Inorganic Trace Elements

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Introduction

Trace element are elements that are usually found at low concentrations in soils, plants, and natural waters. These elements can be naturally present in the soil or can be introduced by human activities. The major natural sources of trace elements in soil are weathering (erosion and wind-blown deposition) of parent materials high in trace elements, volcanic eruptions, and forest fires. However, the concentration of trace elements in soils may be increased due to human activities, such as coal and gasoline combustion, mining, smelting, waste incineration, wood burning, land disposal of industrial co-products and waste (coal fly ash, wood ash), agrochemicals (pesticides), and land application of animal manure, biosolids, and other co-products from agricultural and food industries (Hooda, 2010).

Benefits and risks of trace elements

Some trace elements are essential for plants, animals, and humans in small quantities, but they can be toxic in higher concentrations. Such essential trace elements include iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), nickel (Ni), cobalt (Co), and chlorine (Cl). Selenium (Se), chromium (Cr), iodine (I), fluorine (Fl) and tin (Sn) have been shown to be essential for animal growth but not for plants. Essential trace elements are important for the performance of metabolic and physiological processes in organisms, such as the functioning of enzymes and protein synthesis, and adequate growth. However, other trace elements such as arsenic (As), lead (Pb), mercury (Hg), cadmium (Cd) and beryllium (Be) play no nutritive role for plants, animals or humans but, rather, can be toxic and cause severe health problems (Pierzynski et al. 2005).

Serious problems can occur when plants, animals, and humans accumulate inadequate or excessive amounts of essential trace elements. Deficiencies may cause plants to be stunted, leaves to become yellow, stems to grow distorted, and plants to have poor flowering and fruiting, and die (Epstein and Bloom, 2005). The deficiency of trace elements can also cause growth and reproduction problems in animals and humans. Trace elements are particularly essential for the immune system of animals and humans (Wada, 2004).

In contrast, excessive concentrations of trace elements in humans tend to be concentrated in organs like the brain, liver, and kidneys, and in bones, which can cause acute and chronic diseases (Duruibe et al., 2007). High concentrations of Mo and Se in animals, such as cattle, can cause molybdenosis and selenosis, respectively, which result in severe gastrointestinal irritation, coma, and death from cardiac failure. Human exposure to trace elements can also cause diseases, such as cancers, renal dysfunction and failure, skin disorders, and neurological problems (Duruibe et al., 2007; Kumpiene et al., 2017).

Trace elements in biosolids

Trace elements in biosolids can enrich soils upon repeated land application. The potential for excessive soil accumulation of potentially deleterious trace elements in biosolids was addressed by Federal regulations found in the U.S. EPA Standards for the Use or Disposal of Sewage Sludge (Tittle 40 of the Code of Federal Regulations, Part 503).

The Part 503 rule established specific limits for trace elements in biosolids that must be met if biosolids are to be beneficially applied to land. Ceiling Concentration Limits (CCL), or the maximum concentrations of trace elements allowed to be contained in biosolids, were established to ensure that biosolids with potentially hazardous trace element concentrations are not applied. Pollutant Concentration Limits (PCL) were also established to categorize biosolids quality. “Exceptional Quality” (EQ) biosolids are those that meet PCL standards (and PFRP – see Regulations fact sheet). Exceptional Quality biosolids can be applied without accounting for long term (i.e., lifetime) loading rates of trace elements because the trace element binding capacity of biosolids meeting PCLs exceeds the potential bioavailability of the trace elements, thus resulting in long-term immobilization of trace elements in soil. Trace elements in land-applied CCL biosolids must be summed for all applications of such quality biosolids. The Cumulative Pollutant Loading Rate (CPLR) is the total amount of a pollutant (e.g., regulated trace element) that can be applied to a site in its lifetime by all bulk applications of biosolids meeting ceiling concentration limits. No additional biosolids meeting CCL can be applied to a site after maximum cumulative pollutant loading rate is reached at that site for any one of the nine regulated trace elements. Table 1 shows both ceiling and pollutant concentration limits for biosolids, as well as the cumulative pollutant loading rates (U.S. EPA, 1994). Based on this information, if a biosolids adds 1 kg/ha/year of As, then it would take 41 years to reach the cumulative pollutant loading rate.

Table 1. Pollutant limits for biosolids that are land applied (U.S. EPA, 1994)

Trace Element	Ceiling Concentration Limit for all biosolids applied to land (mg/kg)	Pollutant Concentration Limit for EQ biosolids (mg/kg)	Cumulative Pollutant Loading Rate Limits (kg/ha)
Arsenic	75	41	41
Cadmium	85	39	39
Copper	4300	1500	1500
Lead	840	300	300
Mercury	57	17	17
Molybdenum	75		
Nickel	420	420	420
Selenium	100	36	100
Zinc	7500	2800	2800

Bioavailability of trace elements

U.S. EPA regulations help ensure that land application of biosolids don’t result in excessive concentrations of trace elements in the soil. One must realize that the “total” concentration of a trace element in a soil is different from the “bioavailable” concentration of that trace element. Bioavailability refers to the amount of an element that is accessible for uptake by an organism. The total concentration of a trace element in the soil is not necessarily bioavailable and might not deleteriously affect the plants, animals, or humans in contact with it.

The bioavailability of a trace element in the soil depends on the occurrence of chemical reactions that can result in the element being in solution (available) or in the solid phase (unavailable). Chemical reactions that can modify the availability of a trace element include soil pH, soil organic matter, and the concentration of other elements in the soil (Chen et al., 2010; Basta et al., 2005). In general, a higher soil pH decreases the availability of heavy metal trace elements (e.g., Cd, Cu, Pb, Ni, Zn), so soils with a low pH (acidic soils) will pose a greater risk of heavy metal availability. Trace elements can also be adsorbed to soil organic matter and Al, Fe and Mn hydrous oxides, reducing their availability. Research has also shown that the capacity of soil organic matter to bind trace elements in biosolids-amended soils can become stronger over time (Basta et al., 2005; Sukkariyah et al., 2005).

In additional to soil properties, the properties of biosolids affect the availability of trace elements. The chemical forms of trace elements in biosolids can be modified and their availability can be reduced during wastewater treatment through the addition of Fe (Chen et al., 2010; Liu et al., 2007). Finally, plant species have variable mechanisms that can regulate uptake of different trace elements. For instance, lettuce grown in biosolids-amended soil showed higher accumulations of Cd and Zn, while radishes showed greater accumulations of Cu (Sukkariyah et al., 2005).

Trace element bioavailability in biosolids-amended soils shouldn't be oversimplified since it is dependent on many variable factors (trace element chemical form, soil properties, biosolids properties, and crop type). However, current research conducted with various trace elements and environmental conditions suggest that the availability of trace elements from biosolids-amended soils is low due to long-term trace element sorption to organic matter and Al/Fe/Mn oxides.

Human exposure

The bioavailability of trace elements to humans is largely influenced by exposure. The extent of human exposure is affected by the amount of the trace element entering the body (bioavailabilty), and the absorption of that trace element by the digestive system (bioaccessbility). Both factors, bioavailability and bioaccessibility, are important and are considered when performing risk assessments for trace metals (Kumpiene et al., 2017; Hough et al., 2010). For example, Cd concentrations in a soil could be high, but the risk of exposure could be low if Cd is strongly bound to organic matter or if people don't come in contact with this soil. The relative amount of Zn that competes with Cd is also a critical factor regulating Cd uptake by plants and animals (Chaney, 2010). Children are the most prone to exposure to trace elements from soil through direct ingestion because they play outside, their toys are in contact with the soil, and they tend to place their hands in their mouths (Pierzynski et al., 2005).

Risk assessments for human exposure to trace elements have been developed by the U.S. EPA. Their analysis uses environmental parameters, site-specific soil properties, and possible routes for human exposure (ingestion, inhalation, dietary intake, and skin absorption). When results of risk assessment reveal the possibility of exposure over acceptable limits, then remediation technologies or restricted public contact are implemented to prevent human exposure (U.S. EPA, 2007; Kumpiene et al., 2017).

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