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Comparison of Extractants for Removing Heavy Metals from Contaminated Clayey Soils

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This article describes the removal of heavy metals from contaminated clayey soils by soil washing using various extractants. Two clayey soils, kaolin, a low buffering soil with pH of 5, and glacial till, a high buffering soil with pH of 8, were used to represent various soil conditions. These soils were spiked with chromium (Cr), nickel (Ni), and cadmium (Cd) to simulate improper disposal of typical electroplating waste constituents. The following extracting solutions were investigated for the removal of heavy metals from the soils: deionized water, distilled water, and tap water; acetic acid and phosphoric acid; chelating agents ethylenediaminetetraacetic acid (EDTA) and citric acid; and the oxidizing agents potassium permanganate and hydrogen peroxide. The effect of extractant concentration on removal of heavy metals was also investigated. Complete removal of Cr was achieved using 0.1 M potassium permanganate for kaolin, while a maximum of 54% was removed from glacial till. A maximum Ni removal of 80% was achieved using tapwater for kaolin, while a maximum removal of 48 to 52% was achieved using either 1M acetic acid or 0.1 M citric acid for glacial till. A maximum Cd removal of 50% was achieved using any of the extractants for kaolin, while a maximum removal of 45 to 48% was obtained using either acids or chelating agents for glacial till. Overall, this study showed that complete removal of Cr, Ni, and Cd from clayey soils is difficult to achieve using the soil-washing process, and also the use of one extractant may not be effective in removing all metals. A sequential extraction using different extractants may be needed for the removal of multiple metal contaminants from clayey soils.

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INTRODUCTION

Soil contamination resulting from improper waste disposal practices is a major concern in the U.S. (Bredehoeft, 1994). As of 1997, there were 1500 USEPA Superfund sites, 3000 USEPA RCRA sites, 295,000 USTs, 7300 DOD, and 4000 DOE sites that were awaiting cleanup (USEPA, 1997). This estimate does not include accidental releases, current industrial processes, thousands of known potential sites, or the sites that are undiscovered. Over 30% of the Superfund sites contain heavy metals, with most common metals detected include lead, chromium, arsenic, nickel, and cadmium. Cr, Ni, and Cd are commonly found in soils that have been contaminated with electroplating wastes (Burford and Masselli, 1953; Cherry, 1982). Exposure to these contaminants poses health problems to humans due to their toxicity and carcinogenicity; therefore, remediation of these soils is necessary when certain threshold concentrations are present. The development of effective and low-cost remediation methods to treat contaminated soils has been the focus of many environmental remediation professionals during the last decade. Soil washing, solidification/stabilization, electrokinetics, bioremediation and phytoremediation are the remediation technologies that are applicable to treat metal contaminated soils (USEPA, 1995; USEPA, 1997).

Soil washing is the most commonly used treatment technology for the remediation of metal-contaminated soils (USEPA, 1995). This technique is an *ex situ* treatment method and is less expensive than many traditional or innovative treatment technologies, especially when smaller soil volumes are to be treated (USEPA, 1995). In this method, the contaminated soil is excavated and mixed with an extractant solution. The extractant solution may be water, acid, oxidizing agent, chelating agent, or surfactant, depending on the type of contaminant. The soil and the extractant solution are mixed thoroughly for a specified time, and the soil is dewatered to separate the soil and liquids. The resulting soil that meets regulatory requirements can be backfilled at the excavated site. The liquids that contain contaminants are further processed using conventional wastewater treatment technologies to recover the contaminants (USEPA, 1995).

Soil washing has been employed successfully for the remediation of soils containing less than 30% fine fraction that is less than 0.075 mm in particle size, such as sands and silty or clayey sands, which have been contaminated with various organic and inorganic contaminants (Hanson *et al*., 1993; Chen and Hong, 1995; Semer and Reddy, 1996; Abumizer and Khan, 1996; Neale *et al*., 1997; and Pichtel and Pichtel, 1997). However, the use of soil washing to remediate contaminated fine-grained soils, particularly clayey soils that contain more than 30% fines fraction, has been limited (Griffin *et al*., 1977a,b; Farrah and Pickering, 1978; Pickering, 1983; Tuin and Tels, 1990 a,b). These studies provided valuable information on the distribution of heavy metals in clayey soils and the removal of heavy metals from clayey soils using acids and complexing agents. The present study was aimed at investigating the removal of Cr, Ni, and Cd from two diverse clayey soils using different extractants: acids, chelating agents, and oxidizing agents at different concentrations to determine an effective washing solution for the remediation of metal-contaminated clayey soils.

MATERIAL AND METHODS

Batch tests were performed according to the ASTM Standard D3987 to determine the removal of Cr, Ni, and Cd from two different clayey soils using various extracting solutions (ASTM, 1996).

Soils

Two clayey soils, kaolin and glacial till, were used in this study. Kaolin was obtained from the American Clay Mineral Society. It is a low buffering soil consisting of mainly kaolinite clay mineral (100% fines). Glacial till was obtained from a site near Chicago, Illinois. It is a high buffering soil consisting of 31% quartz, 13% feldspar, 35% carbonates, 15% illite, 4 to 6% chlorite, 0.5% vermiculite, and trace amounts of smectite. The high carbonate content of this soil is mainly responsible for the high acid buffering capacity. In terms of grain sizes, glacial till consists of 16% sand and 84% fines. The initial average pH values measured according to ASTM D4972 (soil:water ratio 1:1) were 5.0 for kaolin and 8.0 for glacial till. The kaolin is free of organic matter, while the glacial till contains 2.8% organic matter (ASTM D2974). The cation exchange capacity is 1.6 meq/100g for kaolin and 18.0 meq/100 g for glacial till (Method 9080 in USEPA, 1986). The detailed test procedures and properties of these soils were reported by Reddy *et al.* (1997).

Contaminants

The soils were spiked with Cr(III), Ni(II), and Cd(II) to simulate typical electroplating waste constituents. Chromic chloride, nickel chloride, and cadmium chloride were used as sources of the Cr, Ni, and Cd, respectively, for both soils. The soils were spiked by adding these chemicals dissolved in deionized water to the air-dried soils. The resulting moisture contents were 35% for kaolin and 25% for glacial till. After the preparation of the contaminant-spiked soils, they were placed in sealed glass bottles and refrigerated. The soils were equilibrated for at least 2 weeks. The initial contaminant concentrations were measured based on the USEPA acid digestion procedure followed by analysis with atomic absorption spectrophotometer (USEPA, 1986). The concentrations of Cr, Ni, and Cd based on the dry soil weight were 684 mg/kg, 340 mg/kg, and 230 mg/kg in kaolin and were 764 mg/kg, 414 mg/kg, and 246 mg/kg in glacial till, respectively.

Extractants

Acetic acid and phosphoric acid were selected to investigate solubilization of metal precipitates, thereby enhancing contaminant removal. Acetic acid was used in concentrations of 1 *M*, 0.1 *M*, and 0.01 *M* in kaolin and 2 *M*, 1 *M*, and 0.5 *M* in glacial till. Phosphoric acid was used in concentrations of 0.1 *M*, 0.01 *M*, and 0.001 *M* in kaolin and 1 *M*, 0.5 *M*, and 0.1 *M* in glacial till. These concentrations were selected to reduce the pH of the soil-extractant mixture to less than 5.0, the pH at which Cr, Ni, and Cd exist in ionic form (Pourbaix, 1974). Two chelating agents, ethylenediaminetetraacetic acid (EDTA) and citric acid, were selected as chelating agents to examine the solubility of metals in complex forms. Both EDTA and citric acid were used at concentrations of 0.1 *M*, 0.05 *M*, 0.01 *M*, and 0.001 *M* in both soils. Two oxidants, potassium permanganate and hydrogen peroxide, were selected to determine the extent of oxidation of Cr(III) to Cr(VI) and consequent effects on removal. These oxidants were used at concentrations of 0.1 *M*, 0.01 *M*, 0.005 *M*, and 0.001 *M* in both soils. In addition, deionized water, distilled water, and tap water were used to compare metal removal efficiencies with the various extractants.

Extraction Procedure

Extraction was performed with a liquids to solids ratio (L/S) of 10:1. The mixture was stirred constantly for 1 h using a magnetic stirrer, and then the pH and redox potential of the soil slurry were measured using a digital pH/ORP meter. It should be noted that equilibrium conditions may not exist after 1 h of mixing (Griffin *et al*., 1977a,b); however, the 1 h mixing time was selected to investigate the easily removable Cr, Ni, and Cd fractions and to compare the relative removal efficiencies by various extractants. The soil solids were separated by centrifuging at 4000 rpm for 10 min and then filtering using a Whatman No.1 filter paper. The supernatant was analyzed for Cr, Ni, and Cd concentrations using an atomic absorption spectrophotometer according to USEPA methods 7190, 7520, and 7130, respectively (USEPA, 1986). All tests were performed in duplicate in order to ensure the reproducibility of the test results. Finally, the removal of each contaminant was calculated using the following equation:

$$Contaminant\ Removal\,(\%) = \frac{Contaminant\ Mass\ in\ Supernatant\,(C_L V_L)}{Initial\ Contaminant\ Mass\ in\ Soil\,(C_S M_S)} \times 100$$

where C_L and C_S are the concentrations of contaminant in supernatant (in mg/L) and soil (in mg/kg), respectively, V_L is the volume of supernatant (in L), and M_S is the dry mass of the soil (in kg).

RESULTS AND ANALYSIS

Extraction Using Water

Table 1 presents the measured pH and redox potential as well as the calculated percent removal of Cr, Ni, and Cd for both kaolin and glacial till using the different water extractants. The measured pH values of kaolin were less than 3.5 using all three types of water. Even though the pH was below 3.5, Cr may have partially existed as $Cr(OH)_3$ due to its high concentration (1.32×10^{-3} *M*) (Pourbaix, 1974). The presence of Cr as insoluble $Cr(OH)_3$ may be responsible for less than 50% removal of Cr in kaolin. Other studies have shown that Cr adsorbs strongly to soil surfaces resulting in low removal using water (Ososkov and Bozzelli, 1994). The removal of Ni and Cd ranged from 69 to 87% and 47 to 52%, respectively, for kaolin. The higher removal of Ni when compared with Cd may be due to competitive adsorption of these metals to the negatively charged clay particle surfaces and/or metal hydroxides. The measured pH values of glacial till were greater than 7.0 using all three water extractants. At such high pH conditions, Cr, Ni, and Cd precipitate as hydroxides/carbonates, thereby preventing removal of these metals (Stumm and Morgan, 1996).

Extraction Using Acids

Table 2 shows the measured pH, redox potential, and metal removals from both kaolin and glacial till using the two acids at different concentrations. It should be noted here that lower concentrations of phosphoric acid were used when compared with the concentrations of acetic acid. Being triprotic and relatively strong, low concentration of phosphoric acid lowers the soil pH; however, being monoprotic and weak, acetic acid requires higher concentrations to decrease the soil pH. Higher concentrations of both acids were used for glacial till to overcome its high acid buffering capacity. All of the selected acid concentrations resulted in pH values less than 5 in both soils. It should be noted here that phosphoric acid and acetic acid may also behave as complexing agents; therefore, the metal removal depends on solubilization of metal hydroxides/carbonates due to lowering of pH as well as on the formation of metal complexes (Stumm and Morgan, 1996).

In kaolin, Cr removal ranged from 3 to 8% using acetic acid and 2 to 11% using phosphoric acid. As stated earlier, about 50% of the Cr was removed using water (Table 1); thus, the use of acids reduced the Cr removal. Nickel removal varied from 35 to 47% using acetic acid and from 42 to 65% using phosphoric acid. Cadmium removal varied from 32 to 38% using acetic acid and 35 to 40% using phosphoric acid. Slightly higher removal of both Ni and Cd was achieved using phosphoric acid. The removal of Ni and Cd was lower when compared with the removal achieved using water. Increased acid concentrations did not increase metal

TABLE 1
Removal of Cr, Ni, and Cd from Clayey Soils Using Water

Soil	Parameter	Distilled Water	Deionized Water	Tap Water
Kaolin	pH	3.3±0.02	3.3±0.02	3.47±0.1
	Redox Potential (mV)	411±1	410±2	401±6
	Cr Removal (%)	48±3	47±2	43±1
	Ni Removal (%)	71±1	69±1	87±1
	Cd Removal (%)	49±1	47±0.5	52±1
Glacial Till	pH	7.15±0.05	7.05±0.04	7.3±0.02
	Redox Potential (mV)	183±3	191±3	172±1
	Cr Removal (%)	0	0	0
	Ni Removal (%)	0	0	0
	Cd Removal (%)	0	0	0

TABLE 2
Removal of Cr, Ni, and Cd from Clayey Soils Using Acids

Soil	Parameter	Acetic Acid					Phosphoric Acid				
		2.0M	1.0M	0.5M	0.1M	0.01M	1.0M	0.5M	0.1M	0.01M	0.001M
Kaolin	pH		2.58±0.02		2.93±0.01	3.45±0.04			1.93±0.04	2.68±0.05	3.44±0.1
	Redox Potential(mV)		451±0		431±1	402±2			490±1	447±3	402±7
	Cr Removal (%)		8±1		3±1	3±1			11±1	5±1	2±1
	Ni Removal (%)		47±1		35±2	43±2			65±3	53±1	42±4
	Cd Removal (%)		33±1		32±4	38±4			40±2	38±2	35±2
Glacial Till	pH	3.7±0.02	4.2±0.01	4.8±0.02			2.02±0.02	3.38±0.03	4.48±0.04		
	Redox Potential(mV)	387±1	357±1	322±1			485±1	406±1	341±3		
	Cr Removal (%)	43±1	16±1	11±1			43±10	14±1	1±1		
	Ni Removal (%)	48±1	23±3	19±1			43±10	44±1	15±1		
	Cd Removal (%)	45±1	40±1	36±1			35±6	36±1	9±1		

removal in kaolin. The presence of phosphoric acid or acetic acid along with the chloride ions in porewater may have caused the metals (Ni, Cd, and Cr) to combine with the phosphate ions or chloride ions to form complexes (e.g., $Ni_3(PO_4)_2$, $NiCl_2$, $CdPO_4$, and $CdCl_2$) leading to lower removal efficiencies when compared with those obtained using water alone.

The effect of acids on metal removal in glacial till was different from that observed in kaolin. The Cr removal increased with an increasing concentration of acids; 11 to 43% using acetic acid and 1 to 43% using phosphoric acid. Similar results were observed for Ni and Cd. The Ni removal ranged from 19 to 48% using acetic acid and 15 to 44% using phosphoric acid. The Cd removal ranged from 36 to 45% using acetic acid and 9 to 36% using phosphoric acid. Metal removal increased with the use of acids when compared with using water. The acids decreased the soil pH values to 2 to 4.8, causing solubilization of metal hydroxides/ carbonates (Griffin *et al*., 1977a,b). Unlike kaolin, the formation of metal complexes with the phosphate ions, chloride ions, or other naturally occurring ions in glacial till is difficult to analyze accurately. Therefore, the effects of such metal complexes on the removal efficiency are difficult to quantify.

Extraction Using Chelating Agents

Table 3 shows the pH, redox potential, and metal removal from both soils using EDTA and citric acid at different concentrations. Chelating agents modify metal concentrations in soil solution by forming various soluble complexes, thus enhancing metal removal.

The Cr removal from kaolin ranged from 29 to 61% using EDTA and 42 to 47% using citric acid. The Ni removal ranged from 71 to 80% using EDTA and 67 to 80% using citric acid. The Cd removal ranged from 45 to 51% using EDTA and 47 to 52% using citric acid. The Cr, Ni, and Cd removal did not increase using chelating agents when compared with the use of water. This may be due to the fact that these metals initially exist in soil solution due to low pH, and the addition of chelating agents did not result in additional solubilization of metals. The pH of kaolin increased slightly from 2.9 to 4.0 with increased EDTA concentration; however, the pH decreased from 2.7 to 1.7 with increased citric acid concentration.

The pH of glacial till increased slightly from 7.7 to 8.0 with increased EDTA concentration, and the pH decreased from 7.2 to 2.5 with increased citric acid concentration. Thus, the change in soil pH with EDTA is negligible, but a decrease in soil pH occurred with the use of citric acid. Less than 2% Cr was removed with EDTA. This may be due to the fact that all of the Cr in glacial till was initially present as precipitate, thus preventing the Cr to complex with EDTA. The log stability constant of Cr(III) and OH^- is 47.8, while the log stability constant of Cr(III) and EDTA is 32.2; therefore, EDTA may not be effective in forming complexes with Cr(III) in high pH conditions (Stumm and Morgan, 1996). With

TABLE 3
Removal of Cr, Ni, and Cd from Clayey Soils Using Chelating Agents

Soil	Parameter	EDTA				Citric Acid			
		0.1M	0.05M	0.01M	0.001M	1M	0.1M	0.01M	0.001M
Kaolin	pH	3.96±0	3.68±0.02	2.96±0.01	2.9±0.02	1.72±0.01	2.02±0.03	2.38±0.01	2.67±0.04
	Redox Potential (mV)	372±0	389±3	430±1	433±2	504±1	486±1	466±1	447±3
	Cr Removal (%)	61±1	42±1	29±3	47±3	47±1	42±3	44±1	46±1
	Ni Removal (%)	80±1	73±2	71±1	64±1	67±2	70±1	80±2	79±1
	Cd Removal (%)	51±1	48±1	45±1	47±3	47±1	50±2	52±1	51±1
Glacial Till	pH	8.04±0.17	7.82±0.01	7.89±0.01	7.67±0.01	2.52±0.02	3.98±0.05	7.44±0.04	7.23±0.3
	Redox Potential (mV)	133±10	145±1	141±0	154±1	456±1	371±4	167±3	183±15
	Cr Removal (%)	2±1	0	0	0	47±1	24±1	0	0
	Ni Removal (%)	33±1	14±7	8±1	2±1	52±2	45±1	6±1	2±1
	Cd Removal (%)	49±2	48±1	37±2	32±1	41±1	26±19	2±1	0

lower concentrations of citric acid, Cr removal was also not achieved due to precipitation of Cr resulting from high soil pH (Pourbaix, 1974). However, at higher concentrations of citric acid, the soil pH was lowered to values ranging from 2.5 to 4.0, thus solubilizing metal precipitates partially. The combined effects of solubilization of metals and enhanced solubilization of metal complexes may be responsible for Cr removal ranging from 24 to 47%. Similar results were observed by Peters *et al*. (1996) on a field-contaminated soil. The removal of Ni and Cd increased from 2 to 33% and 37 to 49%, respectively, with increased EDTA concentration. These results show that even though pH is relatively high, a significant increase in metal removal when compared with removal using water was achieved. This is mainly attributed to the formation of soluble complexes of Ni and Cd with EDTA. Nickel and Cd form complexes with EDTA preferably over OH^- (Stumm and Morgan, 1996). The removal of Ni and Cd using citric acid at low concentrations is negligible; however, at high concentrations of citric acid, metal removal increased with concentration, ranging from 45 to 52% for Ni and 26 to 41% for Cd. The removal of Ni and Cd using citric acid appears to be due to enhanced solubilization caused by a significant decrease in soil pH. The effects of complexation of metals with citric acid on Ni and Cd removal appear to be minimal. As citric acid forms relatively nonstable complexes, the H^+ ion in citric acid may be responsible for the removal of metals by direct solubilization (Stumm and Morgan, 1996). Overall, these results show that the formation of soluble EDTA-metal complexes in glacial till at relatively high pH may provide improved removal efficiency of metals such as Ni and Cd. The selectivity of EDTA to complex with a metal in the presence of multiple metals, and the effects of soil pH and high concentrations of EDTA on metal removal require further investigation.

Extraction Using Oxidizing Agents

Potassium permanganate and hydrogen peroxide were used as oxidizing agents to observe the effect of oxidizing Cr(III) into Cr(VI) on the removal of Cr. Table 4 summarizes the pH, redox potentials, and metal removal efficiencies using $KMnO_4$ and H_2O_2 at different concentrations from both soils. The pH of kaolin ranged from 2.2 to 3.3, while the pH of glacial till ranged from 7.1 to 7.3 with different concentrations of the two oxidants. In kaolin, Cr removal increased with increasing concentration of $KMnO_4$, from 62% at 0.001 *M* to 100% at 0.1 *M*. The Cr removal did not change with varying concentrations of H_2O_2 and ranged from 50 to 58%. The higher removal of Cr using these oxidizing agents is attributed to oxidation of Cr(III) into Cr(VI) (Bartlett and James, 1979; Rai *et al*., 1989; Chinthamreddy and Reddy, 1998). Cr(VI) exists as oxyanions, such as $HCrO_4^-$, CrO_4^{2-} and $Cr_2O_7^{2-}$, and are highly soluble over a wide pH range, allowing for easy removal. There was no consistent change in the removal of Ni and Cd with increasing concentrations of $KMnO_4$ and H_2O_2. The Ni removal ranged from 69 to 86% using either $KMnO_4$ or

TABLE 4
Removal of Cr, Ni, and Cd from Clayey Soils Using Oxidizing Agents

Soil	Parameter	Potassium Permanganate				Hydrogen Peroxide			
		0.1M	0.01M	0.005M	0.001M	0.1M	0.01M	0.005M	0.001M
Kaolin	pH	2.25±0	2.24±0	2.3±0	2.65±0	2.83±2	3.16±0.09	3.33±0.10	3.27±0.01
	Redox Potential (mV)	472±1	472±2	469±1	448±1	438±2	420±7	409±5	413±1
	Cr Removal (%)	102±1	82±1	86±1	62±1	50±3	54±1	50±3	58±1
	Ni Removal (%)	86±5	69±1	71±1	83±2	68±6	83±2	77±2	88±2
	Cd Removal (%)	40±4	60±1	39±1	52±1	48±1	50±2	51±1	54±1
Glacial Till	pH	7.28±0.03	7.12±0.01	7.12±0.04	7.18±0.03	7.1±0.03	7.13±0.03	7.1±0.01	7.02±0.06
	Redox Potential (mV)	178±1	187±1	186±3	183±2	188±2	186±2	188±1	194±3
	Cr Removal (%)	54±7	32±1	19±1	5±1	48±1	30±1	21±1	6±1
	Ni Removal (%)	0	0	0	0	1	0	0	0
	Cd Removal (%)	0	0	0	0	1	0	0	0

H_2O_2, while the Cd removal ranged from 39 to 60% using $KMnO_4$ and 48 to 54% using H_2O_2. These Ni and Cd removal efficiencies were approximately the same as those observed using water as an extractant.

In glacial till, Cr removal increased with increasing concentration of $KMnO_4$, ranging from 5% at 0.001 *M* to 54% at 0.1 *M*. A similar trend was observed with H_2O_2, with Cr removal of 6% at 0.001 *M* to 48% at 0.1 *M*. Stochiometrically, the higher the concentrations of the oxidants, the greater will be the amount of Cr(III) oxidized into Cr(VI). The presence of higher amounts of Cr(VI) increased Cr removal from the soil. The Cr removal in glacial till is lower than that observed in kaolin using the same oxidants. This may be due to the initial existence of Cr(III) as precipitate in glacial till due to high soil pH, limiting the Cr available for immediate reaction with the oxidant. When compared with the removal observed using water as an extractant, significant removal of Cr was achieved using oxidants. The effect of using oxidizing agents on the removal of Ni and Cd was insignificant. These results show that oxidation of Cr(III) into Cr(VI) through the use of oxidants did not affect the form and distribution of Ni and Cd in the soils.

SUMMARY AND CONCLUSIONS

Batch tests were conducted on two types of clayey soils, kaolin and glacial till, spiked with Cr, Ni, and Cd to investigate the removal of the heavy metals using water, acids, chelating agents, and oxidizing agents as extracting solutions. Based on these test results, the following conclusions were drawn:

1. The overall removal of the Cr, Ni, and Cd was higher in kaolin when compared with glacial till. The low metal removal from glacial till is attributed to its high pH and high acid buffering capacity, which in turn caused heavy metals to precipitate. Therefore, the buffering capacity of the soil should be an important consideration in designing a soil-washing system.
2. Total removal of Cr from kaolin was achieved using 0.1 *M* potassium permanganate. The Cr removal was moderate using chelating agents as well as water, but the lowest removal, less than 10%, was observed using acids. In glacial till, a maximum Cr removal of 54% was achieved using 0.1 *M* $KMnO_4$ and 43% using acids. Among chelating agents, citric acid yielded higher removal efficiencies. Water was completely ineffective in removing any Cr from glacial till.
3. Nickel removal from kaolin was about 80%, using all the extractants except acids. For glacial till, both acids and chelating agents provided high Ni removal efficiencies.

4. All extractants removed about 50% Cd from the kaolin. However, a maximum of 45 to 49% of Cd was removed using either acids or chelating agents within the glacial till.
5. Overall, this study showed that complete removal of Cr, Ni, and Cd from clayey soils is difficult to achieve using the soil-washing process. Additionally, the use of one extractant may not be effective in removing all of the metals from clayey soils. A sequential extraction using different extractants may be needed for the removal of multiple metal contaminants from clayey soils.

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