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Transport and interaction of arsenic, chromium, and copper associated with CCA-treated wood in columns of sand and sand amended with peat

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Abstract

Laboratory column leaching experiments were conducted to investigate the transport and interaction of As, Cr, and Cu associated with CCA-treated wood in sand with and without peat amendment. Results showed that leaching behavior of As, Cr, and Cu in these substrates were totally different. Substrate characteristics and microorganism activity posed distinct effects on the transport and transformation of these three elements. Arsenic was rapidly leached out from the columns with or without the amendment of peat, while Cr remained in all columns during the entire experimental period (215 days). Copper was leached out only in the substrate column without peat. The presence of microorganism clearly facilitated the transport of As, while it did not show obvious effects on the transport of Cr and Cu. Interactions among these three elements were observed during the processes of adsorption and transport. The adsorption of Cu on soil was enhanced with the adsorption of As, likely caused by a more negatively charged soil surface because of As adsorption. The adsorption of Cr on soil increased the adsorption of As due to the additional As binding sites induced by Cr adsorption. These results suggest that As concentrations in the soil affected by CCA-treated wood could largely exceed predictions based on soil adsorption capacity for As. The evaluation of the impact on human health associated with CCA-treated wood should take consideration of the distinct transport characteristics of three elements and their interactions in soils.

Keywords

CCA-treated wood; leachability; microorganism; sand; transport; interaction

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INTRODUCTION

Chromated-copper-arsenate (CCA)-treated wood was widely used for the construction of outdoor structures in the United States since 1970s'. Since both arsenic (As) and chromium (Cr) have been classified as human carcinogens (IARC, 2007; U.S.EPA, 2009), the potential risks of exposure to As and Cr from the sources associated with CCA-treated wood commanded intensive attention over the last decade (Saxe et al., 2007; Solo-Gabriele et al., 2008). Copper (Cu) has also raised concerns due to its potential adverse effects on aquatic organisms (Weis and Weis, 2006). Due to the pressure from increased public awareness and risk assessments conducted by various regulatory groups (U.S.CPSC, 2003; U.S.EPA, 2005), the wood treatment industry voluntarily withdrew the treated products for most residential settings effective from January 1, 2004. However, the utilization of new CCA-treated wood will continue for several uses, including industrial applications, structures in marine environments and load bearing components of structures in terrestrial environments. Even for the CCA-treated wood sold for residential and industrial uses prior to 2004, metal release will likely continue for at least several decades due to its long service life (Khan et al., 2006). Consequently, a better understanding of the fate, transport, and transformation of all three elements in soil substrate is needed for current uses, for disposal and for remediation of soil contaminated with CCA-treated wood.

In the leachate from CCA-treated wood, arsenate, As(V), is the predominate species and a small proportion of arsenite, As(III) can also be observed (Khan et al., 2006). Cr(III) is the main species in the leachate from treated wood (Song et al., 2006; Pan et al., 2009), despite Cr(VI) presents in the original treatment solution. Chromium in the treated wood mainly exists as Cr/As complex or as Cr(OH)₃ (Nico et al., 2004). Once released to soil, the rate and the extent of adsorption of As, Cr and Cu on soil are determined by their species and by the soil physicochemical characteristics (Chirenje and Ma, 2006). Microbial redox transformations are important (if not the principal) drivers controlling environmental As and Cr speciation (Feng et al., 2005; Li et al., 2007). Soil physicochemical characteristics determine the bioavailability of these elements, which is a key factor for microorganism-facilitated transformation.

Considerable progress has been made in recent years in understanding As, Cr, and Cu leachability from soils affected by CCA-treated wood. However, information on the effect of soil characteristics and microorganism activity on leaching of all three elements and the potential interactions among these elements during the leaching in soil is scarce. Previous studies revealed that the amount of As, Cr, and Cu leached from CCA-treated wood was not proportional to their concentrations in the original formulation (Stefanovic and Cooper, 2006). Considering the distinct differences in physicochemical properties of these elements, it is expected that their leachability and the factors controlling their migration in soil could be different. Since these elements could exist in high concentrations in the leachate, competitive or enhanced adsorption of the cation or anion on soil in the multiple adsorbate system can become significant (Benjamin, 1983).

The objective of this work was to study the transport and transformation of As, Cr, and Cu in soils associated with CCA-treated wood with an emphasis on the potential interactions among the three elements and the key factors controlling the species transformation and transport in soil. Our previous studies on As leaching from soils indicated that the organic matter content and microorganism activity plays an important role on controlling the transport and transformation of As in soils (Feng et al., 2005; Chen et al., 2006; Chen et al., 2008). Therefore, these two factors were selected in this study and assessed on their roles in the transport and transformation of As, Cr, and Cu in soil. In order to more clearly elucidate what is happening in the column, simplified soil substrate, sand and sand amended with peat were employed. This study was accomplished through a laboratory scale soil column experiment.

MATERIALS AND METHODS

Chemicals and Materials

Individual As(III) and As(V) stock solutions (1000 mg L^{-1}) were prepared by dissolving appropriate amounts of sodium metaarsenite (98%, Aldrich) and sodium hydrogen arsenate heptahydrate (98%, Aldrich) in water. ICP-MS grade standards for Cr(III) ($10,000 \text{ mg L}^{-1}$ in 5% HNO_3), Cu(II) and Cr(VI) ($1,000 \text{ mg L}^{-1}$ in 5% HNO_3) were purchased from Ricca Chemicals Company. An ICP-MS grade standard solution used for total As analyses ($1,000 \text{ mg L}^{-1}$ in 5% HNO_3) was purchased from GSF Chemicals, Inc. Water used in the experiments was produced by a BarnsteadTM water purified system (Thermo Fisher Scientific Inc).

Soil substrate selection and column set up

Two different soil components, plain sand (S) and sand plus Canadian Sphagnum peat moss at 10% (V/V) (SP) were used for the experiments. The plain sand was common quartz sand, light gray or colorless, and did not have silt and clay sized coatings. Details about the particles size distribution and chemical properties of the soil substrates used can be found elsewhere (Snyder, 2003). The cation exchange capacities of the plain sands and Canadian Sphagnum peat moss were 0.1 and 110–130 $\text{cmol}_c \text{ kg}^{-1}$, respectively (Chen et al., 2006).

Eight PVC columns with 5 cm internal diameter and 31 cm in length were constructed. Details of column construction were reported previously (Chen et al., 2008) and column set up is illustrated in Figure S1 (Supplementary material). All columns were loaded with 0.8 kg soil, corresponding to about 22 cm height after packing. Before packing the soil, all purpose cement (manufactured by OATEY, OH, U.S.A) for polyvinyl chloride (PVC) was used to coat a thin layer of plain sand onto the inside wall of the column to minimize boundary flow.

Four sets of columns with replicates (4×2) were used to evaluate each experimental condition (Table 1). The influent to all 8 columns was composed of artificial rain water (ARW, detailed information for its composition and preparation can be found in Supplementary material (Chen, 2006)). ARW was spiked with As(V), Cr(III) and Cu(II) at 800, 80, and $60 \mu\text{g L}^{-1}$, respectively, corresponding to the average concentrations of As(V), Cr(III) and Cu(II) found in the leachates from the CCA-treated wood (weathered fence post with medium retention level of CCA). Formaldehyde (0.04%) was added to the influent for the control columns to inhibit microorganism activity (Tuominen et al., 1994). The columns were fed with solutions delivered with a peristaltic pump (Ismatec, Germany) with a constant flow rate at the inlet (250 mL d^{-1} , pore volume = 175 mL). The flow rate of effluent solution was also 250 mL d^{-1} controlled from the outlet with another peristaltic pump. The soil in column was covered with a layer of influent solution (about 5 cm) during the entire experiment. All columns were preconditioned by percolation with ARW for three days to homogenize the composition of ion exchange surfaces and stabilize ionic strength before starting the leaching experiments. Both pH and Eh were monitored by a pH/ORP controller (Model 3671, JENCO Instruments, INC., USA). Details about measuring pH and Eh were reported elsewhere (Chen, 2006) and the results are presented in Figure S2 (Supplementary material).

Sampling and Analysis

The duration of the column experiments was 215 days. Samples were collected daily or every two days for the first month, then at an interval of once per week for the following three months, and finally at monthly intervals for the remaining time. Speciation analysis for As and Cr was conducted immediately after sample collection according to a procedure described in the Supplementary material. After the leaching experiment, soil substrate in the columns were dissected into 2 cm sections and then dried in an oven at 35°C for one week. The substrate were digested according to EPA method 3050B and measured with ICP-MS.

RESULTS

Elevated As concentrations in the leachate (Figure 1, As) were observed on the third day from the columns with peat (SP and SPF), and the leaching of As reached steady state within 13 days. Slower increases in As concentrations were observed from columns without peat (S and SF) with measureable increases in As appearing in the effluent by the eighth day. The time to reach steady state was different for S and SF columns. Arsenic in the effluent solution from S column reached steady state on day 13th, whereas column SF reached steady state on day 25th.

Arsenic speciation analysis which was conducted for the effluent samples collected up to the 25th day, showed only inorganic As species in the leachate. Different As species distributions were found in the leachate from S and SF columns (Figure 2). Arsenic remained in the original form of As(V) in SF column, while it was almost entirely reduced to As(III) in S column. For columns amended with peat (SP and SPF), As remained as the original form of As(V) at the beginning of the experiments and transformed to As(III) gradually as the experiments progressed (Figure 2). This is particularly true for the SP column. After the percentage of As (III) reached a maximum on the 15th day, As(III) then gradually declined.

Elevated concentrations of Cu in leachates were observed from S and SF columns eighteen days after applying the influent solution to the columns (Figure 1, Cu). Cu concentration increased to $\sim 30 \mu\text{g L}^{-1}$ in the following week and seemed to reach steady state after 3 months. For columns with peat added (SP and SPF), the Cu concentrations in leachates remained at background levels during the entire experiment. The presence of formaldehyde in influent solution did not significantly affect the transport of Cu. Chromium concentrations in the effluent remained at background levels for all columns during the entire experimental period (Figure 1, Cr).

Similar trends of distribution for As and Cr in the soil substrate for all columns were observed (Figure 1). In columns without peat (S and SF), concentrations of As and Cr decreased gradually from the top to the depth of around 10 cm and then remained unchanged through the end of column. In columns with peat (SP and SPF), concentration of As decreased gradually from the top to a depth of around 6 cm and then remained constant, while Cr was mainly concentrated in the top layer (0–2 cm) and decreased sharply and stayed constant from 8 cm on. The Cr concentrations in the top layers for SP and SPF were approximately 4 times higher than those in columns without peat. Distribution patterns of Cu in the substrate were different from As and Cr in the corresponding columns. For S and SP columns, Cu concentrations decreased gradually from the top to 4 cm (SP) or 6 cm (S) depth, and then stayed constant through the end. However, Cu was evenly distributed in SF and SPF columns. The distributions of As and Cr in the substrate for all columns were highly correlated, especially for the columns without peat (Figure S3, Supplementary material). The mass balance of these three element was checked by comparing the metals detected in effluents and substrates with the metals pumped in, the recovery of these three elements ranged from 81.3 to 111.5%.

DISCUSSION

Transport and transformation of As

Adding peat to sand significantly increased As mobility (Figure 2). Generally, the mobility of As in the natural aquatic environment is controlled by adsorption/desorption on the soil. The adsorption/desorption of As on hydrous metal oxides, such as Fe_2O_3 , Al_2O_3 or MnO_2 , has been considered as one of the main mechanisms controlling As mobility (Kumpiene et al., 2009). The presence of dissolved organic matter (DOM) can alter the As adsorption by forming As-DOM complexes (Wang and Mulligan, 2009). DOM can also modify the metal oxide surface,

causing changes in As adsorption. The apparent distribution coefficient (K_d) represents the distribution of a chemical between dissolved and associated phase and defined as the ratio of concentration in associated phase over dissolved phase. For the convenience of discussion, K_{d1} and K_{d2} are defined as the apparent distribution coefficients of As associated with soil substrate and DOM in aqueous solutions, respectively. The $\text{Log}K_{d1}$ were 0.54 and 0.63 on S and SF column, respectively, estimated using the average concentration of As absorbed on soil substrate in whole column and the concentration in effluent solution after As leaching reached steady state. These $\text{Log}K_{d1}$ values are in good agreement with those obtained by others with different soils (Smith et al., 1999). According to our previous results obtained using similar soil substrates, the apparent distribution coefficients ($\text{Log}K_{d2} = 6.2$ to 7.7) of As on DOM derived from peat were much higher than those on soil substrates, indicating a much stronger association between As and DOM than As and soil substrate (Chen et al., 2006). In columns without peat, the total organic carbon (TOC) of the sand was 0.01%, and ARW-extractable dissolved organic carbon (DOC) was 1.03 mg L^{-1} ; With peat, soil TOC increased to 0.17% and ARW-extractable DOC increased to 6.38 mg L^{-1} (Chen, 2006). As a result, more As remained in the effluent solution because of the association of As with DOM and consequently led to the higher mobility of As. DOM could also react with the hydrous metal oxide surface through ligand exchange and tend to compete with As for active surface binding sites. In addition, the adsorption of DOM on the soil surface generates a more negatively charged surface, therefore inhibiting the adsorption of As anions (Wang and Mulligan, 2006). The presence of organic matter can also dissolve the Fe, Al, and Mn oxides from the soil surface, which in turn could reduce the adsorption of As on the soil surface (Wilkie and Hering, 1996).

Microorganism activity impacted the transport of As and the degree of impact varied with the type of soil substrate. For columns without peat (Figure 2, As), the mobility of As was reduced in the presence of formaldehyde, SF. The difference in As mobility with or without the presence of formaldehyde is likely caused by the difference in As species present in different columns. As(V) spiked in the influent was almost entirely reduced to As(III) in S column, while it remained as As(V) in SF column (Figure 3). Since Eh and pH values remained relatively stable and Eh was always more than 300 mV for all columns during the entire experiments (Figure S2), it is plausible that the changes in Eh and pH were not the controlling factors causing the reduction of As(V) to As(III). Therefore, microorganism activity is believed to be the main factor causing the reduction in S column. Since As(V) normally has higher affinity for the soil surface than As(III) at neutral and acidic conditions (Masue et al., 2007), microorganism reduced As(V) to As(III), and facilitated As mobility in soil. In addition, the DOM originated from the microorganism could interact with As and enhance its mobility (Karthikeyan et al., 1999).

When peat was added, the derived DOM competed with microorganism for free As. In other words, interactions between As and DOM likely reduced the bioavailability of As, consequently slowing down the conversion from As(V) to As(III). By comparing As speciation in S and SP columns (Figure 3), the presence of peat in sand is shown to inhibit, to some extent, the transformation of As species. Appreciable reduction of As(V) to As(III) in SPF column may be mediated by peat. It has been suggested that organic matter can mediate As transformations indirectly by using organic matter as an electron shuttle (Redman et al., 2002). Obviously, the rate and extent of reduction of As(V) to As(III) resulting from microorganism activity were faster and higher without peat relative to sand amended with peat. According to the As elution curves (Figure 2, As), the mobility of As appears to be enhanced to a greater extent in sand amended with peat relative to microorganism activity. This can also be illustrated by the differences between estimated K_d values. For example, the difference between SF ($K_d = 4.2$) and SPF ($K_d = 1.2$) shows that the effect of peat is obviously larger than

the difference between S ($K_d = 3.4$) and SF ($K_d = 4.2$) which shows the effect of microorganism activity.

Transport of Cu

Addition of peat greatly enhanced the retention of Cu (Figure 2, Cu). For columns packed with sand alone (S and SF), the adsorption of Cu onto sand can be predominantly due to either cation exchange or surface complexation on the hydrous metal oxides (Prasad and Saxena, 2004). Due to the low cation exchange capacity (CEC) of sand ($CEC = 0.1 \text{ cmol}_c \text{ Kg}^{-1}$) (Chen, 2006), elevated Cu concentrations should be observed in a short period of time if cation exchange is the major mechanism for Cu adsorption (as per the modeling program PHREEQCI-2, Figure S4, Supplementary material). The difference between the experimental and simulated results of Cu transport in columns with sand indicates that surface complexation with hydrous metal oxides, rather than cation exchange, could be the dominant mechanism for Cu adsorption. When peat was added, the mobility of Cu was apparently controlled by the presence of organic matter. Contradictory effects of organic matter on Cu mobility have been proposed previously. On the one hand, the solid phase organic matter could complex with Cu and reduces its mobility. On the other hand, the DOM derived from peat could also form complexes with Cu and consequently enhance Cu mobility (Kumpiene et al., 2008). Our results suggest that Cu is strongly bound to organic matter with negligible amounts of free Cu ion and/or Cu associated with DOM. This phenomenon could possibly be explained by the fact that Al and Fe have higher adsorption reactivity on DOM than Cu (Tipping et al., 2002; Lippold et al., 2007). ARW-extractable Fe and Al of the soil substrates packed in SP and SPF columns were 2.18 and 11.56 mg L^{-1} (Chen, 2006) respectively, which were much higher than the Cu concentration in the influent solution ($60 \mu\text{g L}^{-1}$). Al and Fe present in high concentrations in the soil solution could compete with Cu for binding with DOM, and suppress the interaction between Cu and DOM. As a result, Cu, existing likely in the form of $\text{Cu}(\text{H}_2\text{O})_6^{2+}$, tends to be bound to the negatively charged surface of the solid phase organic matter. Compared with the mobility of As, the effect of addition of peat resulted in an opposite effect on the mobility of Cu. The reason leading to this difference may lie on the interactions between DOM and Al or Fe.

In an ideal single adsorbate adsorption system, Cu concentrations in effluent should increase after the influent solution is applied to the columns, and keep increasing at similar rate until reaching steady state. As shown by the fitted Cu elution curves (Figure 4, data was fitted with nonlinear fit curve function provided in OriginTM 8), an obviously slow leaching rate is observed on the curve at about 50% of the steady state concentration. The decrease in Cu leaching rate after about 25 days implies that an additional factor contributed to the enhancement of Cu adsorption on soil substrate. The adsorption of Cu on soil in other studies has been observed to be affected by several parameters such as soil type, pH, organic matter content, cation exchange capacity and the content of Al and Fe hydrous oxides (Karthikeyan et al., 1999; Sipos et al., 2008). Variations in these parameters during the experiment were either not observed or not expected. Therefore, it is believed that another factor induced during the course of experiment affected the adsorption of Cu on soil substrate. In general, the possibility of competitive adsorption between anions and cations for binding sites is relatively low because different binding sites are normally involved in these adsorptions. However, anion adsorption may enhance cation adsorption in a multiple adsorbate system and vice versa (Benjamin, 1983). The most likely reason for the enhanced adsorption is the formation of a secondary surface phase, which alters the physical or electrical properties of the primary surface phase and causes the adsorbate to bind more strongly to the new phase than to the original phase (Benjamin and Bloom, 1981; Benjamin, 1983). It has been reported that the adsorption of arsenite and arsenate on ferrihydrite can result in surface charge reduction, especially under slightly acidic conditions (Jain et al., 1999) and the presence of arsenate in solution can increase

the amount of Cu absorbed on iron-oxide-coated sand (Khaodhiar et al., 2000). It is, therefore, plausible that changes in the rate of Cu leaching in this study could be attributed to the adsorption of As on the soil substrate, which induced a more negatively charged soil surface, and consequently enhanced the adsorption of cationic Cu.

Transport of Cr

Cr(III) was strongly bound to the soil substrates with or without peat. Several factors can contribute to the low mobility of Cr(III) in soil: 1) strong adsorption on negatively charged soil surfaces; 2) the formation of complexes on metal oxide surfaces; and 3) complexation with organic matter in the soil (Stewart et al., 2003). Because of the low CEC value of the soil substrates in S and SF columns, elevated concentrations of Cr in the effluent solutions should be observed if cation exchange is the main mechanism controlling the mobility of Cr. Excluding the cation exchange mechanism, formation of complexes on metal oxides surfaces seems to be the possible mechanism controlling Cr(III) mobility in S and SF columns. In other words, surface complexation was the mechanism that controls the mobility of Cu(II) and Cr(III) in S and SF columns. Cr(III) concentrations in influent solution ($80 \mu\text{g L}^{-1}$) was higher than Cu ($60 \mu\text{g L}^{-1}$). The $\text{Log}K^{\text{int}}$ (K^{int} is the intrinsic binding constant) of Cr(III) and Cu(II) binding constant on hydrous ferric oxide is 2.06 and 2.89, respectively, binding constant of Cr(III) is lower than Cu(II) (Dzombak and Morel, 1990). Therefore, elevated Cr(III) should be observed earlier than Cu in S and SF columns when the mechanism of surface complexation employed to describe the mobility of Cu(II) and Cr(III). However, elevated Cu concentrations in leachates were observed from S and SF columns eighteen days after applying the influent solution to the columns, while Cr concentrations in the effluent solution remained at background levels through the end of the experiment. These results indicate that another mechanism was possibly involved in the adsorption. Several studies suggested that Cr(III) rapidly adsorbed and nucleated on hydrous metal oxides and could form multinuclear species on the surface (Charlet and Manceau, 1992; Fendorf, 1995). These adsorbed multinuclear species can further expand and form surface precipitates when more Cr(III) is available. In other words, the binding sites for Cr(III) were determined by not only the hydrous metal oxides but also the bound Cr(III), which could also serve as the binding site for additional Cr(III).

Complexation of Cr(III) with solid organic matter is generally involved to describe its adsorption/desorption in organic matter enriched soil (Stewart et al., 2003). Comparing the distribution patterns of Cr in all columns (Figure 1), it is observed that more Cr was concentrated in the upper top layer ($< 4 \text{ cm}$) in sand amended with peat (SP and SPF) relative to significant increases in Cr in the upper 10 cm for columns with sand only (S and SF). It is expected that Cr(III), present as $\text{CrOH}^{2+}(\text{aq})$ and $\text{Cr}(\text{OH})_2^+(\text{aq})$ under the experimental conditions (Ball and Nordstrom, 1998) was adsorbed by the sand amended with peat via a similar mechanism as that for Cu. In other words, the presence of higher concentrations in Al and Fe in the soil solution inhibited the partitioning of Cr(III) into the dissolved phase. For S and SF columns, Al and Fe concentrations in the soil solution (water-extractable Al and Fe was 0.58 and 0.24 mg L^{-1} , respectively) were much lower than columns SP and SPF (water-extractable Al and Fe was 2.18 and 11.56 mg L^{-1} , respectively). Therefore, Cr mobilized faster in S and SF than in SP and SPF (Figure 1). In addition, humic acid and macromolecular organic compounds can form insoluble complexes with Cr(III) and enhance its adsorption on soil (Stewart et al., 2003; Kyziol et al., 2006).

As presented before, the distribution of As and Cr in soil substrate for all columns were highly correlated, especially for the columns without peat (Figure S3, Supplementary material). From the elution curve of As (Figure 2, As), it can be observed that As reached steady state after 25 days in all columns. In other words, the adsorption of As was thereafter saturated without additional factors contributing to the adsorption of As, and should distributed evenly in the soil

substrate. The uneven distribution of As in the columns and the high correlation between the distribution of As and Cr could indicate a possible interaction between adsorption of Cr(III) and As on the substrate surface. Previous studies found the existence of Cr/As clusters in CCA-treated wood (Nico et al., 2004). Probably, Cr(III) bound on substrate serves as an additional binding site for As and enhances the adsorption of As. Since Cr was mainly concentrated in upper layer of the columns, the interaction between As and Cr adsorption was more obvious in the top layer relative to the bottom layers of the columns. The ratio of As concentrations in the top layer over the concentration in the bottom layer ranged from 2 to 10. Hence, the presence of Cr in the influent could significantly enhance the retention of As in soil.

Conclusions

Arsenic, copper and chromium, simultaneously leached at high concentration levels associated with CCA-treated wood, have the distinct leaching behavior and may behave differently in soil substrates compared with the situation of a single element because of the possible interactions between these elements. Therefore, prediction of the fate of As, Cr, and Cu associated with CCA-treated wood in the environment and the health effect on human should take into account all these three elements collectively and their different environmental behavior. Among the three elements, As is the one that is most easily leached out from soil substrate, which could pose potential problems to groundwater. Organic matter and microorganism activity may increase this potential either through enhancing the mobility or through facilitating formation of the more toxic and mobile form of As(III). On the other hand, Cr, which tends to remain in the top soil for a long period with or without the presence of organic matter. In addition, the adsorption of Cr could enhance the accumulation of As in the soil substrate, causing the As levels in the soil affected by leachates from CCA-treated wood to increase over time. Amendment of soil with peat could substantially slow down Cu transport through soil. Considering that the concern on Cu mainly originated from its potential effects on aquatic organism, the present of peat trapping Cu in soil may reduce its adverse effects.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Figure 1. Comparison of leaching behavior of As, Cr, and Cu in soils. The concentration of As(V), Cr(III), and Cu(II) spiked in the influent solution was 800, 80, and 60 $\mu\text{g L}^{-1}$, respectively.

Figure 2.
Speciation of As in the leachates from columns.

Figure 3.
Distribution pattern of As, Cr, and Cu in soil.

Figure 4.
Fitted leaching curves of Cu in columns S and SF.

Table 1

Column coding, soil components, and composition of the influent solutions

Column	Substrate	Influent solution
S	Uncoated sand	ARW
SF		ARW spiked with 0.04% formaldehyde
SP	Uncoated sand with peat	ARW
SPF		ARW spiked with 0.04% formaldehyde