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EFFICIENCY OF TRIPLE SUPERPHOSPHATE FERTILIZER TO STABILIZE CADMIUM IN DIFFERENT SOIL TEXTURE CHARACTERISTICS

ประสิทธิภาพของปุ๋ยทริปเปิลซุปเปอร์ฟอสเฟตในการปรับเสถียรแคดเมียม ในดินที่มีลักษณะเนื้อดินต่างกัน

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Abstract

This research investigated the effectiveness of Triple Superphosphate (TSP) as a stabilizing agent for cadmium (Cd) in three representative soils having different texture characteristics (loamy-sand, clay loam, and clay soils). Results showed that addition of TSP proved to be an effective method for reduction of Cd leachability in all Cd contaminated soils. The partitioning of Cd from the potentially available phase to the more stable phase was observed in all TSP treatments based on the sequential extraction data. Moreover, performance of TSP to immobilize Cd depended on soil types and compositions. The effectiveness of TSP to reduce Cd leachability was found to be more pronounced in loamy sand soils with a 94% reduction of Cd leachability when TSP was applied at a molar ratio of available phosphate to Cd in soil of 2:1 aged for 30 d. Presence of other heavy metals altered the ability of TSP to stabilize Cd in contaminated soils. Whereas zinc had little influence on the Cd stabilization performance by TSP, presence of copper enhanced ability of TSP to immobilize Cd in contaminated soils. Conversely, a decrease in Cd stabilization performance by TSP was observed when lead was a co-contaminant.

Keywords: immobilization, phosphate fertilizer, competitive metals, soil texture

บทคัดย่อ

งานวิจัยนี้ทำการศึกษาประสิทธิภาพของปุ๋ยทริปเปิลฟอสเฟตในการเป็นสารปรับเสถียรแคดเมียมในดินตัวอย่างที่มีลักษณะเนื้อดินแตกต่างกัน 3 ชนิดคือ ดินทรายปนร่วน ดินร่วนปนเหนียว และดินเหนียว จากการศึกษาพบว่าการเติมปุ๋ยฟอสเฟตจัดเป็นวิธีการที่สามารถลดการชะละลายของแคดเมียมจากตัวอย่าง

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ดินทั้งหมดที่มีการปนเปื้อนได้ ผลจากการสกัดแบบลำดับขั้นพบว่ามีการเปลี่ยนรูปของแคดเมียมจากรูปที่มีพืชหรือสิ่งมีชีวิตสามารถนำไปใช้ได้เป็นรูปที่มีความเสถียรในทุกตัวอย่างที่มีการเติมปุ๋ยทริปเปิลซุปเปอร์ฟอสเฟต นอกจากนี้พบว่าประสิทธิภาพในการปรับเสถียรแคดเมียมของปุ๋ยทริปเปิลซุปเปอร์ฟอสเฟตขึ้นอยู่กับชนิดและองค์ประกอบของดิน การปรับเสถียรแคดเมียมเกิดขึ้นได้สูงสุดในดินทรายปนร่วนที่มีการเติมปุ๋ยฟอสเฟต โดยการเติมปุ๋ยด้วยอัตราส่วนโดยโมลระหว่างฟอสเฟตที่สามารถนำไปใช้ได้ในปุ๋ยกับแคดเมียมทั้งหมดในดินเท่ากับ 2:1 สามารถลดการชะละลายของแคดเมียมได้สูงถึงร้อยละ 94 ภายหลังจากการบ่มดินที่เติมปุ๋ยไว้นาน 30 วัน การมีโลหะอื่นร่วมในดินส่งผลต่อความสามารถในการปรับเสถียรของปุ๋ยทริปเปิลซุปเปอร์ฟอสเฟต ในขณะที่สังกะสีส่งผลเล็กน้อยต่อประสิทธิภาพในการปรับเสถียรแคดเมียมด้วยปุ๋ยฟอสเฟต การมีทองแดงอยู่ร่วมกับแคดเมียมจะช่วยเพิ่มความสามารถของปุ๋ยทริปเปิลซุปเปอร์ฟอสเฟตในการปรับเสถียรแคดเมียม ในทางกลับกันพบว่าความสามารถในการปรับเสถียรแคดเมียมของปุ๋ยทริปเปิลซุปเปอร์ฟอสเฟตมีค่าลดลงเมื่อมีตะกั่วปนเปื้อนอยู่ร่วมกับแคดเมียม

คำสำคัญ: การตรึง, ปุ๋ยฟอสเฟต, โลหะร่วม, ลักษณะเนื้อดิน

Introduction

Mining, smelting and refining activities of many nonferrous metals ores like zinc (Zn), lead (Pb) and copper (Cu) are commonly reported as the primary reason for the contamination of Cd in soils since Cd is a primarily companion element in these metal ores especially sulfide ore concentrates of Zn[1]. Through geochemical weathering processes acting upon mining wastes and by-products, heavy metals are able to be transported from contaminated area and redistributed them to surrounding soils; surface and groundwater[2-4]. Particular concern is given to Cd contamination in paddy fields which have produced rice grains because the potential transfer of Cd from soils to these grains and subsequently may affect human health if there is an excessive intake of these food crops. Given that Cd uptake for many Asian countries was almost exclusively via the dietary route[5] and the reason for high Cd in Asia has been discussed in relation to Cd content in locally consumed rice[6, 7], remediation of Cd contaminated soils particularly agricultural soils is then considered as a high priority task to prevent and/or reduce any human/animal health risk through Cd mobility in food chain.

Among available technologies that are employed to remediate heavy metal contaminated soils, chemical stabilization is considered as a promising technique that is seen as simple, cost-effective and less destructive to the environment[8-11]. This technique is based on a mean of addition of solid or liquid stabilizing agents to modify either pollutant characteristics (e.g. speciation or valence) and/or soil properties such as sorption capacity, buffering capacity[12]. The main goal of stabilization is to convert contaminants to their low leachability and least bioavailability forms which are more geochemically stable in leaching environment[4, 8, 13, 14].

Many studies have recognized the ability of phosphates to immobilize divalent heavy metal ions especially Pb in contaminated soils[4, 8, 13, 15-19]. According to the differences in solubility, the phosphate sources used for the immobilization of heavy metals may be divided into three major categories: readily soluble phosphates such as phosphoric acid; moderately soluble phosphates such as mono-, di- and tricalcium phosphate; and less soluble phosphates including phosphate containing minerals[20]. Phosphate material in fertilizer forms such as TSP which are mixtures of the above phosphate compounds is one stabilizing agent of recent interest because of its cost-effectiveness compared to the chemical grade of phosphate-based salts. Addition of commercial phosphate fertilizers have been applied to remediate soils being contaminated with mono metal like Cd-contaminated soils[21] and soils being contaminated with multiple heavy metals such Cd co-contaminated with Pb and Zn[15, 17]. All these works have shown that phosphate fertilizers are an effective stabilizer for the tested metals.

While soil texture is a crucial parameter affecting both performance of soil amendments to stabilize heavy metals and the practical applicability of soil remediation techniques, evaluation of the performance of phosphates to immobilize heavy metals being contaminated in a variety of soil textures are very limited. In addition, stabilization performance of various phosphate amendments has usually been evaluated using contaminated soils containing multiple heavy metals including Cd, Pb, Cu, and Zn [3, 15, 18, 22, 23]. Competition among these metals affecting overall stabilization performance of phosphates has not been extensively evaluated. Therefore, the present study aims to assess the effectiveness of TSP as a Cd stabilizer in three varieties of soil textures in Thailand. Furthermore, influence of other three metals including Cu, Pb and Zn on the performance of TSP to stabilize Cd in contaminated soils was also investigated.

Materials and Methods

Materials

All chemicals used in this study with the exception of a phosphate fertilizer were analytical or higher grade (Carlo Erba, Italy). TSP in form of a commercial fertilizer was obtained from a local fertilizer supplier. Available phosphate and the apparent solubility that was measured in term of log K_{sp} were 838±11 mg/kg and -1.43, respectively. Soil samples with three different textures were collected (0-20 cm in depth) from three provinces of Thailand: Bang Nok

Khwaek sub district, Samut Songkhram province; Na Chom Thian sub district, Chonburi province; and Lam Pla Thio sub district, Bangkok. Soil samples were labeled as SS, CB, and BK, respectively. Before use, the soils were air dried, homogenized, and sieved to a less than 2 mm fractions. Analysis of total Cd concentration and leachable Cd concentration in the soil samples revealed that both Cd concentrations were below method detection limit which is 1.6 mg/kg for Cd.

Soil spiking with mono-metal or di-metals

For subsequent Cd stabilization tests, soil samples in the preceding paragraph were spiked with cadmium nitrate solution to yield approximately 300 mg/kg of total Cd concentration. Soils were mixed for being homogenous by shaking overnight and left at room temperature for one month with frequent thorough mixing. After that the soils were air dried, kept in plastic containers, and labeled as SS-Cd, CB-Cd, and BK-Cd for following studies.

To determine competitive effects of other metal ions on ability of TSP to immobilize Cd, soils being contaminated with heavy metals in the binary system were prepared by spiking the nitrate form of Cd and one of the following heavy metal ions either Cu, Pb or Zn into the air dried SS soils to yield approximately 300 mg/kg of each metal in the soil. SS soils were selected as representative soil samples for this study because its soil types and constituents were similar to soil characteristics in one area of Thailand where problem with Cd contamination in soil has been reported(21). The soils were treated in the same manner as described previously. The di-metals loaded soils were then air-dried and labeled as Cd-Cu, Cd-Pb and Cd-Zn.

Cd stabilization tests

TSP in the form of phosphate fertilizer was selected as a stabilizer according to its high performance on immobilization of Cd in contaminated soils(21). TSP was added to each Cd spiked soil at three different molar ratios of available phosphate in the fertilizer to Cd in the soil. Each stabilization test included 1 kg of Cd-spiked soil, a predetermined weight ratio of TSP to dry soil weight, and amounts of water sufficient to reach soil saturation level. All materials were thoroughly mixed in a plastic container. The containers were systematically hydrated and kept saturated in order to promote the chemical reactions between Cd ions retained in soil and the phosphate additive. After 30 d of incubation time, representative soil samples from each container were collected for leaching test and sequential extraction analysis.

Competitive effects of other heavy metal ions

Presence of co-contaminants like other heavy metal ions affects performance of TSP to immobilize Cd in soils. To further assess the competitive effect of other metals on Cd stabilization by phosphate fertilizer, TSP was added to soils being contaminated with heavy metals in the binary system at a molar ratio of available phosphate to Cd in soil of 2:1. The experiments were carried out in the same manner as previously described for Cd stabilization tests. The competitive effect of the tested heavy metal on Cd stabilization performance was assessed by comparing the percent stabilization of Cd in the di-metal spiked soils with those values in the Cd-spiked soils. An increase in percentage of Cd stabilization in any binary system or di-metal spiked soils relative to those values in the Cd-spiked soils suggests that the tested metal ion has positive influence on Cd immobilization in the presence of TSP. Conversely, the test metal ions would have negative influence on Cd immobilization by TSP if the decrease values in Cd stabilization were observed.

Methods for evaluating stabilization performance of TSP

1. Leaching Test

Toxicity Characteristic Leaching Procedure (TCLP, SW-846 Method 1311) was conducted to quantify the leachability of test metals from the untreated metal spiked soils and TSP-treated soils. TCLP using fluid I (diluted glacial acetic acid, pH=4.93) was carried out with scaling down the amounts of soil and leaching solution. Stabilization performance in each soil sample was calculated by dividing the difference of mass of Cd leached between the untreated metal spiked soils and the TSP-treat soils by the initial mass of Cd in the untreated metal spiked soils.

2. Sequential extraction of soil samples

Soil samples were subjected to sequential extraction using the method of Silveira et al.[24] in order to determine the change in Cd speciation in soils before and after TSP additions. The procedure separates metals into seven operationally defined fractions: (1) soluble-exchangeable, (2) surface adsorbed, (3) organic bound, (4) easily reducible Mn oxides bound, (5) poor crystalline Fe oxides bound,

(6) crystalline Fe oxides bound and (7) residual. Sequential extractions were carried out in triplicate by placing 1 g of air-dried soils in 80-ml polycarbonate centrifuge tube. Soil samples were mixed with various reagents in a stepwise fashion, and the suspensions equilibrated as described in Silveira et al.[24]. Following equilibration, the solution and solid phases were separated by centrifugation at 3000g for 10 min. The supernatant was decanted and filtered through a 0.45 μm membrane filter. The filtrate was acidified and stored for metal analysis, and the soil residue was retained for the subsequent extractions. Extraction results were focused on the weakly bonded and easily releasable forms of Cd which is defined here as "available form" and is calculated by summing Cd concentrations from the first three steps of the sequential analysis. The summation of Cd concentrations from the remaining extraction steps yields the theoretically insoluble forms of Cd and is defined here as "stable form." Thus the decrease of Cd in the potentially available forms reflects the effectiveness of TSP for stabilization of Cd in contaminated soils.

Soil and leachate analysis

Soil pH was measured in deionized water in a 1:1 soil: water (g: mL) suspensions after 24 hr equilibrium. Available phosphate in soil and fertilizer was determined by colorimetric method using Bray II solution[25]. The content of sand, silt, and clay was determined using the hydrometer method while cation exchange capacity (CEC) and organic carbon of the bulk soil were determined using the ammonium acetate method and wet oxidation method, respectively, as described in Land Development Department[25]. Total concentrations of Cd, Pb, Zn, and Cu in soils were determined according to SW-846 Method 3050B. The concentrations of Cd, Pb, Zn, and Cu in the various extracts were analyzed by flame atomic absorption spectrophotometer (GBC 932, GBC Scientific Equipment). Detection limit for these metals are 0.65, 1.6, 2.1 and 5.0 mg/kg for Zn, Cd, Cu and Pb, respectively.

Result and Discussion

Characteristics of tested soils

Selected physical and chemical properties of test soils are listed in Table 1. The soils collected from the province of Samut Songkhram (SS) and Chonburi (CB) are considered to be calcareous soils with pH values of 7.7 and 7.4, respectively, while BK-Cd is slightly acidic soil with a pH of 5.7. Among the three soil samples, BK-Cd soils have finest texture, contain highest organic matter (OM), and have highest cation exchange capacity (CEC) followed by SS-Cd and CB-Cd soils. Based on the percentage of sand, silt and clay in the tested soils, the three representative samples have different soil texture characteristics: clay, clay loam and loamy sand for BK-Cd, SS-Cd and CB-Cd soils, respectively.

Table 1 Selected physicochemical properties of tested Cd-contaminated soils.

Soil sample	pH	CEC[a] (meq/100g)	OM[b] (%)	Sand (%)	Silt (%)	Clay (%)	Available PO_4^{3-} (mg/kg)	Cd_{Total} (mg/kg)	Cd_{TCLP} (mg/kg)
SS-Cd	7.71±0.34	12.76±1.20	0.58±0.06	37.6	24.1	38.6	7.17±2.40	326±87	83.9±10.8
CB-Cd	7.41±0.02	0.80±0.00	0.12±0.03	84.8	9.1	6.1	4.26±1.59	289±13	192.0±3.0
BK-Cd	5.66±0.12	18.4±0.94	1.11±0.09	31.0	22.0	47.0	5.70±0.58	303±54	66.4±2.0

[a] Cation exchange capacity , [b] Organic matter

Table 1 also presents total Cd concentrations and leachable Cd concentrations in the SS-Cd, CB-Cd and BK-Cd soils as extracted by U.S.EPA Method 3050B and Method 1311, respectively. In general, total Cd concentrations in the three tested soils were quite similar: 326±87 mg/kg in the SS-Cd, 289±13 mg/kg in the CB-Cd and 303±54 mg/kg in the BK-Cd. On the other hand, the concentrations of leachable Cd were significant different in the three soils and appear to be related to soil texture characteristics. Fine-textured soils like BK-Cd and SS-Cd which contain higher clay contents as well as higher organic matter and high CEC values were able to retain Cd greater than soils with coarse texture like CB-Cd[26-28]. Both clays and soil organic matter which are major compositions in the fine-grained soils are known for their ability to effectively retain heavy metals by specific adsorption, ion exchange, surface complexation and surface precipitation[26]. Therefore, leachable Cd concentrations in the TCLP extracts of fine-textured soils like BK-Cd and SS-Cd soils were significant lower than the leachable Cd concentration in the CB-Cd soils.

Cd stabilization performance by TSP

Effects of TSP amendment on stabilization of Cd in three soil texture were first examined by comparing Cd leachability in the three untreated soils to those values in the soils being treated with different concentrations of TSP after 30-d contact (or aging) time (Figure 1). Without TSP addition, the leachable Cd concentration was approximately 66, 84, and 192 mg/kg for clay, clay-loam, and loamy sand textures, respectively. The addition of TSP at molar ratio of 0.5 mol PO_4^{3-}/mol Cd significantly reduced the leaching of Cd in all soil samples especially the loamy sand soils. Continuous reduction of Cd leachability was observed when the soils were treated with greater amounts of TSP (Figure 1).

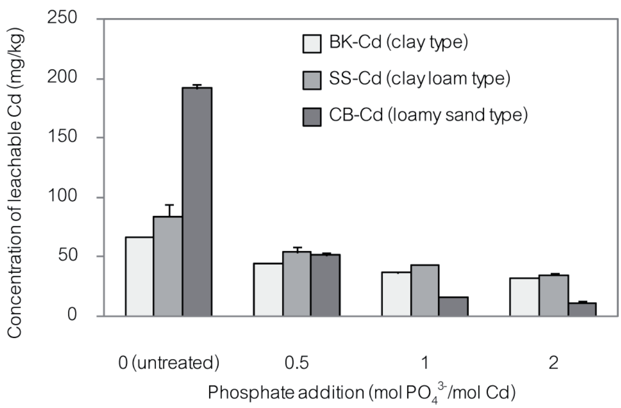

Figure 1 TCLP leachable Cd concentrations in soils with different textures after soils were amended with different quantity of TSP for 30 d.

Using information on reduction in percentage of Cd leachability, stabilization performance of TSP immobilization of Cd was then evaluated: the more the reduction of Cd leachability in the treated soils, the more the stabilization performance of TSP. As usually is the case, stabilization performance of TSP in the three soils increased when the soils were treated with a greater phosphate dose (Figure 2). Even though the three untreated soils contained a comparable amount of total Cd as shown in Table 1, it was found that stabilization performance of TSP in loamy sand soils was greater than those in clay loam and clay soils. Stabilization performance of TSP with 30-d aging for this type of soil texture was 94% when the soil was treated with a molar ratio of 2 mol PO_4^{3-}/mol Cd while only a 58% and 52% reduction of Cd leachability was observed in clay loam and clay soils, suggesting an important role of soil type and compositions for Cd immobilization. Different stabilization performance was attributed to both the sorption behavior of clay fraction and organic matter in preventing the leaching of metals from contaminated soils especially fine-textured soils[29, 30]. Bradl[26] reported that coarse-grained soils generally exhibit lower tendency for heavy metal adsorption than fine-grained soils. Therefore, Cd contaminated in coarse-texture soils like CB-Cd with loamy sand texture is considered as weakly bonded and easily releasable resulting in much greater opportunity for leachable Cd to interact with available phosphates. These findings suggest that application of a phosphate fertilizer like TSP as a soil amendment material is much superior in coarse-textured soils than those in fine-textured soils.

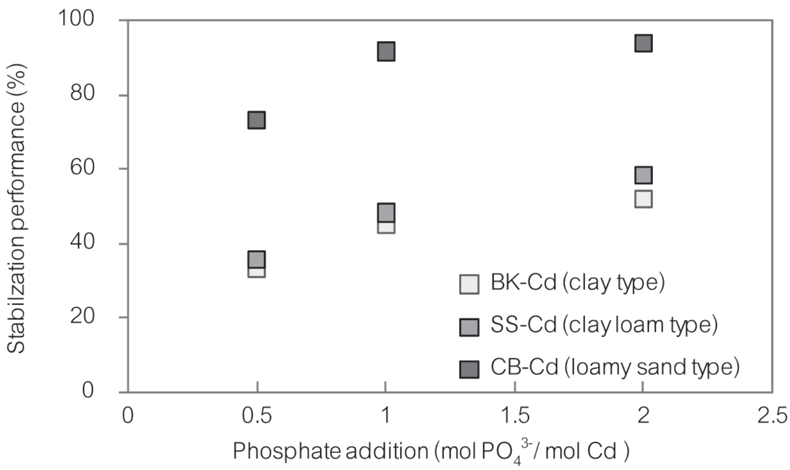

Figure 2 Stabilization performance of TSP for immobilization of Cd in soils with different texture characteristics as a function of phosphate concentration after 30-d amendment.

Effect of TSP on Soil Cd speciation

Sequential extraction was used to study the changes in the forms of Cd bound in TSP-treated soils compared to the untreated soils after 30 d of incubation. Figure 3 shows the distribution of Cd in the three untreated soils and the TSP treated soils with different texture characteristics. Cd in the three untreated soils was bound to the soil predominantly in the first three fractions: the soluble-exchangeable fraction (EX), the surface adsorbed fraction (AD) and the organic matter bound fraction (OM). The sum of Cd associated with EX, AD, and OM fractions in the three untreated soils (defined here as “available forms”) accounted over 90% of total Cd concentrations with the relative availability following, the sequence of loamy sand soil > clay loam > clay soils (Figure 3). This result helps to demonstrate the observed much higher TCLP leachability of Cd in CB-Cd soil with loamy sand texture compared to the clay loam and the clay soils. When the soil was amended with TSP, all TSP treated soils displayed the partitioning of Cd from the potentially available fractions to the less available or more stable ones (Figure 3). The extent of partitioning was varied depending on soil texture characteristic. Among the three tested soils, CB-Cd with loamy sand texture showed a substantial reduction of Cd in the potentially available forms: summation values for the first three steps of the untreated soil, 99%, decreased to 67% after 30-d aging. These observations evidenced the much higher effectiveness of TSP in immobilization of Cd in coarse-textured contaminated soils compared to the contaminated soils with fine texture characteristic. This was probably occurred as a result of the leaching of Cd that, in general, was found to be more pronounced in loamy sand soils than those in fine-grained soils as reported by Bradl[26].

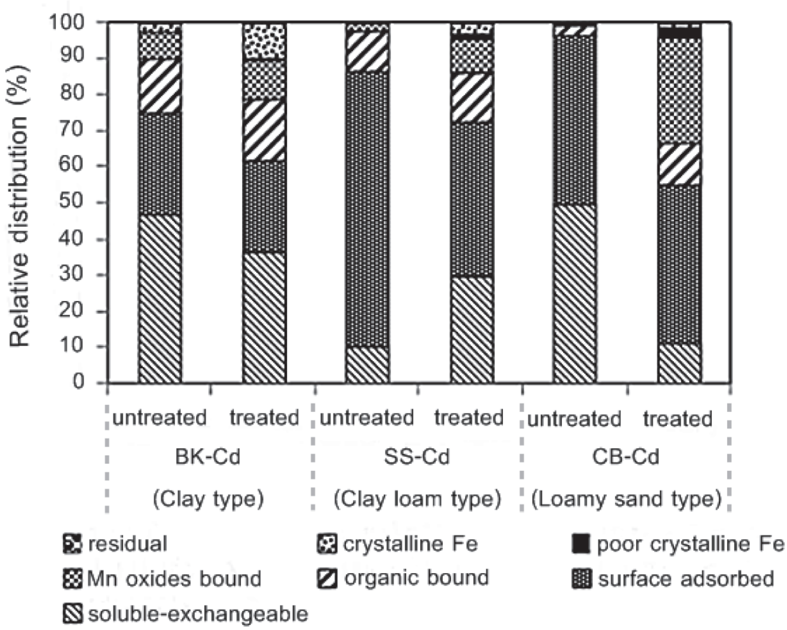

Figure 3 Distribution of Cd bound to the soil in the untreated and treated soils with three different textures after 30-d amendment with TSP.

Competitive effects of other metal ions

Table 2 presents leachable concentrations of Cd as well as leachable concentrations of other tested metal ions in the soil samples (both untreated and TSP-treated soil) after soils were incubated for 30 d. TSP proved to be effective in reducing leaching of heavy metals from contaminated soils as seen from the leachable concentrations of Cd as well as other heavy metals decreased in TSP-treated soils compared with the untreated soils (Table 2). Comparison between leachable Cd concentrations in the untreated di-metal spiked soils and those in the untreated soils being spiked with only Cd, it was found that presence of other metals did increase the leachability of Cd as retention in the soil particle. An increased leachability of Cd relative to Cu and Pb has been previously reported[31-33]. When Cd stabilization performance in the binary system either Cd-Cu, Cd-Pb or Cd-Zn were compared to those values in the mono metal system (SS-Cd soils), it is found that the presence of other metals affect performance of TSP to stabilize Cd in both negative and positive ways depending on heavy metal ions. Stabilization performance of TSP for immobilization of Cd in contaminated soils increased from 58% in the SS-Cd soils to 71% in the Cd-Cu soils when Cu was present as co-contaminants. In soil amended with phosphates, it is well documented that the formation of metal phosphate precipitates or minerals is the main mechanism in retention of metals especially Pb in contaminated soils[11, 19, 22, 34]. Therefore, increased Cd stabilization performance values in the binary system like Cd-Cu soils compared to those values in the soils being contaminated with only Cd (SS-Cd soils) are probably due to the favorable formation of cadmium phosphates [e.g. $Cd_3(PO_4)_2$] over the copper phosphate formation [e.g. $Cu_3(PO_4)_2$] since the solubility of $Cd_3(PO_4)_2 < Cu_3(PO_4)_2$[11, 14]. While Zn had little negative effect on Cd stabilization performance by TSP, the presence of Pb significantly reduced the Cd stabilization performance of TSP as seen from 54% in the Cd-Zn soils and 17% in the Cd-Pb soils compared to 58% in the SS-Cd soils (Table 2). The decrease in Cd stabilization performance of TSP in the presence of Pb suggests that TSP has the higher affinity for Pb than Cd. These observations are supported by the fact that the stability product of lead phosphates are significantly greater than the stability product of cadmium phosphates especially hydroxypyromorphite, a commonly observed lead phosphate mineral that is found in many soils amended with phosphate materials[11, 14]. These results are concurred with the findings of Cao et al.[22] and

Takeuchi and Arai[35] who observed that Pb had significantly influence on the immobilization of other metal ions like Cu and Zn by phosphate materials in the competitive stabilization process.

Table 2 Mean (n=3) leachable metal concentrations in mg/kg and the percent stabilization (as shown in parentheses) of metal species eluted in TSP-treated soils compared with the untreated soil after 30 d aging.

Types of Metal	SS-Cd soils		Cd-Cu soils		Cd-Pb soils		Cd-Zn soils	
	Untreated	Treated	Untreated	Treated	Untreated	Treated	Untreated	Treated
Cd	83.9 †	35.1 (58.2)	112	33.1 (70.5)	278	232 (16.6)	122	56.5 (53.7)
Cu	—	—	133	99.5 (25.2)	—	—	—	—
Pb	—	—	—	—	107	ND‡ (100)	—	—
Zn	—	—	—	—	—	—	54.4	8.27 (84.8)

† "—" = Not determined.

‡ ND = Less than detection limit. Detection limits for Cd, Cu, Pb and Zn are 1.6, 2.1, 5.0 and 0.65 mg/kg, respectively.

Conclusion

Addition of a phosphate fertilizer, TSP proves to be an effective method in transforming Cd from the potentially available forms into the less available/more stable forms. The efficiency of TSP in reducing Cd leachability in Cd-spiked soils is found to vary among soil types and compositions. TSP exhibits greater Cd stabilization performance in coarse-textured soils like loamy sand texture than in fine-textured soils (e.g. clay loam and clay textures). After 30-d aging, application of TSP at a molar ratio of 2 mol PO_4^{3-}/mol Cd reduced Cd leaching by 94%, 58% and 52% in loamy sand, clay loam and clay textures, respectively. The effective immobilization of Cd in loamy sand soils is attributed to weakly bonded and easily releasable Cd in this type of soils due to low contents of sorptive materials like clay and organic matter in the soils. The presence of other heavy metals affects performance of TSP to immobilize Cd in contaminated soils. In a Cd-Cu binary system, TSP exhibits an increase in Cd stabilization performance compared to the soils being contaminated with only Cd. While Zn had little effect on Cd stabilization by TSP, significant reduction in Cd stabilization performance is observed in the presence of Pb suggesting that TSP has a higher affinity for Pb than for Cd.

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