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Effect of pH and soil environment

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ABSTRACT

The pH dependence of adsorption reactions of cationic metals is due, in part, to the preferential adsorption of the hydrolyzed metal species, in comparison to the free metal ion (McBride, 1977; McLauren and Crawford, 1973; Davis and Leckie, 1978; Farrah and Pickering, 1976a,b; James and Healy, 1972; McBride, 1982; Cavallaro and McBride, 1980; Harter, 1983). The pH of the soil system is a very important parameter that directly influences sorption/desorption, precipitation/ dissolution, complex formation, and oxidation-reduction reactions. In general, maximum retention of cationic metals occurs at $\text{pH} > 7$ and maximum retention of anionic metals occurs at $\text{pH} < 7$. However, because of the complexity of the soil-waste system, with its myriad of surface types and solution composition, such a generalization may not hold true. For example, cationic metal mobility has been observed to increase with increasing pH due to the formation of metal complexes with dissolved organic matter.

Keywords: pH, soil environment

pH AND SOIL ENVIRONMENT

The pH, either directly or indirectly, affects several mechanisms of metal retention by soils. Figure 1 shows the impact of soil pH on the adsorption of Pb, Ni, Zn, and Cu by two soils adjusted to various pHs ranging from approximately 4.3 to 8.3 (Harter, 1983). As is true for all cationic metals, adsorption increased with pH. The author, however, points out that the retention of the metals did not significantly increase until the pH was greater than 7. Figure 2 illustrates the adsorption of selenite, SeO_3^{2-} , on five soils adjusted to various pHs. As is true with all oxyanions, i.e., arsenic, selenium and hexavalent chromium, sorption decreases with

pH. The pH dependence of adsorption reactions of cationic metals is due, in part, to the preferential adsorption of the hydrolyzed metal species in comparison to the free metal ion (McBride, 1977; McLauren and Crawford, 1973; Davis and Leckie, 1978; Farrah and Pickering, 1976a,b; James and Healy, 1972; McBride, 1982; Cavallaro and McBride, 1980; Harter, 1983). The proportion of hydrolyzed metal species increases with pH.

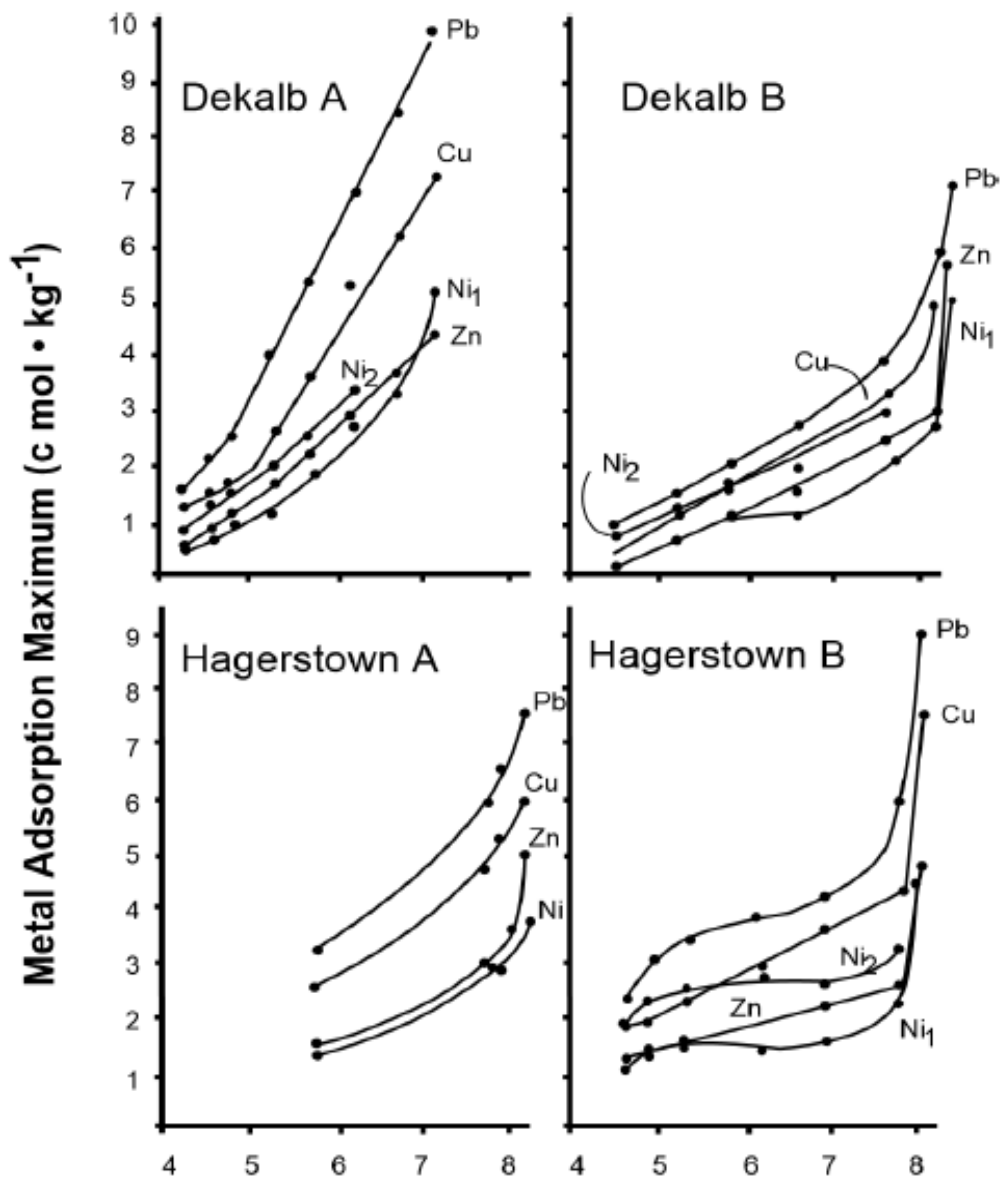


Figure 1. Effect of soil pH level on maximum Pb, Cu, Zn, and Ni retention by Dekalb and Hagerstown A and B horizons. Ni1 and Ni2 refer to two apparent sorption maxima. (Harter, 1983).

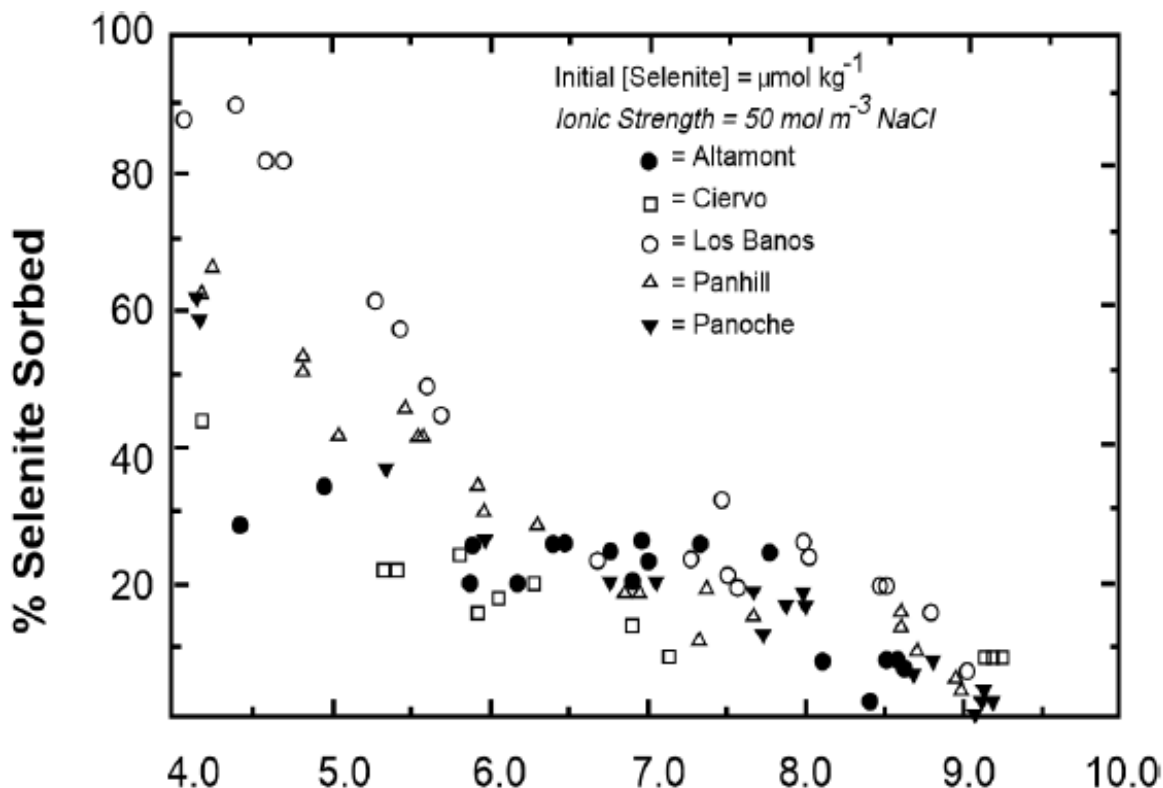


Figure 2. Selenite adsorption envelope for five alluvial soils. The initial total selenite concentration was approximately $2 \mu\text{mol kg}^{-1}$ (Neal, et al., 1987a).

Cavallaro and McBride (1980) found that copper adsorption by soils showed a stronger pH dependence than Cd. This finding is consistent with the hypothesis that hydrolysis of Cu at pH 6 increases its retention by soil, while cadmium does not hydrolyze until pH 8. Zinc was shown to be retained in an exchangeable form at low pH in four Fe and Mn oxide dominated soils but became nonexchangeable as the pH was increased above 5.5 (Stahl and James, 1991). The researchers attributed this change in mechanism of sorption as being due to the hydrolysis of Zn and the adsorption of the hydrolysis species by the oxide surfaces.

Many adsorption sites in soils are pH dependent, i.e., Fe and Mn oxides, organic matter, carbonates, and the edges of clay minerals. As the pH decreases, the number of negative sites for cation adsorption diminishes while the number of sites for anion adsorption increases. Also as the pH becomes more acidic, metal cations also face competition for available permanent charged sites by Al^{3+} and H^+ .

All trace metal hydroxide, oxide, carbonate, and phosphate precipitates form only under alkaline conditions (Lindsay, 1979). The dissolution of these metal precipitates is strongly dependent on the pH of the system. Jenne (1968) stated that hydrous oxides of Fe and Mn play a principal role in the retention of metals in soils. Solubility of Fe and Mn oxides is also pH-related. Below pH 6, the oxides of Fe and Mn dissolve, releasing adsorbed metal ions to solution (Essen and El Bassam, 1981).

Work by McBride and Blasiak (1979) showed increased retention of Zn with increasing pH, as is usual for metal cations. When the pH was increased above 7.5, however, the solution

concentration of Zn increased. This phenomena has been observed in other studies when acid soils were adjusted to $\text{pH} > 7$ (Kuo and Baker, 1980) and it has been attributed to the solubilization of organic complexing ligands which effectively compete with the soil surfaces for the metal cation. Most functional groups of complexing ligands are weak acids, thus the stability of the metal complex is pH-dependent with little association in acid media. The degree of association increases with pH. Baham and Sposito (1986) and Inskeep and Baham (1983) demonstrated that the adsorption of Cu to montmorillonite, in the presence of water soluble ligands extracted from sludges and various other organic materials, decreased with increasing pH. This behavior is the opposite of the typical relationship between metal adsorption and pH. Figure 3, taken from Baham and Sposito (1986), illustrates that nearly 100% of the Cu added to the clay in the absence of the organic ligands was removed from solution at $\text{pH} > 7$. In the presence of the organic ligands, the maximum amount of Cu removed from solution was at $\text{pH}^3 5.5$. As the pH was increased above 5.5, adsorption of Cu decreased.

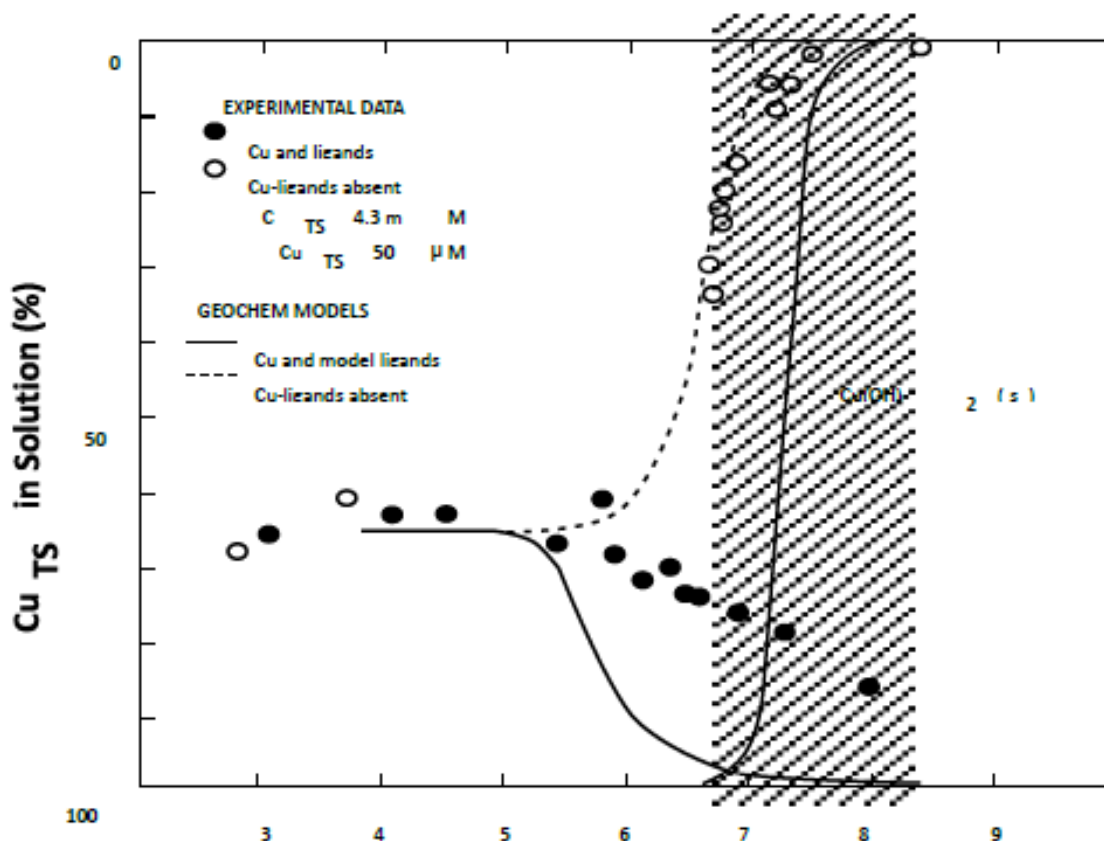


Figure 3. Adsorption of Cu [50 mmol m^{-3} (50 mM)] by Na montmorillonite in the presence and absence of water soluble extract of sewage sludge (WSE). GEOCHEM simulations were constructed employing the "mixture model" (Baham and Sposito, 1986).

The explanation for this phenomena is that at low pH, H^+ competes with the Cu for complexation with the organic matter. As the pH increases, more of the Cu can be complexed with the organic matter and less is therefore adsorbed by the clay. This phenomena has

important implications with regards to the practice of liming acid soils to raise the pH increasing metal retention. In soils with significant levels of dissolved organic matter, increasing soil pH may actually mobilize metal due to complex formation.

The pH of the soil system is a very important parameter, directly influencing sorption/desorption, precipitation/ dissolution, complex formation, and oxidation-reduction reactions. In general, maximum retention of cationic metals occurs at $\text{pH} > 7$ and maximum retention of anionic metals occurs at $\text{pH} < 7$. Because of the complexity of the soil-waste system, with its myriad of surface types and solution composition, such a generalization may not hold true. For example, cationic metal mobility has been observed to increase with increasing pH due to the formation of metal complexes with dissolved organic matter.

CONCLUSION

The pH of the soil system is a very important parameter, directly influencing sorption/desorption, precipitation/ dissolution, complex formation, and oxidation-reduction reactions. In general, maximum retention of cationic metals occurs at $\text{pH} > 7$ and maximum retention of anionic metals occurs at $\text{pH} < 7$. Because of the complexity of the soil-waste system, with its myriad of surface types and solution composition, such a generalization may not hold true. For example, cationic metal mobility has been observed to increase with increasing pH due to the formation of metal complexes with dissolved organic matter.

References

- [1] Ainsworth, C. C., D. C. Girvin, J. M. Zachara and S. C. Smith. 1989. Chromate adsorption on goethite: effects of aluminum substitution. *Soil Sci. Soc. Am. J.* 53: 411-418.
- [2] Amrhein, C., J. E. Strong, and P. A. Mosher. 1992. Effect of deicing salts on metal and organic matter mobility in roadside soils. *Environ. Sci. Technol.* 26: 703-709.
- [3] Anderson, M. C. and D. T. Malotky. 1979. The adsorption of protolyzable anions on hydrous oxides at the isoelectric pH. *J. Colloid Interface Sci.* 72: 413-427.
- [4] Anderson, M. C., J. F. Ferguson and J. Gavis. 1976. Arsenate adsorption on amorphous aluminum hydroxide. *J. Colloid Interface Sci.* 54: 391-399.
- [5] Baham, J., N. B. Ball and G. Sposito. 1978. Gel filtration studies of trace metal-fulvic acid solutions extracted from sewage sludge. *J. Environ. Qual.* 7: 181-188.
- [6] Baham, J. and G. Sposito. 1986. Proton and metal complexation by water-soluble ligands extracted from anaerobically digested sewage sludge. *J. Environ. Qual.* 15: 239-244.
- [7] Balistrieri, L. S. and T. T. Chao. 1987. Selenium adsorption by goethite. *Soil Sci. Soc. Am. J.* 51: 1145-1151.
- [8] Bar-Yosef, B. and D. Meek. 1987. Selenium sorption by kaolinite and montmorillonite. *Soil Sci.* 144: 11-19.

- [9] Bartlett, R. J. 1991. Chromium cycling in soils and water: links, gaps, and methods. *Environ. Health Perspective* 92: 17-24.
- [10] Bartlett, R. J. and B. James. 1979. Behavior of chromium in soils: III. oxidation. *J. Environ. Qual.* 8: 31-35.
- [11] Bartlett, R. J. and J. M. Kimble. 1976. Behavior of chromium in soils: II. hexavalent forms. *J. Environ. Qual.* 5: 383-386.
- [12] Behel, D., D. W. Nelson and L. E. Sommers. 1983. Assessment of heavy metals equilibria in sewage sludge-treated soil. *J. Environ. Qual.* 12: 181-186.
- [13] Benjamin, M. M. 1983. Adsorption and surface precipitation of metals on amorphous iron oxyhydroxide. *Environ. Sci. Technol.* 17:6 86-692.
- [14] Benjamin, M. M. and J. O. Leckie. 1981. Multiple-site adsorption of Cd, Zn, and Pb on amorphous iron oxyhydroxide. *J. Colloid Interface Sci.* 79: 209-221.
- [15] Benjamin, M. M. and J. O. Leckie. 1982. Effects of complexation by Cl, SO₄, and S₂O₃ on adsorption behavior of Cd on oxide surfaces. *Environ. Sci. Technol.* 16: 162-170.
- [16] Bloomfield, C. and G. Pruden. 1980. The behavior of Cr(VI) in soil under aerobic and anaerobic conditions. *Environ. Pollut. Ser. A.* 103-114.
- [17] Bolland, M. D. A., A. M. Posner and J. P. Quick. 1977. Zinc adsorption by goethite in the absence and presence of phosphate. *Aust. J. Soil Res.* 15: 279-286.
- [18] Boyd, S. A., L. E. Sommers and D. W. Nelson. 1979. Infrared spectra of sewage sludge fractions: evidence for an amide binding site. *Soil Sci. Soc. Am. J.* 43: 893-899.
- [19] Boyd, S. A., L. E. Sommers, D. W. Nelson and D. X. West. 1983. Copper(II) binding by humic acid extracted from sewage sludge: an electron spin resonance study. *Soil Sci. Soc. Am. J.* 47: 43-46.
- [20] Boyle, M. and W. H. Fuller. 1987. Effect of municipal solid waste leachate composition on zinc migration through soils. *J. Environ. Qual.* 16: 357-360.
- [21] Calvet, R., S. Bourgeois, and J. J. Msaky. 1990. Some experiments on extraction of heavy metals present in soil. *Intern. J. Environ. Anal. Chem.* 39: 31-45.
- [22] Cary, E. E., W. H. Allaway and O. E. Olson. 1977. Control of chromium concentration in food plants. II. chemistry of chromium in soils and its availability to plants. *J. Agric. Food Chem.* 25: 305-309.
- [23] Catts, J. G. and D. Langmuir. 1986. Adsorption of Cu, Pb, and Zn by MnO₂; applicability of side binding-surface complexation model. *Appl. Geochem.* 1: 255-264.
- [24] Cavallaro, N. and M. B. McBride. 1978. Copper and cadmium adsorption characteristics of selected acid and calcareous soils. *Soil Sci. Soc. Am. J.* 42: 550-556.
- [25] Cavallaro, N. and M. B. McBride. 1980. Activities of Cu²⁺ and Cd²⁺ in soil solutions as affected by pH. *Soil Sci. Soc. Am. J.* 44: 729-732.
- [26] Cavallaro, N. 1982. Sorption and fixation of Cu and Zn, and phosphate by soil clays as influenced by the oxide fraction. PhD thesis. Cornell Univ. (Diss. Abstr. 8210799).

- [27] Chao, T. T. and R. F. Sanolone. 1989. Fractionation of soil selenium by sequential partial dissolution. *Soil Sci. Soc. Am. J.* 53: 385-392.
- [28] Davis, J. A. 1984. Complexation of trace metals by adsorbed natural organic matter. *Geochim. Cosmochim. Acta.* 48: 679-691.
- [29] Davis, J. A. and J. O. Leckie. 1978. Effect of adsorbed complexing ligands on trace metal uptake by hydrous oxides. *Environ. Sci. Technol.* 12: 1309-1315.
- [30] Davis, J. A. and J. O. Leckie. 1980. Surface ionization and complexation at the oxide/water interface. III. adsorption of anions. *J. Colloid Interface Sci.* 74: 32-43.
- [31] Doner, H. E. 1978. Chloride as a factor in mobilities of Ni(II), Cu(II), and Cd(II) in soil. *Soil Sci. Soc. Am. J.* 42: 882-885.
- [32] Dragun, J., J. Barkach, and S. A. Mason. 1990. Misapplication of the EP-TOX, TCLP, and CAM-WET tests to derive data on migration potential of metals in soil systems. In P. T. Kostecki and E. J. Calabrese (eds.). *Petroleum contaminated soils*. Lewis Publ. Chelsea, MI.
- [33] Dudley, L. M., J. E. McLean, R. C. Sims and J. J. Jurinak. 1988. Sorption of copper and cadmium from the watersoluble fraction of an acid mine waste by two calcareous soils. *Soil Sci.* 145: 207- 214.
- [34] Dudley, L. M., J. E. McLean, T. H. Furst, and J. J. Jurinak. 1991. Sorption of Cd and Cu from an acid mine waste extract by two calcareous soils: column studies. *Soil Sci.* 151: 121-135.
- [35] Dudley, L. M., B. L. McNeal, J. E. Baham, C. S. Coray and H. H. Cheng. 1987. Characterization of soluble organic compounds and complexation of copper, nickel, and zinc in extracts of sludge-amended soils. *J. Environ. Qual.* 16: 341-348.
- [36] Dunnivant, F. M., P. M. Jardine, D. L. Taylor, and J. F. McCarthy. 1992. Cotransport of cadmium and hexachlorobiphenyl by dissolved organic carbon through columns containing aquifer material. *Environ. Sci. Technol.* 26: 360-368.
- [37] Eary, L. E. and D. Rai. 1991. Chromate reduction by subsurface soils under acidic conditions. *Soil Sci. Soc. Am. J.* 55: 676-683.
- [38] Egozy, Y. 1980. Adsorption of cadmium and cobalt on montmorillonite as a function of solution composition. *Clays Clay Min.* 28: 311-318.
- [39] Elkhatib, E. A., O. L. Bennett and R. J. Wright. 1984 a. Kinetics of arsenite sorption in soils. *Soil Sci. Soc. Am. J.* 48: 758-762.
- [40] Elkhatib, E. A., O. L. Bennett and R. J. Wright. 1984 b. Arsenite sorption and desorption in soils. *Soil Sci. Soc. Am. J.* 48: 1025-1030.
- [41] Elliott, H. A., M. R. Liberati and C. P. Huang. 1986. Competitive adsorption of heavy metals by soils. *J. Environ. Qual.* 15: 214-219.
- [42] Elprince, A. M. and G. Sposito. 1981. Thermodynamic derivation of equations of Langmuir-type for ion equilibrium in soils. *Soil Sci. Soc. Am. J.* 45: 277-282.

- [43] Elrashidi, M. A., D. C. Adriano and W. L. Lindsay. 1989. Solubility, speciation, and of selenium in soils. In L. W. Jacobs (Ed). Selenium in agriculture and the environment. American Society of Agronomy. Madison, WI.
- [44] Elrashidi, M. A. and G. A. O'Connor. 1982. Influence of solution composition on sorption of zinc by soils. *Soil Sci. Soc. Am. J.* 46: 1153-1158.
- [45] Essen, J. and N. El Bassam. 1981. On the mobility of cadmium under aerobic soil conditions. *Environ. Pollut. Ser. A.* 15-31.
- [46] Farrah, H. and W. J. Pickering. 1976 a. The adsorption of copper species by clays: I. kaolinite. *Aust. J. Chem.* 29: 1167-1176.
- [47] Farrah, H. and W. J. Pickering. 1976 b. The adsorption of copper species by clays: II. illite and montmorillonite. *Aust. J. Chem.* 29: 1649-1656.
- [48] Fio, J. L., R. Fujii, and S. J. Deveral. 1991. Selenium mobility and distribution in irrigated and non-irrigated alluvial soils. *Soil Sci. Soc. Am. J.* 55: 1313-1320.
- [49] Forbes, E. A., A. M. Posner and J. P. Quick. 1976. The specific adsorption of divalent Cd, Co, Pb, and Zn on goethite. *J. Soil Sci.* 27: 154-166.
- [50] Garcia-Miragaya, J., R. Cardenas and A. L. Page. 1986. Surface loading effect on Cd and Zn sorption by kaolinite and montmorillonite from low concentration solutions. *Water, Air, Soil Pollut.* 27: 181-190.
- [51] Garcia-Miragaya, J. and A. L. Page. 1976. Influence of ionic strength and complex formation on sorption of trace amounts of Cd by montmorillonite. *Soil Sci. Soc. Am. J.* 40: 658-663.
- [52] Goldberg, S. and R. A. Glaubig. 1988. Anion sorption on a calcareous montmorillonite soil-selenium. *Soil Sci. Soc. Am. J.* 52: 954-958.
- [53] Griffin, R. A. and A. K. Au. 1977. Lead adsorption by montmorillonite using a competitive Langmuir equation. *Soil Sci. Soc. Am. J.* 41: 880-882.
- [54] Griffin, R. A. and N. F. Shimp. 1978. Attenuation of pollutants in municipal landfill leachate by clay minerals. EPA-600/2-78-157.
- [55] Grove, J. H. and B. G. Ellis. 1980. Extractable chromium as related to soil pH and applied chromium. *Soil Sci. Soc. Am. J.* 44: 238-242.
- [56] Gruebel, K. A., J. A. Davies and J. O. Leckie. 1988. The feasibility of using sequential extraction techniques for arsenic and selenium in soils and sediments. *Soil Sci. Soc. Am. J.* 52: 390-397.
- [57] Gschwend, P. M. and M. D. Reynolds. 1987. Monodisperse ferrous phosphate colloids in an anoxic groundwater plume. *J. of Contaminant Hydrol.* 1: 309-327.
- [58] Haas, C. N. and N. D. Horowitz. 1986. Adsorption of cadmium to kaolinite in the presence of organic material. *Water Air Soil Pollut.* 27: 131-140.
- [59] Harrison, R. M., D. P. H. Laxen and S. J. Wilson. 1981. Chemical associations of lead, cadmium, copper, and zinc in street dust and roadside soils. *Environ. Sci. Technol.* 15: 1378-1383.

- [60] Harter, R. D. 1992. Competitive sorption of cobalt, copper, and nickel ions by a calcium saturated soil. *Soil Sci. Soc. Am. J.* 56: 444-449.
- [61] Harter, R. D. 1979. Adsorption of copper and lead by Ap and B2 horizons of several northeastern United States soils. *Soil Sci. Soc. Am. J.* 43: 679-683.
- [62] Harter, R. D. 1983. Effect soil pH on adsorption of lead, copper, zinc, and nickel. *Soil Sci. Soc. Am. J.* 47: 47-51.
- [63] Harter, R. D. 1984. Curve-fit errors in Langmuir adsorption maxima. *Soil Sci. Soc. Am. J.* 48: 749-752.
- [64] Harter, R. D. and D. E. Baker. 1977. Application and misapplication of the Langmuir equation to soil adsorption phenomena. *Soil Sci. Soc. Am. J.* 41: 1077-1080.
- [65] Harter, R. D. and R. G. Lehmann. 1983. Use of kinetics for the study of exchange reactions in soils. *Soil Sci. Soc. Am. J.* 47: 666-669.
- [66] Harter, R. D. and G. Smith. 1981. Langmuir equation and alternative methods of studying "adsorption" reactions in soils. In R. H. Dowdy, J. A. Ryan, V. V. Volk, and D. E. Baker (Eds.). *Chemistry in the soil environment*. American Society of Agronomy. Madison, WI.
- [67] Hendrickson, L. L. and R. B. Corey. 1981. Effect of equilibrium metal concentration on apparent selectivity coefficients of soil complexes. *Soil Sci.* 131: 163-171.
- [68] Hickey, M. G. and J. A. Kittrick. 1984. Chemical partitioning of cadmium, copper, nickel, and zinc in soils and sediments containing high levels of heavy metals. *J. Environ. Qual.* 13: 372-376.
- [69] Hingston, F. J., A. M. Posner, and J. P. Quick. 1971. Competitive adsorption of negatively charged ligands on oxide surfaces. *Faraday Soc.* 52: 334-342.
- [70] Hirsch, D., S. Nir and A. Banin. 1989. Prediction of cadmium complexation in solution and adsorption to montmorillonite. *Soil Sci. Soc. Am. J.* 53: 716-721.
- [71] Inskip, W. P. and J. Baham. 1983. Competitive complexation of Cd(II) and Cu(II) by water-soluble organic ligands and Na-montmorillonite. *Soil Sci. Soc. Am. J.* 47: 1109-1115.
- [72] James, B. R. and R. J. Bartlett. 1983a. Behavior of chromium in soils: V. fate of organically complexed Cr(II) added to soil. *J. Environ. Qual.* 12: 169-172.
- [73] James, B. R. and R. J. Bartlett. 1983b. Behavior of chromium in soils, VI. Interaction between oxidation-reduction and organic complexation. *J. Environ. Qual.* 12: 173-176.
- [74] James, B. J. and R. J. Bartlett. 1983c. Behavior of chromium in soils. VII. Adsorption and reduction of hexavalent forms. *J. Environ. Qual.* 12: 177-181.
- [75] James, R. O. and T. W. Healy. 1972. Adsorption of hydrolyzable metal ions at the oxide-water interface: III. thermodynamic model of adsorption. *J. Colloid Interface Sci.* 40: 65-81.

- [77] Jenne, E. A. 1968. Control of Mn, Fe, Co, Ni, Cu, and Zn concentrations in soils and water-the dominant role of hydrous manganese and iron oxides. *Adv. in Chem.* 7: 337-387.
- [78] Jurinak, J. J. and N. Bauer. 1956. Thermodynamics of zinc adsorption on calcite, colomite, and magnesite-type minerals. *Soil Sci. Soc. Am. Proc.* 20: 466-471.
- [79] Khan, S., D. Nonden and N. N. Khan. 1982. The mobility of some heavy metals through Indian red soil. *Environ. Pollut. Ser. B.* 119-125.
- [80] Kheboian, C. and C. F. Bauer. 1987. Accuracy of selective extraction procedures for metal speciation in model aquatic sediments. *Anal. Chem.* 59: 1417-1423.
- [81] Kinniburgh, D. G. and M. L. Jackson. 1978. Adsorption of mercury (II) by iron hydrous oxide gel. *Soil Sci. Soc. Am. J.* 42: 45-47.
- [82] Korte, N. E., J. Skopp, W. H. Fuller, E. E. Niebla and B. A. Aleshii. 1976. Trace element movement in soils: influence of soil physical and chemical properties. *Soil Sci.* 122: 350-359.
- [83] Kotuby-Amacher, J. and R. P. Gambrell. 1988. Factors affecting trace metal mobility in subsurface soils. Editor. *Factors affecting trace metal mobility in subsurface soils.* U. S. Environmental Protection Agency. EPA/600/2-88/ 036.
- [84] Kramer, J. R. and H. E. Allen. 1988. *Metal speciation: theory, analysis and application.* Lewis Publishers, Inc., Chelsea, MI.
- [85] Kuo, S. and A. S. Baker. 1980. Sorption of copper, zinc, and cadmium by some acid soils. *Soil Sci. Soc. Am. J.* 44: 969-974.
- [86] Kuo, S., P. E. Heilman and A. S. Baker. 1983. Distribution and forms of copper, zinc, cadmium, iron, and manganese in soils near a copper smelter. *Soil Sci.* 135:101-109.
- [87] Kuo, S. and B. L. Mc Neal. 1984. Effect of pH and phosphate on cadmium sorption by a hydrous ferric oxide. *Soil Sci. Soc. Am. J.* 48: 1040-1044.
- [88] Kurdi, F. and H. E. Doner. 1983. Zinc and copper sorption an interaction in soils. *Soil Sci. Soc. Am. J.* 47: 873-876.
- [89] Lake, D. L., P. W. W. Kirk and J. N. Lester. 1984. Fractionation, characterization, and speciation of heavy metals in sewage sludge and sludge-amended soils: a review. *J. Environ. Qual.* 13: 175-183.
- [90] Latterell, J. J., R. H. Dowdy and W. E. Larson. 1978. Correlation of extractable metals and metal uptake of snap beans grown on soil amended with sewage sludge. *J. Environ. Qual.* 7: 435-440.
- [91] Lehmann, R. G. and R. D. Harter. 1984. Assessment of copper-soil bond strength by desorption kinetics. *Soil Sci. Soc. Am. J.* 48: 769-772.
- [92] Lindsay, W. L. 1979. *Chemical equilibria in soils.* John Wiley and Sons. New York.
- [93] Loganathan, P. and R. G. Burau. 1973. Sorption of heavy metals by a hydrous manganese oxide. *Geochim. Cosmochim. Acta.* 37: 1277-1293.

- [94] Mattigod, S. V. and G. Sposito. 1979. Chemical modeling of trace metals equilibrium in contaminated soil solutions using the computer program GEOCHEM. In E. A. Jenne (ed.). Chemical modeling in aqueous systems. ACS No. 93, Am. Chem. Soc., Washington, D.C.
- [95] Mattigod, S. V., G. Sposito, and A. L. Page. 1981. Factors affecting the solubilities of trace metals in soils. In D. E. Baker (Ed.). Chemistry in the soil environment. ASA Special Publication No 40. Amer. Soc. Agronomy, Madison, WI.
- [96] McBride, M. B. 1977. Copper (II) interaction with kaolinite factors controlling adsorption. *Clays Clay Miner.* 26: 101106.
- [97] McBride, M. B. 1980. Chemisorption of Cd^{2+} on calcite surfaces. *Soil Sci. Soc. Am. J.* 44: 26-28.

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