Inorganic Trace Elements

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Background

When domestic sewage is transported and conveyed to a wastewater treatment plant, it is treated to separate liquids from the solids, which produces a semi-solid, nutrient-rich product known as “sewage sludge”. The terms “biosolids” and “sewage sludge” are often used interchangeably by the public; however, the U.S. Environmental Protection Agency (EPA) and wastewater treatment facilities typically use the term “biosolids” to mean sewage sludge that has been treated to meet the requirements in the EPA’s regulation entitled, “Standards for the Use or Disposal of Sewage Sludge,” promulgated at 40 CFR Part 503, and intended to be applied to land as a soil conditioner or fertilizer.

Biosolids are primarily composed of water and organic (carbon-rich) materials. Biosolids contain macronutrients like nitrogen, phosphorus and potassium as well as micronutrients like copper, zinc and iron. Additionally, biosolids contain inert (no carbon) solids like sand, trace elements and, depending on the level of treatment, low concentrations of microorganisms. Biosolids that comply with state and federal regulations are considered safe for the environment and protective of human health and may be beneficially used for land application as a fertilizer and soil amendment, as well as for use in composted products.

Biosolids are recycled on farms and forests throughout the United States and in most developed countries worldwide. As of 2023, the EPA estimates about 60% of the total biosolids produced annually in the United States are applied for beneficial uses, while the remainder is either incinerated or disposed of in landfills.

In Virginia, the Department of Environmental Quality (DEQ), reports 37,786 acres received biosolids applications in 2024, an increase from 36,145 acres in 2023. Despite this, the acreage where biosolids are recycled represents less than 1% of all agricultural land in Virginia.

What are Inorganic Trace Elements

Inorganic elements that are usually found at low concentrations (generally less than 0.01%) in soils, plants, and natural waters are known as “inorganic trace elements” (Islam et al., 2023). These inorganic trace elements occur naturally in soil or can be introduced through human activity. Major natural sources include the weathering, erosion, and wind-blown deposition of parent materials rich in trace elements, as well as volcanic eruptions and forest fires. Human activities can significantly increase the concentration of trace elements in the soil. Common contributors include the combustion of coal and gasoline, mining and smelting operations, waste incineration, wood burning, and the land disposal of industrial by-products such as coal fly ash and wood ash. Additionally, the use of agrochemicals, such as pesticides, and the land application of animal manure, biosolids, and other agricultural or food industry co-products can add trace elements to the soil (Hooda, 2010; Kumar, 2022).

Benefits and Risks of Inorganic Trace Elements

Some inorganic trace elements are essential for plants, animals, and humans in small quantities but can become toxic at higher concentrations. Selenium, chromium, iodine, fluorine, and tin have been shown to be essential for animal health but not for plants. Essential inorganic trace elements, some of which are micronutrients, include iron, manganese, zinc, copper, boron, molybdenum, nickel, cobalt, and chlorine. These elements play critical roles in metabolic and physiological processes such as enzyme function, protein synthesis, immune system support, and healthy growth and development.

For example, manganese, iron, copper, zinc, and molybdenum are vital for many plant functions. Specifically, copper and iron are involved in photosynthesis and respiration, while manganese, molybdenum, and zinc support enzyme activities that regulate root development, amino acid production, and DNA replication (Johnston et al., 2022).

In contrast, some inorganic trace elements — such as arsenic, lead, mercury, cadmium, and beryllium — have no nutritional value for plants, animals, or humans and can cause severe health hazards even at low concentrations (Mehri, 2020).

Imbalances in inorganic trace element levels can lead to serious problems. In plants, deficiencies can stunt growth, reduce fruit production, decrease resistance to pests and environmental stress, and cause leaf yellowing that limits photosynthesis (Kaur et al., 2022). In animals and humans, deficiencies can impair growth, reproduction, and immune function (Wada, 2004).

On the other hand, excessive inorganic trace element intake can lead to accumulation in organs such as the brain, liver, kidneys, and bones, causing acute and chronic diseases (Leal et al., 2023). In animals like cattle, high levels of molybdenum and selenium can cause molybdenosis and selenosis, leading to severe gastrointestinal irritation, coma, or death due to cardiac failure. In humans, overexposure to inorganic trace elements can result in conditions such as cancers, kidney dysfunction and failure, skin disorders, and neurological diseases (Duruibe et al., 2007; Kumpiene et al., 2017).

Inorganic Trace Elements in Biosolids

Biosolids can be a significant source of inorganic trace elements, and repeated land application may lead to their accumulation in soils — sometimes reaching potentially undesirable levels (Onchoke and Fateru, 2021). However, the risk of excessive buildup of harmful inorganic trace elements has been addressed through federal regulations outlined in the U.S. EPA Standards for the Use or Disposal of Sewage Sludge (Title 40 of the Code of Federal Regulations, Part 503).

In addition, soil properties, such as pH, influence the mobility and availability of inorganic trace elements. For example, higher soil pH can reduce the availability and uptake of certain heavy metals by fixing them in less soluble forms.

The Part 503 Rule established specific limits for inorganic trace elements in biosolids that must be met for land application to be considered safe and beneficial. Two key limits were defined:

- Ceiling Concentration Limits (CCL): These are the maximum allowable concentrations of inorganic trace elements in biosolids. They ensure that biosolids containing potentially hazardous levels of inorganic trace elements are not applied to land.
- Pollutant Concentration Limits (PCL): These define concentration thresholds for inorganic trace elements that determine biosolids quality.

Biosolids that meet PCL standards (and comply with Processes to Further Reduce Pathogens, or PFRP — see Regulations fact sheet) are classified as “Exceptional Quality” (EQ) biosolids. EQ biosolids can be applied without restrictions on long-term (lifetime) loading rates for inorganic trace elements because their inorganic trace element binding capacity exceeds the potential bioavailability, resulting in long-term immobilization in the soil.

For biosolids that meet CCL standards but not PCL standards, the total amount of each regulated inorganic trace element applied over time must be tracked. This is called the Cumulative Pollutant Loading Rate (CPLR) — the total amount of an inorganic trace element that can be applied to a site over its lifetime from all bulk biosolids applications. Once the CPLR is reached for any of the nine regulated inorganic trace elements, no additional biosolids meeting only CCL can be applied to that site.

Table 1 (U.S. EPA, 1994) presents both ceiling and pollutant concentration limits, as well as CPLRs for biosolids. For example, if a biosolids application adds 1 kg/ha/year of arsenic, it would take 41 years to reach the cumulative pollutant loading rate for arsenic at that site.

	Ceiling Concentration	**Pollutant Concentration**	**Cumulative Pollutant**
Inorganic Trace Element	***Limit for all biosolids applied to land (mg/kg)***	***Limit for EQ biosolids (mg/kg)***	***Loading Rate Limits (kg/ha)***
Arsenic	75	41	41
Cadmium	85	39	39
Copper	4,300	1,500	1,500
Lead	840	300	300
Mercury	57	17	17
Molybdenum	75		
Nickel	420	420	420
Selenium	100	36	100
Zinc	7,500	2,800	2,800

Table 1

Bioavailability of Inorganic Trace Elements

The above U.S. EPA regulations help ensure that the land application of biosolids does not result in the accumulation of excessive concentrations of trace elements in soil. It is important to understand that the total concentration of an inorganic trace element in soil is different from its bioavailable concentration, which refers to the portion that is accessible for uptake by plants, animals, or humans. Any form of an inorganic trace element that can be readily absorbed by an organism is considered bioavailable. Therefore, total concentration alone does not necessarily pose a risk if much of it is bound in forms that are not bioavailable. For this reason, determining the bioavailable forms of inorganic trace elements in biosolids is essential for accurately evaluating their environmental risks.

The bioavailability of an inorganic trace element in soil depends on various chemical reactions and soil conditions that affect whether the element remains in solution (and thus available) or is bound in the solid phase (and thus unavailable). Key factors that influence these reactions include soil pH, soil organic matter, and the presence of other elements that can interact with inorganic trace elements in synergistic or antagonistic ways (Uchimiya et al., 2020; Onchoke and Fateru, 2021; Zaragueta et al., 2021).

Among these factors, soil pH is considered the master variable controlling inorganic trace element availability. Generally, lower soil pH (more acidic conditions) increases the availability of inorganic trace elements such as cadmium, copper, lead, nickel, and zinc, raising the risk of plant and environmental exposure.

Inorganic trace elements can also be adsorbed onto soil organic matter and hydrous oxides of aluminum, iron, and manganese, which reduces their availability through chemical binding and speciation (Uchimiya et al., 2020). Research has shown that the capacity of soil organic matter to bind inorganic trace elements in soils amended with biosolids can strengthen over time, further helping to immobilize these elements and limit their bioavailability (Basta et al., 2005; Mossa et al., 2020; Zaragueta et al., 2021).

In addition to soil properties, the properties of biosolids themselves influence the availability of inorganic trace elements. The chemical forms of inorganic trace elements in biosolids can be altered during wastewater treatment, often reducing their availability. For example, adding iron during treatment can bind inorganic trace elements and decrease their mobility (Chen et al., 2010; Liu et al., 2007). Similarly, alkaline stabilization raises the pH, promoting the precipitation of inorganic trace elements and thus lowering their availability.

Microbial processes, such as composting, also help immobilize inorganic trace elements by promoting sorption to organic matter, forming stable chelate complexes, or changing their oxidation states (Elgarahy et al., 2024). Other treatment methods like thermochemical processes, incineration, and pyrolysis are being explored to further manage inorganic trace elements and other pollutants in biosolids (Husek et al., 2022).

Plant species also play an important role in regulating inorganic trace element uptake. For example, lettuce grown in biosolids-amended soil has shown higher accumulations of cadmium and zinc, whereas radishes tend to accumulate more copper but also exhibit stronger defense mechanisms against lead and arsenic uptake (Sukkariyah et al., 2005; You et al., 2025). Turfgrass has been found to accumulate higher levels of copper, zinc, manganese, and molybdenum when fertilized with biosolids — yet without harmful effects on growth (Johnston et al., 2022). In addition, some studies have found a negative correlation between potentially toxic inorganic trace elements in plant tissues and biosolids application rates and soil attributes — for instance, in lettuce grown with biosolids (Goncalves et al., 2022).

Overall, inorganic trace element bioavailability in biosolids-amended soils is complex and depends on many factors, including the chemical form of the element, soil properties, biosolids treatment methods, and the crop species. However, current research indicates that while inorganic trace element concentrations may increase over time with repeated biosolids application, their bioavailability — and therefore their potential to pose significant environmental risks — remains low due to long-term binding to organic matter and aluminum, iron, and manganese oxides. Finally, plant species have variable mechanisms that can regulate uptake of different inorganic trace elements.

Human Exposure

The bioavailability of inorganic trace elements to humans largely depends on the level of exposure. Two key factors influence this: the amount of the inorganic trace element that enters the body (bioavailability) and the extent to which the digestive system absorbs it (bio accessibility). Both factors are critical and are considered in risk assessments for inorganic trace metals (Kumpiene et al., 2017; Hough et al., 2010).

For example, soil cadmium concentrations might be high, but the risk of human exposure could remain low if the cadmium is strongly bound to soil organic matter or if people have minimal contact with the soil. Additionally, the relative amount of zinc present can influence cadmium uptake in plants and animals, because zinc competes with cadmium for absorption sites (Chaney, 2010).

Children are especially vulnerable to inorganic trace element exposure through soil ingestion. This is because they often play outdoors and their toys come into contact with soil, and they frequently put their hands in their mouths (Pierzynski et al., 2005).

To address these risks, the U.S. EPA has developed comprehensive risk assessments for human exposure to inorganic trace elements. These assessments consider environmental conditions, site-specific soil properties, and all potential exposure routes, including ingestion, inhalation, dietary intake, and skin contact. If an assessment indicates that exposure could exceed safe limits, appropriate remediation measures or access restrictions are implemented to protect public health (U.S. EPA, 2007; Kumpiene et al., 2017; Onchoke and Fateru, 2021).

References

1. Basta, N.T., J.A. Ryan, and R.L. Chaney. 2005. Key Concepts and Metal Bioavailability. Journal of Environmental Quality. 34: 49-63.
2. Chaney, R.L. 2010. Cadmium and zinc. Pp. 409-439. In P.S. Hooda (ed), Trace elements in soil. Blackwell Publishing Ltd. UK.
3. Chen, W., A.C. Chang, L. Wu, A.L. Page, and B. Koo. 2010. Trace elements in biosolids-amended soils. In P.S. Hooda (ed), Trace elements in soil. Blackwell Publishing Ltd. UK.
4. Gonçalves, P. W. B., da Costa, C. A., Cardoso, P. H. S., Pegoraro, R. F., Cardoso, G. R., & Versiani, L. C. F. (2022). Bioaccumulation of potentially toxic elements in lettuce and soil fertility treated with biosolid. Journal of Soil Science and Plant Nutrition, 22(1), 815-823.
5. Elgarahy, A. M., Eloffy, M. G., Priya, A. K., Yogeshwaran, V., Yang, Z., Elwakeel, K. Z., & Lopez-Maldonado, E. A. (2024). Biosolids management and utilizations: A review. Journal of Cleaner Production, 141974.
6. Hooda, P.S. 2010. Introduction. In P.S. Hooda (eds), Trace elements in soil. Blackwell Publishing Ltd. UK.
7. Hough, R.L. 2010. Bioavailability: Exposure, Dose, and Risk Assessment. In P.S. Hooda (eds), Trace elements in soil. Blackwell Publishing Ltd. UK.
8. Hušek, M., Moško, J., & Pohořelý, M. (2022). Sewage sludge treatment methods and P-recovery possibilities: Current state-of-the-art. Journal of environmental management, 315, 115090.
9. Islam, M. R., Akash, S., Jony, M. H., Alam, M. N., Nowrin, F. T., Rahman, M. M., ... & Thiruvengadam, M. (2023). Exploring the potential function of trace elements in human health: a therapeutic perspective. Molecular and cellular biochemistry, 478(10), 2141-2171.

10. Johnston, T., Tian, G., Voigt, T., Lindo, P., Cox, A., Granato, T., ... & Podczerwinski, E. (2022). Assessment of availability of trace elements in turf soil after biosolids application. Agronomy Journal, 114(5), 2981-2993.
11. Kaur, H., Kaur, H., Kaur, H., & Srivastava, S. (2023). The beneficial roles of trace and ultratrace elements in plants. Plant Growth Regulation, 100(2), 219-236.
12. Kumar, P., Dipti, Kumar, S., & Singh, R. P. (2022). Severe contamination of carcinogenic heavy metals and metalloid in agroecosystems and their associated health risk assessment. Environmental Pollution, 301(January), 118953. 10.1016/j.envpol.2022.118953
13. Kumpiene, J., L. Giagnoni, B. Marschner, S. Denys, M. Mench, K. Adriaensen, J. Vangronsveld, M. Puschenreiter, and G. Renella. 2017. Assessment of Methods for Determining Bioavailability of Trace Elements in Soils: A review. Pedosphere. 27 (3): 389-406.
14. Liu, Y.S., L.L. Ma, Y.Q. Li, L.T. Zheng. 2007. Evolution of heavy metal speciation during the aerobic composting process of sewage sludge. Chemosphere. 67: 1025–1032.
15. Leal, M. F. C., Catarino, R. I., Pimenta, A. M., & Souto, M. R. S. (2023). The influence of the biometals Cu, Fe, and zinc and the toxic metalscadmium and lead on human health and disease. Trace Elements and Electrolytes, 40(1), 1.
16. Mossa, A. W., Bailey, E. H., Usman, A., Young, S. D., & Crout, N. M. (2020). The impact of long-term biosolids application (> 100 years) on soil metal dynamics. Science of the Total Environment, 720, 137441.
17. Onchoke, K. K., & Fateru, O. O. (2021). Evaluating bioavailability of elements in municipal wastewater sludge (Biosolids) from three rural wastewater treatment plants in East Texas (USA) by a sequential extraction procedure. Results in Chemistry, 3, 100211.
18. Pierzynski, G.M., J.T. Sims, and G.F. Vance. 2005. Soils and Environmental Quality. Third Edition. CRC Press. Boca Raton, FL.
19. Sukkariyah, B.F., G.K. Evanylo, L. Zelazny, and R.L. Chaney. 2005. Cadmium, Copper, Nickel, and Zinc Availability in Biosolids- Amended Piedmont Soil Years after Application. Journal of Environmental Quality. 34: 2255-2262.
20. USEPA. 1994. A Plain English Guide to the EPA Part 503 Biosolids Rule. United States Environmental Protection Agency. Office of Wastewater Management. Washington DC.
21. USEPA. 2007. Guidance for Evaluating the Oral Bioavailability of Metals in Soil for Use in Human Health Risk Assessment. US EPA, Washington D.C.
22. Uchimiya, M., Bannon, D., Nakanishi, H., McBride, M. B., Williams, M. A., & Yoshihara, T. (2020). Chemical speciation, plant uptake, and toxicity of heavy metals in agricultural soils. Journal of Agricultural and Food Chemistry, 68(46), 12856-12869.
23. Wada, O. 2004. What are Trace Elements? —Their deficiency and excess states. Journal of the Japan Medical Association. 47(8): 351–358.
24. You, R., Margenat, A., Cañameras, N., Carazo, N., Matamoros, V., Bayona, J. M., & Díez, S. (2025). Impact of repeated organic amendments on trace element exposure and health risks via the soil-vegetable-human pathway. Environmental Research, 275, 121326.
25. Zaragüeta, A., Enrique, A., Virto, I., Antón, R., Urmeneta, H., & Orcaray, L. (2021). Effect of the long-term application of sewage sludge to a calcareous soil on its total and bioavailable content in trace elements, and their transfer to the crop. Minerals, 11(4), 356.