inland and mountainous regions such as the western parts of the country, and about one third of China's total population lives in regions where iodine deficiency disease is endemic. The severity of IDD is related to the severity of environmental iodine content (Ma et al., 1993).

Another concern with iodine in the environment is that the accumulation of radioactive isotopes of iodine, particularly ^{131}I and ^{129}I , can be deleterious (Hu et al., 2008). Radioactive iodine released from nuclear facilities may contribute to the global iodine budget, and consequently lead to bio-accumulation in organisms, posing serious

health risks to humans through food chain transfer. Therefore, with the rapid development of the nuclear industry and the prevalence of IDD in China, there is an urgent concern regarding the behavior of iodine in the environment in relation to both human nutrition and radioecology.

Many studies have demonstrated the possibility of iodine supplementation in the food chain through plant uptake to mitigate IDD. Vegetable uptake is believed to be a cost-effective way to improve human nutrition and to help reduce the incidence of IDD (Cao et al., 1994; Jopke et al., 1996; Jiang et al., 1997; Zhu et al., 2003; Dai et al., 2004b). However, the availability of iodine for plant uptake and its migration depend largely on its interactions with various soil components (Yoshida et al., 1992; Hu et al., 2005). Therefore, it is important to fully understand iodine geochemistry in different types of Chinese soil in order to efficiently manage and control environmental iodine.

Both inorganic forms of iodine (iodate and iodide) can coexist in soils (Yu, 1992). Plants can take up and translocate both of these iodine species from the environment. Some solution-culture studies found that the accumulation of iodate in spinach (Zhu et al., 2003) and

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rice (Mackowiak and Grossl, 1999) was much lower than that of iodide. However, other soil pot experiments indicated that the potential of iodine enrichment in spinach plants was much greater for iodate than for iodide (Dai et al., 2006). Studies also found that iodine concentrations in soil solutions of rhizosphere were generally higher after iodate treatments than iodide treatments, with or without planting spinach (Dai et al., 2006). It is well known that plant uptake of iodine is dependent on the availability of iodine, which is essentially governed by the adsorption–desorption characteristics of soils. Therefore, the differences in plant uptake of iodate and iodide or any other translocation processes in environments could be related to the differences in adsorption–desorption processes of iodine speciation on soil particles.

We have studied adsorption and desorption of iodate by various Chinese soils (Dai et al., 2004a). There were different distinct adsorption–desorption characteristics by iodate among the different soils with distinct properties in terms of soil organic matter, pH, CEC and free Fe/Al oxides. For example, the soils rich in iron oxide had high affinities for iodate. Based on the previous work, the primary objectives of this study were: (1) to study iodate adsorption on two Chinese soils (Orthic Aridisols soil, XJ1; Udic Luvisols soil, BJ) to further complement the work of Dai et al. (2004a); (2) to investigate iodide adsorption isotherms in five soils from China and to assess principal factors controlling iodide adsorption on soils; (3) to compare the adsorption of iodate and iodide by 17 Chinese soils; and (4) to elucidate the mechanisms responsible for the sorption of iodine species onto soils in China.

2. Materials and methods

2.1. Soils

To study iodide adsorption and to compare the sorption behavior of iodate and iodide, typical soil samples were collected at 17 locations

across China (Fig. 1). All of the soil samples in the study were air-dried, and then passed through a 1-mm sieve. Portions of the samples were set aside for determination of iodate adsorption and desorption, as well as for soil pH. Sample splits were then further ground to pass through a 0.25-mm sieve for cation exchange capacity (CEC) determination, and were finally passed through a 0.125-mm sieve for organic matter (OM) and free Fe/Al oxides analysis.

2.2. Determination of soil properties

The procedures for determining basic soil properties were derived from standard methods recommended by the Chinese Society of Soil Science (Lu, 2000). Soil pH in a 1:2.5 H₂O suspension was determined with Thermo Orion (Model 828). Organic matter was measured by oxidation with potassium dichromate–titration of FeSO₄. Free Fe/Al oxides were extracted with DCB (dithionite citrate sodium–bicarbonate) reagent, with Fe concentration determined by AAS (Z-6100, Hitachi Co., Japan) and Al concentration using ICP-AES (Optima 2000, Perkin Elmer Co., USA). Cation exchange capacity was analyzed using the method of acetic ammonium saturation. These basic properties of 17 soils used in this study are shown in Table 1.

2.3. Determination of iodate and iodide sorption

Batch experiments of iodate and iodide adsorption were carried out by shaking soil samples equivalent to 2.5 g dry weight with 25 mL of iodine (either iodate or iodide) solution. This was performed in centrifuge tubes fitted with caps, on an end-over-end shaker (160 rpm) at 25 °C and shaken for 40 h (Whitehead, 1973; Yoshida et al., 1992; Dai et al., 2004a). For the sorption isotherm studies, concentrations of KIO₃ in the solution were 0, 1, 2, 4, 6, 8 mg l L^{−1} for the two soil types from Xinjiang Province and Beijing City; the above concentrations in the solution of KI were used for five soil types from Hai'nan Province, Jilin Province, Beijing City, Xinjiang Province and

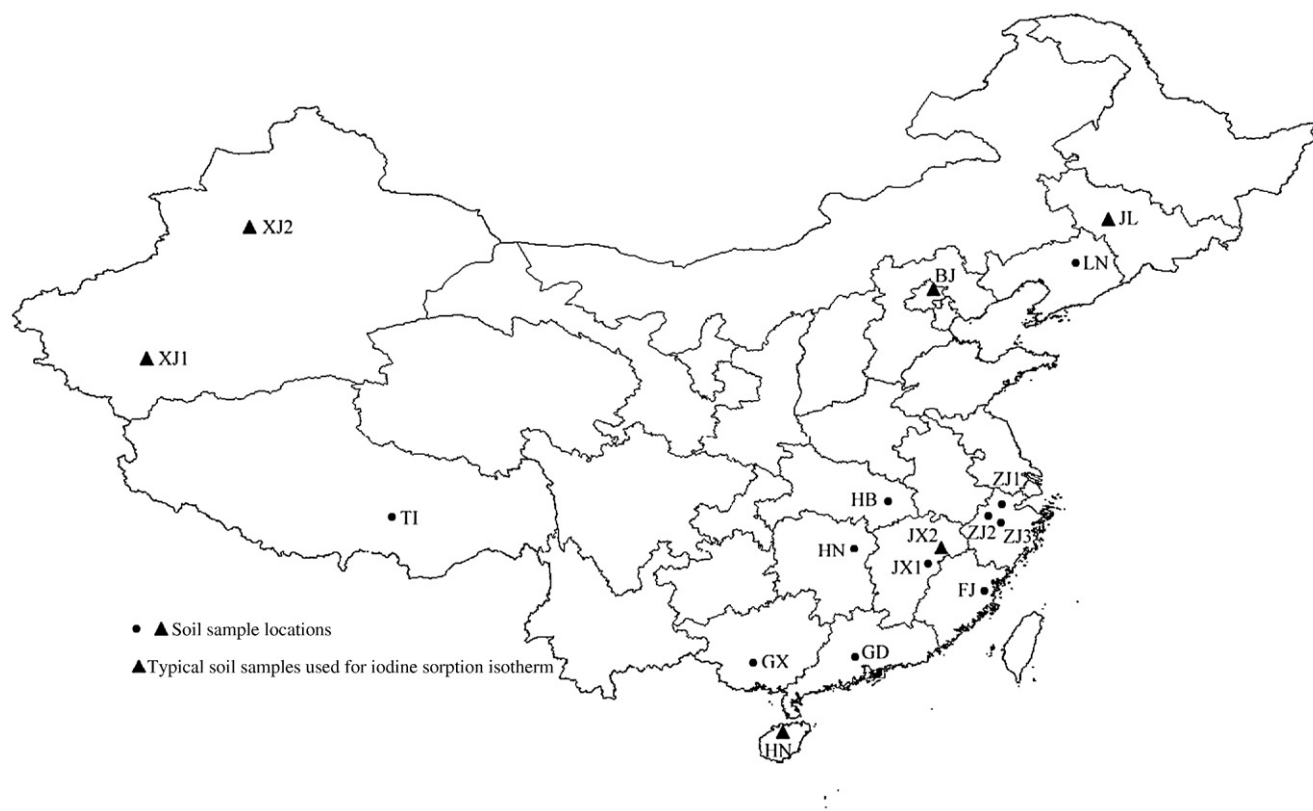


Fig. 1. Approximate sample locations on a map of China.

Table 1
Basic properties of soils used in this study and iodine sorption results.

No.	Soil type ^a	Location	Abbreviation	pH (H ₂ O)	OM (%)	CEC (cmol kg ⁻¹ soil)	Free Fe oxide (%)	Free Al oxide (‰)	The sorbed amounts (mg kg ⁻¹ soil)		K _d values (L kg ⁻¹)	
									Iodate ^b	Iodide	Iodate ^b	Iodide
1	Orthic Aridisols	Hetian, Xinjiang Province	XJ1	8.13	0.97	2.80	0.64	0.60	34.08	2.35	57.60	0.64
2	Orthic Aridisols	Kuitun, Xinjiang Province	XJ2	8.51	0.94	13.6	0.53	0.76	9.03	2.91	2.91	0.76
3	Udic Luvisols	Huai'rou, Beijing	BJ	7.85	1.39	9.16	1.08	1.07	7.05	2.93	2.14	0.78
4	Ustic Cambisols	Tibet	TI	5.25	1.74	5.44	0.92	2.19	4.37	0.78	1.23	0.20
5	Udic Ferrisols	Yingtian, Jiangxi Province	JX1	4.79	2.13	12.12	4.47	7.38	23.17	3.85	13.77	1.07
6	Udic Ferrisols	Jiangxi Province	JX2	5.45	1.06	9.83	4.87	8.01	29.85	4.57	29.40	1.15
7	Stagnic Anthrosols	Hangzhou, Zhejiang Province	ZJ1	4.96	2.27	7.43	1.87	1.85	18.23	2.28	8.37	0.60
8	Udic Ferrisols	Fuyang, Zhejiang Province	ZJ2	4.27	1.53	5.33	0.69	1.55	9.29	2.26	3.03	0.60
9	Fimic Anthrosols	Fuyang, Zhejiang Province	ZJ3	5.82	4.56	19.6	1.44	1.64	6.44	6.33	1.92	1.88
10	Fimic Anthrosols	Wuhan Hubei Province	HB	5.19	1.98	15.2	2.12	2.38	14.19	4.59	5.50	1.30
11	Udic Isohumisols	Gongzhuling, Jilin Province	JL	7.95	3.21	28.5	1.34	2.47	10.91	2.89	3.75	0.75
12	Udic Cambisols	Shenyang, Liaoning Province	LN	5.89	1.64	13.7	1.94	2.48	15.26	5.02	6.17	1.44
13	Perudic Ferrisols	Fujian Province	FJ	5.60	5.36	19.7	2.12	3.44	8.64	3.71	2.75	1.02
14	Fimic Anthrosols	Nanning, Guangxi	GX	5.52	2.42	8.81	1.89	3.88	3.15	3.68	0.85	1.01
15	Udic Ferrisols	Changsha, Hunan Province	HN	6.13	2.85	11.2	4.52	7.17	9.31	4.11	3.04	1.14
16	Hydragric Anthrosols	Guangdong Province	GD	6.9	4.60	45.6	4.81	5.66	12.40	6.59	4.49	1.97
17	Perudic Ferrisols	Danzhou, Hai'nan Province	HN	5.05	1.19	5.16	7.11	11.0	33.73	3.13	53.75	0.84

^a Soil classification according to (Gong, 1999).

^b Data from Dai et al. (2004a).

Jiangxi Province. For evaluating adsorption capacity, 4 mg I L⁻¹ of iodide concentration was used for all 17 soils. Sorption tests for each iodine concentration were duplicated. The adsorption solution was prepared using 0.01 M CaCl₂ as the background electrolyte. After the equilibration period, the suspensions were centrifuged at 10,000 rpm for 5 min, and then passed through a 0.22 μm filter. Iodide concentration was directly determined by an ion chromatography (Model 600, Dionex Corp., USA), and iodate was determined after its reduction to iodide using 1% vitamin C (50 μL in 10 mL solution). Adsorption amounts of iodine were calculated from the difference between the initial and equilibrium concentrations of IO₃⁻ or I⁻.

For the desorption experiment, 25 mL of 0.01 M CaCl₂ solution was added to each test tube, and then the same procedure used in adsorption was followed. The desorbed amounts of IO₃⁻ and I⁻ from each soil were then calculated based on their concentrations in the desorption solutions.

2.4. Data analysis

The sorption data were analyzed using the following equations:

$$\text{Langmuir equation: } 1/y = 1/y_m + 1/(y_m * k_1) * 1/c \quad (1)$$

$$\text{Freundlich equation: } y = k_2 * c^{1/\alpha} \quad (2)$$

where y is the adsorbed amount (mg kg⁻¹ soil), y_m is the maximum sorption value (mg kg⁻¹ soil), c is the equilibrium concentration in solution (mg L⁻¹), and k_1 , k_2 , and α are constants.

$$K_d (\text{L kg}^{-1}) = [I^-]_s / [I^-]_w \quad (3)$$

where $[I^-]_s$ is the adsorbed iodine onto the soil; $[I^-]_w$ is the equilibrium concentration of iodine in the solution (Lee et al., 1996; Dai et al., 2004a).

All data are subjected to analysis of variance (ANOVA) performed using Windows-based Genstat (6th edition, NAG, England).

3. Results and discussion

3.1. Iodate adsorption isotherms

Adsorption isotherms may provide a means of evaluating the capacity of a soil to adsorb elements. In this study, additional experiments were conducted to obtain iodate adsorption isotherms for two soils (Udic Luvisols soil, BJ; Orthic Aridisols soil, XJ1) and to assess the effect of sorbate concentrations on iodate adsorption. These two soils were selected based on our previous studies of iodate adsorption and desorption by Udic Ferrisols soil, JX2; Perudic Ferrisols soil, HN; and Udic Isohumisols soil, JL (Dai et al., 2004a) (Table 1). Iodate adsorption isotherms are presented in Fig. 2A, which shows that the XJ1 soil has a higher capacity to adsorb iodate compared to the BJ soil. Adsorption data was fitted with both Langmuir and Freundlich equations. Linear regression analysis showed that both Langmuir and Freundlich equations could adequately describe iodate adsorption on these two soils, and the goodness of fit and adsorption parameters derived from these two equations are presented in Table 2.

Two main constants with definite physical meaning were obtained from the Langmuir equation. The monolayer maximum adsorption (y_m) in the Langmuir equation is usually used to compare potential adsorption capacity of different soils. The value of y_m was 84.8 mg kg⁻¹ for the BJ soil and 179 mg kg⁻¹ for the XJ1 soil. Constant k_1 is related to the binding energy and partly reflects adsorption energy level. The larger the value of k_1 is, the stronger the degree of spontaneous reaction is. The k_1 value was 0.08 for BJ soil and 0.28 for XJ1 soil. Therefore the XJ1 soil had the stronger adsorptive intensity and higher adsorptive capacity for iodate than the BJ soil, based on the values of y_m and k_1 (Table 2).

The Freundlich parameters k_2 and α measure the capacity and degree of difficulty for adsorption respectively. The larger the value of $1/\alpha$ is, the more readily adsorption by soils occurs. The k_2 value of the XJ1 soil (55.0) was much higher than that of the BJ (7.60), which suggested that the XJ1 soil had a greater adsorptive capacity for iodate than the BJ soil; this is consistent with the results of the Langmuir equation. However, the BJ soil more readily adsorbed iodate than the XJ1 soil because of the higher $1/\alpha$ value of the BJ soil.

We compared iodate adsorption by five types of soil (the data of JX2, HN and JL soil are from Dai et al., 2004a) and found that the

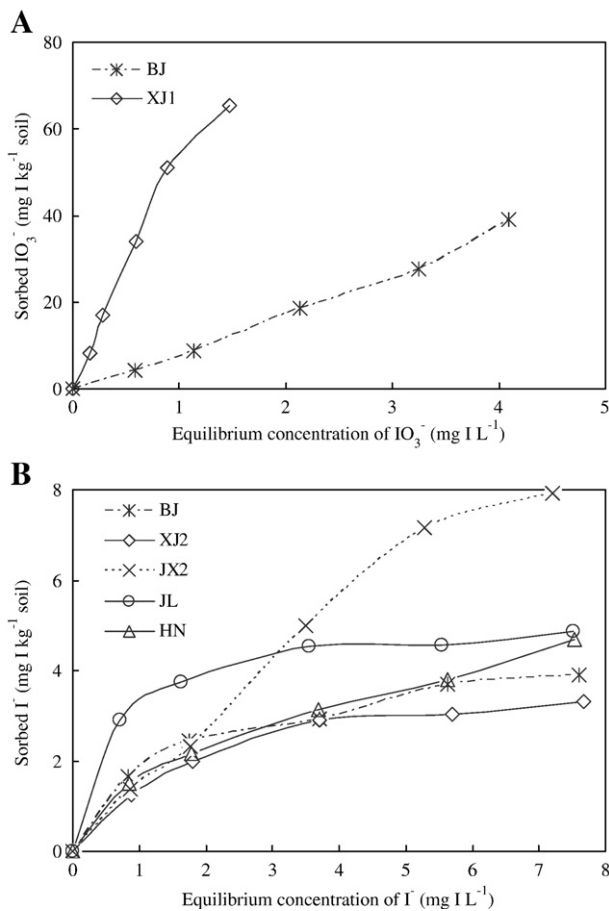


Fig. 2. Adsorption isotherms of iodate (A) and iodide (B) onto soils.

capacity of iodate follows the ranking: HN soil > XJ1 soil > JX2 soil > BJ soil > JL soil. Furthermore, 85.3%, 84.2% and 77.9% of IO₃⁻ adsorption percentages are obtained for HN soil, XJ1 soil and JX2 soil, respectively; while the adsorption percentage values are only 45.2% and 40.8% for BJ soil and JL soil. These results may be explained by the specific (chemical) adsorption of iodate, such as exchange of IO₃⁻ with OH⁻ in allophane or sesquioxides (Yoshida et al., 1992). However, the BJ soil and the JL soil showed lower capacities of iodate adsorption because the negative charges (OH⁻ and IO₃⁻) repelled each other

Table 2

Iodate and iodide sorption isotherm constants derived from Langmuir and Freundlich equations.

Soil		Langmuir equation			Freundlich equation		
		$1/y = 1/y_m + 1/(y_m * k_1) * 1/c$			$y = k_2 * c^{1/\alpha}$		
		y_m	k_1	r	k_2	α	r
Iodate	Perudic Ferrisols, HN ^a	222	0.24	0.975 ^b	57.2	1.03	0.983 ^b
	Udic Ferrisols, JX2 ^a	96.2	0.56	0.999 ^b	33.0	1.32	0.999 ^b
	Udic Isohumisols, JL ^a	74.6	0.12	0.999 ^b	7.69	1.21	0.993 ^b
	Udic Luvisols, BJ	84.8	0.08	0.999 ^b	7.60	0.88	0.999 ^b
	Orthic Aridisols, XJ1	179	0.28	0.990 ^b	55.0	1.04	0.985 ^b
Iodide	Perudic Ferrisols, HN	5.27	0.452	0.990 ^b	1.62	1.96	0.999 ^b
	Udic Ferrisols, JX2	23.6	1.66	0.994 ^b	1.54	1.14	0.993 ^b
	Udic Isohumisols, JL	5.12	1.82	0.996 ^b	3.25	4.67	0.974 ^b
	Udic Luvisols, BJ	4.39	0.724	0.992 ^b	1.85	2.62	0.991 ^b
	Orthic Aridisols XJ2	4.38	0.455	0.998 ^b	1.43	2.22	0.975 ^b

y —the adsorbed amount (mg kg⁻¹ soil); y_m —the maximum sorption value (mg kg⁻¹ soil); c —the equilibrium concentration in solution (mg L⁻¹); k_1 , k_2 —constants; r —correlation coefficient.

^a Data from Dai et al. (2004a).

^b Correlation is significant at 0.01 level.

under weak alkaline conditions (pH 7.85 for the BJ soil and pH 7.95 for the JL soil). Furthermore, the results demonstrate that adsorption of IO₃⁻ on HN soil, XJ1 soil and JX2 soil are predominantly of chemical adsorption rather than simple electrostatic adsorption mechanism. On the other hand, adsorption of IO₃⁻ on the surface of the BJ soil and the JL soil consists mostly of simple physical adsorption, similar to that observed in Yoshida et al. (1992).

The desorbed amount of iodate after adsorption is 10.9% for the XJ1 soil and 7.3% for the BJ soil (Fig. 3A). The desorption percentages for these two soils are lower than the JX2 soil (16.9%), the HN soil (12.4%) and the JL soil (17.5%) reported in Dai et al. (2004a). In other words, the desorption percentages reveal the following trend of iodate adsorption affinity: BJ soil > XJ1 soil > HN soil > JX2 soil > JL soil. The desorbed amounts of iodate are positively correlated with those of iodate adsorption for the XJ1 soil and the BJ soil (Fig. 3A).

3.2. Iodide adsorption isotherms

The same five soil types (Perudic Ferrisols soil, HN; Udic Ferrisols soil, JX2; Udic Isohumisols soil, JL; Udic Luvisols soil, BJ; Orthic Aridisols soil, XJ2) employed for iodate were used to obtain iodide adsorption isotherms, which are shown in Fig. 2B. In order to calculate relevant parameters for iodide adsorption by these soils, adsorption data were fitted with both Langmuir and Freundlich equations. Linear regression analysis showed that both equations could adequately describe iodide adsorption on these five soil types; fitness and adsorption parameters derived from these two equations are shown in Table 2. Results from both equations indicated that the capacity of iodide to the five soils follows the following order: JX2 soil > HN

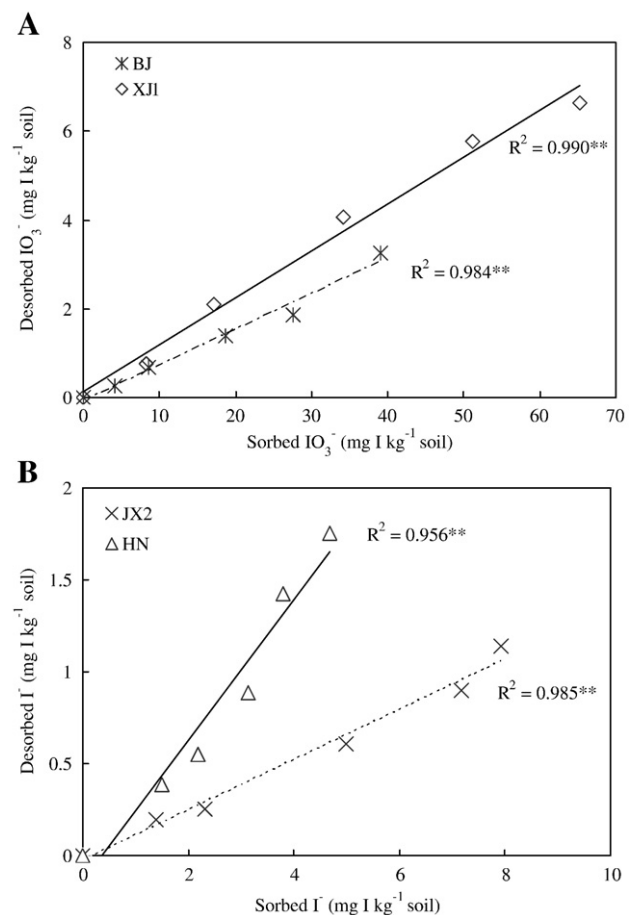


Fig. 3. Relationship between adsorption and desorption of iodate (A) and iodide (B) onto soils.

soil>JL soil>BJ soil>XJ2 soil. This order is probably due to the relatively high level of iron oxides and aluminum oxides in the JX2 soil and the HN soil. Whitehead (1973; 1974) observed that iodide adsorption by soil was dependent on ferric/aluminum oxides and soil organic matter. It is well known that anion sorption occurs at localized positive charges appearing on free hydroxides of Fe and Al, and on the edges of the alumino–silicate clay mineral lattices where the O atoms are not fully coordinated by Al or Si atoms (Whitehead, 1984).

Our results are also consistent with the observation by Muramatsu et al. (1990) that iodide adsorption by a mineral soil increased with decreasing pH. Under acidic conditions, the more positive charges can easily adsorb anions, including iodide. Sheppard et al. (1995) noted that competitive adsorption capacity between I^- and OH^- increases with decreasing positive charge at $pH > 7$. Thus, iodide adsorption capacity by three alkaline soil types in this study was found to be lower than that by two acidic soil types (JX2 and HN soils). Iodide sorption on XJ2 soil has been found to weaken, which may be caused by the stronger competitive adsorption among anions in more alkaline soils (Mott, 1981). Weaker iodide sorption may also occur with specific sorption, i.e. chemical sorption, such as exchange with OH^- . Whitehead (1973; 1974) indicates that soil organic matter was the major sorbing constituent at $pH > 6$ condition. In this study, soil organic matter in the three alkaline soil types (JL, BJ and XJ2 soils) was 3.21%, 1.39% and 0.94%, respectively, and iodide adsorption capacity by these three alkaline soils reduced with decreasing soil organic matter.

The desorbed amounts of iodide ranged from 30.9% for the HN soil, and from 12.8% for the JX2 soil (Fig. 3B). The desorption percentage for the HN soil was significantly higher than that of the JX2 soil, which confirms that the JX2 soil has a higher adsorption capacity for iodide than the HN soil. The desorbed amounts of iodide were positively correlated with those of iodide adsorption for the HN soil and the JX2 soil (Fig. 3B).

3.3. Iodide adsorption by 17 soils

A total of 17 soils from various locations in China, including the five soils used for iodate and iodide sorption isotherm studies, were used to evaluate iodide adsorption capacity. With an initial aqueous iodide concentration of 4 mg L^{-1} , the amounts of iodide adsorption onto 17 soils ranged from 0.78 to 6.59 mg kg^{-1} soil (Table 1 and Fig. 4). Multiple regression analyses showed that soil pH and free iron/aluminum oxides had no significant effects on iodide adsorption. On the contrary, analysis results showed that both soil organic matter (SOM) and cation exchange capacity (CEC) were found to have significant effects on iodide adsorption by these soils, and the relationship could be described by the following equation:

$$Y = 0.141 \times \text{SOM} + 0.079 \times \text{CEC} + 2.232 \quad (p = 0.020)$$

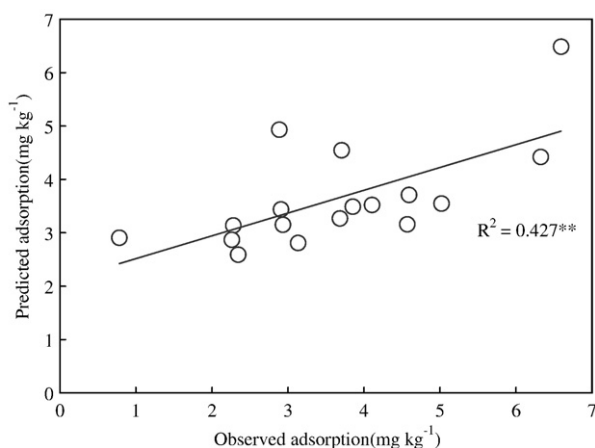


Fig. 4. Relationship between observed and predicted iodide adsorption onto 17 soils.

where Y is the amount of iodide adsorption (mg kg^{-1}). Whitehead (1973) also demonstrated that soil organic matter had a positive effect on iodide adsorption. Multiple regression analysis also showed that the above equation only explained about 43% of the variation in iodide adsorption, indicating that there are unknown factors (possibly clay minerals and soil texture) contributing to iodide adsorption by soils. The inadequacy of the above equation to describe iodide adsorption in 17 soils is further illustrated by the discrepancy between the observed and predicted (according to the above equation) iodide adsorption (Fig. 4).

To better understand the mechanism of iodide adsorption in 17 soils, we derived values of K_d , a solid–liquid partition coefficient, using the added and equilibrium concentrations of iodide. Values of K_d were found to vary slightly with a range from 0.2 to 1.97 L kg^{-1} among 17 different soils in China (Table 1). Multiple regression analysis showed that soil pH and free aluminum oxide content had no significant effects on K_d values of iodide, while soil organic matter ($r = 0.557$, $p < 0.05$), free iron oxide content ($r = 0.585$, $p < 0.01$) and cation exchange capacity ($r = 0.693$, $p < 0.01$) were found to have significant effects on K_d . These three correlations can be described as a linear relationship, a polynomial relationship and a logarithmic relationship, respectively (Table 3).

3.4. Comparison of iodate and iodide adsorption by soils

In order to fully understand the behavior of iodine species (iodate and iodide) in various soils, we compared the soil adsorption for iodate and iodide. The results show that the maximum adsorption values (y_m) of iodate by five soils (Perudic Ferrisols soil, HN; Orthic Aridisols soil, XJ; Udic Ferrisols soil, JX2; Udic Luvisols soil, BJ; Udic Isohumisols soil, JL), which range from 74.6 mg kg^{-1} to 222 mg kg^{-1} , are significantly higher than those of iodide, which vary from 4.38 mg kg^{-1} to 23.6 mg kg^{-1} (Table 2). The results indicate that the capacity of iodate adsorption by the five soils is markedly greater than that of iodide. Furthermore, detailed comparison of sorption parameters based on the Langmuir and the Freundlich adsorption equations supports this finding, showing a greater adsorption capacity for iodate than for iodide due to higher k_2 values of iodate than those of iodide (Table 2).

With an initial aqueous iodine concentration of 4 mg L^{-1} , the amounts of iodate and iodide adsorption on all of the 17 soil types studied range from 3.15 mg kg^{-1} to 34.1 mg kg^{-1} soil for iodate, and from 0.78 mg kg^{-1} to 6.59 mg kg^{-1} soil for iodide (Table 1). The corresponding adsorption percentages vary from 7.87% to 85.2% for iodate and from 1.96% to 16.5% for iodide. The amounts and percentages of iodate adsorption by 16 soils (except for Fimic Anthrosols soil, GX) are greater than those of iodide adsorption (Table 1). The K_d values often serve as an important parameter for assessing the migration behavior of iodine in soil environments; these values for iodate and iodide are shown in Table 1. The values for iodate range from 0.85 L kg^{-1} to 57.6 L kg^{-1} , and are greater than those for iodide, which varies from 0.20 L kg^{-1} to 1.97 L kg^{-1} in the corresponding soils (except for GX soil) (Table 1). Therefore, our results with Chinese soils demonstrate that the capacity of iodate adsorption by various soils (except for GX soil) is greater than those of iodide adsorption. Our results are in agreement with the findings of Fukui et al. (1996).

Table 3

Correlation relationships between K_d and soil basic properties for iodide adsorption in 17 soil samples.

	OM	CEC	Free Fe oxide
Relationship	Linear	Logarithmic	Polynomial
Correlation coefficient	0.557 ^a	0.693 ^b	0.585 ^b

^a Correlation is significant at 0.05 level.

^b Correlation is significant at 0.01 level.

Other studies have also demonstrated that sorption of IO_3^- by ferric oxide was higher than that of I^- (Muramatsu et al., 1990; Hu et al., 2005), that there were higher sorption percentages of IO_3^- onto amorphous aluminum hydroxide precipitate than I^- , and that IO_3^- appeared to be chemically adsorbed (Yoshida et al., 1992).

Another interesting finding from this study is that soil organic matter has significantly negative effects on iodate adsorption in Chinese soils (Dai et al., 2004a), but it has significantly positive effects on iodide adsorption. This supports the findings of Yoshida et al. (1992) that for the organic andosol soil, iodate is sorbed by the inorganic components, unlike iodide that is sorbed by the organic components. Lieser and Steinkopff (1989) and Bors and Martens (1992) also demonstrated the importance of organic matter in iodide sorption. Overall, our studies show that organic matter in soil environments plays an important role in controlling iodine geochemistry.

4. Conclusion

Based on a series of experiments, we found that iodate and iodide adsorption isotherms could be well fitted with both the Langmuir and the Freundlich equations. The XJ1 soil had the stronger adsorptive intensity and higher adsorptive capacity for iodate than the BJ soil. However, the BJ soil more easily adsorbed iodate than the XJ1 soil, though with less adsorptive capacity. The capacity of iodide adsorption to the five soils follows the following order: JX2 soil > HN soil > JL soil > BJ soil > XJ2 soil. Soils rich in organic matter and with high cation exchange capacity had high affinities for iodide. The desorbed amounts of iodate are positively correlated with those of iodate adsorption for the XJ1 soil and BJ soil, and also are the HN soil and JX2 soil for iodide adsorption and desorption. The adsorption capacity of iodate by 17 soils, except for Fimic Anthrosols soil (GX) is greater than that of iodide, and iodate is more readily sorbed by soils than iodide. Furthermore, soil organic matter has significantly negative effects on iodate adsorption in soils, but it has significantly positive effects on iodide adsorption. Therefore organic matter in soil environments plays an important role in controlling iodine availability and iodide is easily retained in soil by the application of organic matter.

Among the 17 soils studied, the XJ1 soil in Xinjiang Province and the HN soil in Hai'nan Province may retain the most amount of iodate while the GX soil in Guangxi Province and the TI soil in Tibet have the least. For iodide, the GD soil in Gangdong Province and the ZJ3 soil in Zhejiang Province retain most of iodide while the TI soil in Tibet has the least. Furthermore, the XJ1 soil (Orthic Aridisols) lies in the desert at Hetian county in Xinjiang Province, an area of severe iodine deficiency where there is also a high infant mortality rate. However the adsorption capacity and desorption amount of iodate for the same soil are much higher than those of iodide. According to these results, iodate can be considered as a top priority of potential iodine species to mitigate IDD by effectively increasing iodine content in soil, especially for in XJ1 soil.

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