Heavy Metals in Agricultural Soils

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Population growth and increasing food demand have led to an intensification of agricultural production systems, putting stress on soils and increasing soil contaminants. Some human-induced contaminants, such as heavy metals (HMs), are well-known and have been present in agricultural soils for a long time. In order to provide an overview of HMs in agricultural soils, it is important to investigate agriculturally related sources of contamination with HMs, behaviour of HMs in agricultural soils, as well as their interactions with soil microorganisms, fauna, and plants.

heavy metals | soil health | soil pollution | soil contamination | agriculture

1. Introduction

The term "heavy metals" refers to metals (e.g., Cd, Co, Hg, Pb) and metalloids (e.g., Se, Sb, As) with an atomic number greater than 20 [1] and a density greater that 5 g/cm^{-3}; the term is often associated with contamination and potential toxicity or ecotoxicity [2][3]. Naturally heavy metals (HMs) occur at low concentrations in soils, and some of them are essential micronutrients for plants, animals, and humans (e.g., Fe, Zn, Ni, Cu, Mn) [4]. However, as a consequence of different agricultural practices, high concentrations of HMs in soil can cause toxic effects. HMs are persistent and non-biodegradable, and some of them are toxic at low concentrations. Where they are bioavailable, they pose a major threat to both soil health and human health. HMs accumulated in soils can be taken up by plants and enter the food chain and the human body [5]. Additionally, they can be inhaled together with soil particles or, in specific cases or at high concentrations, absorbed through the skin. There is evidence linking mutagenic, teratogenic, and carcinogenic effects in humans with HMs exposure [5][6]. So far, various reviews have addressed different aspects of HMs in the plant–soil context, such as transport and redistribution processes in plants [7]; HM inputs and outputs to and from agricultural soils [8]; smart sensing for HM monitoring in agricultural soils [9]; HM toxicity in agricultural soils [10], and evaluation of HMs in agricultural lands [11].

2. Sources of HMs in Agricultural Soils

Sources of elevated HM concentrations in agricultural soils are mainly intentional applications of compounds containing high levels of HMs. These can be fertilizers (e.g., phosphate or nitrate fertilizers, livestock manure, composts, biosolids, or sewage sludge), lime, pesticides, or wastewater for irrigation [10][12][13][14][15][16].

Phosphate (P)-based fertilizers can be a source of diverse HMs (e.g., Zn, Cd) [14] and may cause soil pollution, crop uptake, and bioaccumulation along the food chain, resulting in environmental and human health risks [17]. P fertilizers are estimated to contribute 45% to the total Cd-load in European croplands, and 55% of the total dietary intake of Cd by average consumers is associated with Cd accumulation in soils [18]. This problem is likely to increase, as global production and application of P fertilizers are on the rise, and demand for P-rich rock is growing [19]. More efficient use, recovery, and recycling of P [20] from sewage sludge or ash [21] could help to overcome shortages while alleviating HM pollution [17]. However, risks of regenerated P fertilisers require further assessments [22].

While manure is recognised as a valuable fertiliser, its long-term utilization can lead to accumulation of HMs in soils [21]. The content of HMs in manure varies between animal species and diets, with some HMs (e.g., Cu and Zn) fed as mineral supplements to increase animal performance or to provide protection against bacterial infections [23]. However, application of manure or sewage sludge is also an effective strategy for immobilizing HMs to reduce plant uptake through complexation with organic matter components [23]. The mobility and bioavailability of HMs is strongly influenced by soil conditions. Field studies indicate that the toxicity of potentially toxic elements may decrease over time because of fixation processes in the bulk soil [15]. However, since such phenomena are subject to soil properties and are therefore highly variable, detailed risk assessments are necessary if potentially contaminated material is to be applied to soil [16].

A study conducted by Provolo et al. [23] indicates that soil characteristics play a major role in this regard, as slurry application caused strong interactions with the soil and reduced the content of Cu, Mn, and Zn in plant shoots. Nevertheless, these authors caution against the long-term utilization of manure with high contents of HMs, particularly Cu and Zn, due to potential negative human health impacts.

Mitigating the risk of soil pollution with HMs includes avoidance of excessive fertilizer use [24], monitoring of fertilizer composition [13][23], and periodic soil sampling and testing to assess the concentration and bioavailability of HMs [24]. Since HMs in animal manure originate from livestock feed, feed should be controlled and intentional feeding with HMs restricted to optimal doses rather than maximum permitted levels [9].

3. Behaviour of HMs in Soils

HM accumulation can reduce a soil's biological activity, causing reduced fertility and plant growth, loss of soil organic matter [25], loss of soil structure, and soil acidity [10]. HMs incorporated within agricultural particulate matter [26] can be extensively dispersed throughout the atmosphere [27]. The lifetime of HM-carrying particulate matter (HM-PM) and their possible toxicity is a function of their size. Generally, the smaller and lighter a particle is, the longer it will stay in the atmosphere, while larger particles (>10 µm in diameter) tend to be deposited by gravity in a matter of hours [27].

4. HM Effects on Plants

Some HMs are nutrients of which low amounts are required for plant development, though exposure to excess concentrations can cause damage [10]. Other HMs serve no function in plants. HMs in soils can induce oxidative stress in plants, affect their photosynthetic process, their respiration and transpiration, as well as the uptake and transport of essential micronutrients. Hence, they may inhibit plant development and growth, including germination and root elongation, resulting in a decrease in biomass and a potential reduction in productivity and yields [13][17][25][28][29]. High concentrations of HMs can also cause plant death and motivate the selection species with resistance mechanisms and high HM tolerances [17].

HMs can accumulate in different concentrations in roots, leaves, and fruits [14]. However, few plants translocate high concentrations from the soil to the shoot, and studies have consequently reported the highest concentrations in plant roots, with only a minor fraction translocated and accumulated in the shoot [23][30]. To what extent HMs will be absorbed by plants depends on HM type, concentration, and bioavailability [25][28]. Additionally, HMs uptake by plants depends on plants species, as different plants have different uptake rates of specific metals [28][31]. Studies report that leafy and root vegetables show the highest accumulation of HMs [24][32], in contrast to legumes or solanaceous fruits [33][34]. Plants with either high or low HM uptake rates provide management opportunities for soils contaminated with HMs. Restricting cultivation on these soils to plant species with low HM accumulation rates increases the safety of food production [33]. Additionally, the application of organic amendments (e.g., manure, compost, straw) or inorganic amendments (e.g., lime, zeolites) in order to maintain high pH and organic matter content have been proposed as measures to reduce HM bioavailability and plant uptake [33][35]. On the other hand, plants with high HM accumulation rates can be used for phytoremediation [36][37] to improve polluted soils and stabilize soil fertility [36][38][39]. While in this case they cannot be used for human consumption, their cultivation represents a cost-effective practice that contributes to other food crops growing free of HMs and thus safeguards human health [14].

5. HM Effects on Microorganisms and Soil Fauna

Studies show that HMs in soils can have inhibitory effects on soil microbial and enzymes activities, microbial biomass, populations, growth, and metabolic processes [10][13]. Therefore, the abundance, diversity, and structure of the microbial communities can be affected [40], potentially causing functional changes in soil flora with implications for C or N cycling [41]. However, despite the toxic effect of HMs, microorganisms such as bacteria, fungi, or algae can survive in their presence thanks to several evolutionary strategies enabling them to reduce or tolerate HM toxicity. Multiple mechanisms of microbial detoxification can be applied in bioremediation strategies, which represents an economic, efficient, and eco-friendly approach [42]. However, studies providing a comprehensive analysis of the most effective microbial resources for bioremediation or bacterial-assisted phytoremediation are lacking [42].

Studies indicate that HMs in soils can affect the mortality, reproduction, and growth rate of soil organism [41], thus affecting the density, diversity, and structure of the faunal community [43]. The HM concentrations at which this occurs are a complex combination of the bioavailability of the metals, exposure pathways, duration of exposure, and soil physicochemical properties [41]. However, the presence of HMs can also stimulate soil organisms (e.g., earthworms, nematodes, isopods, snails) to produce chemicals capable of protecting them from damage (e.g., metallothioneins) or repairing damage once it occurs (e.g., heat shock proteins). HMs in soil can act as evolutionary drivers, as studies show the ability of soil organisms to develop mechanisms by which they can tolerate or resist the effects of HM-induced stress (e.g., acclimation and adaptation) [41].

6. Conclusion

Agricultural practices have led to increased concentrations of HMs in soils all over the world. Contaminants are absorbed by plants or are found on their surface. This may lead to adverse human health effects from the ingestion of contaminated products, inhalation of contaminated soil particles, or through dermal contact with contaminated soils. It's recommended to better monitor and regulate the introduction of contaminants into agricultural soils, creating an evidence base for reducing the input of contaminants, setting up thresholds, and implementing effective legislation and better management.

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