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Soil Amendments for Immobilization of Potentially Toxic Elements in Contaminated Soils: A Critical Review

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Abstract
Soil pollution by potentially toxic elements (PTEs) has several detrimental environmental effects. This review emphasizes the element type, soil and amendment, immobilization efficiency and mechanisms, field applicability, etc. Immobilization Technique Soil Amendments Several soil amendments have been used worldwide as retardants of PTEs. Out of these amendments, biochar has been the most favored in recent years because of its unique improved surface properties. The application of suitable amendments in combination is also advisable to maximize efficiency. The physical and chemical processes these amendments employ to reduce PTEs' soil bioavailability include precipitation, complexation, reduction and oxidation, ion exchange, and electrostatic forces. However, such soil properties as initial soil pH, clay content, sesquioxides, organic matter content, and processes such as sorption/desorption and redox highly govern the immobilizing effectiveness of the amendments for PTEs in soils. The capability of immobilizing agents may lead to the development of low-cost yet efficient remedial

applications that adhere to green and sustainable remediation concepts. Analyzing the expenses and the sustainability of the solutions is very important before their application as it guarantees the proper and caring approach to the environment.
Keywords: Soil Amendments; Potentially Toxic Elements (PTEs); Immobilization; Bioavailability; Biochar; Environmental Remediation

Introduction

Soil contamination by potentially toxic elements (PTEs) is a pressing global environmental issue due to its significant impact on soil quality, agricultural productivity, and ecosystem health. PTEs such as lead (Pb), cadmium (Cd), arsenic (As), chromium (Cr), and mercury (Hg) accumulate in soils through industrial emissions, mining activities, agricultural inputs, and improper waste disposal (Alloway, 2013). These contaminants persist in the soil matrix for extended periods and do not undergo natural degradation, unlike organic pollutants (Wuana & Okieimen, 2011). Their long-term presence poses severe ecological risks, including disruption of soil microbial communities, reduced fertility, and contamination of groundwater through leaching (Gao et al., 2021). Additionally, heavy metal-contaminated soils adversely affect plant growth by interfering with nutrient uptake, leading to reduced crop yields and potential food safety hazards (Nagajyoti et al., 2010).

The toxic effects of PTEs extend beyond soil contamination to human and wildlife health through bioaccumulation and biomagnification in the food chain. For instance, Cd and Pb accumulate in edible crops, posing risks of chronic toxicity to consumers, leading to conditions such as kidney dysfunction, neurological disorders, and carcinogenic effects (Tchounwou et al., 2012). Similarly, Hg contamination from industrial activities enters aquatic ecosystems, where it transforms into methylmercury—a highly toxic compound that accumulates in fish and poses significant risks to humans through seafood consumption (Driscoll et al., 2013). The mobility of these elements in the environment is influenced by soil properties such as pH, organic matter content, and redox potential, which regulate their bioavailability and potential for transport (Zhao et al., 2019). Given these severe consequences, effective remediation strategies are crucial to mitigate the environmental and health risks associated with PTE contamination.

Among various remediation strategies, immobilization using soil amendments has gained prominence due to its cost-effectiveness, sustainability, and long-term stability. This technique involves the addition of amendments such as biochar, phosphate compounds, clay minerals, and organic matter to contaminated soils, reducing PTE mobility and bioavailability through adsorption, complexation, precipitation, and ion exchange (Beesley et al., 2011). Compared to other remediation methods like soil washing or excavation, immobilization minimizes soil disturbance and maintains its structural integrity while significantly reducing environmental risks (Kumpiene et al., 2008). However, the efficiency of soil amendments depends on factors such as amendment type, application rate, soil characteristics, and metal speciation (Ahmad et al., 2014). Therefore, further research is necessary to optimize amendment formulations and assess their long-term field applicability for sustainable soil remediation.

Soil Amendments for Immobilization of PTEs

Several soil amendments have been explored to reduce the bioavailability of PTEs, including biochar, organic matter and clay minerals.

Biochar

Biochar, a carbon-rich material produced by heating plant or animal waste in low-oxygen conditions (pyrolysis), has become popular for reducing the harmful effects of heavy metals in contaminated soils. Its highly porous structure and large surface area allow it to trap and hold potentially toxic elements (PTEs) like cadmium (Cd), lead (Pb), and arsenic (As), preventing them from being absorbed by plants or leaching into groundwater. This process, known as immobilization, occurs through several mechanisms, including surface adsorption, where metals stick to biochar particles, and precipitation, where metals form solid compounds that are less mobile (Ahmad et al., 2014). Additionally, biochar contains functional groups, such as carboxyl and hydroxyl, that bind with metals, reducing their toxicity. Studies have shown that biochar can significantly decrease the mobility and bioavailability of Cd, Pb, and As, making it an effective tool for soil remediation (Beesley et al., 2011).

Apart from reducing soil contamination, biochar also improves soil quality by increasing microbial activity and enhancing water retention. It provides a habitat for beneficial microorganisms, which contribute to soil fertility by breaking down organic matter and improving nutrient cycling (Lehmann et al., 2011). Furthermore, biochar helps retain moisture in dry soils, reducing water loss and making it useful in drought-prone areas. These benefits make biochar a promising amendment not only for immobilizing toxic metals but also for enhancing soil health in agricultural and degraded lands. However, the effectiveness of biochar depends on its source material, production conditions, and the specific soil environment where it is applied (Tan et al., 2015).

Organic Matter (Compost and Manure)

Organic amendments such as compost and manure help reduce the mobility of potentially toxic elements (PTEs) in soil by providing functional groups like carboxyl (-COOH) and hydroxyl (-OH). These groups bind with heavy metals, forming stable complexes that prevent them from being absorbed by plants or leaching into groundwater (Zhao et al., 2017). Additionally, organic matter has a high cation exchange capacity (CEC), which means it can hold and exchange positively charged metal ions, reducing their availability in the soil (Bolan et al., 2014). As a result, applying compost and manure can effectively decrease the harmful impact of heavy metals in contaminated soils, making them safer for agriculture and the environment.

However, using too much compost or manure can have unintended consequences. Some organic amendments release dissolved organic matter, which can form soluble complexes with heavy metals and increase their mobility in soil and water systems (Zhou et al., 2021). This secondary pollution can lead to the spread of toxic elements beyond the treated area, posing risks to water quality and ecosystems (Park et al., 2011).

Clay Minerals and Zeolites

Clay minerals, such as montmorillonite and kaolinite, are widely used to reduce the movement of potentially toxic elements (PTEs) in contaminated soils. Their high surface area and negative charge allow them to attract and hold metal ions, preventing them from spreading into water sources or being absorbed by plants. These minerals work through different processes, including ion exchange, where harmful metals replace other ions on the clay's surface, and complexation, where metals form stable bonds with the clay's chemical structure (Bhattacharyya & Gupta, 2008). Another important mechanism is precipitation, where metals react with the clay and form solid particles that remain trapped in the soil. Because of these properties, clay minerals are effective at immobilizing metals such as lead (Pb), zinc (Zn), and copper (Cu) (Ribeiro et al., 2018).

Zeolites, both natural and synthetic, are another powerful tool for reducing PTE mobility in soils. These porous minerals have a unique crystal structure that allows them to trap metal ions within their framework. Like clay minerals, zeolites work through ion exchange, where toxic metals are replaced by harmless ions like sodium or calcium (Misaelides, 2011). Studies have shown that zeolites can significantly reduce Pb, Zn, and Cu contamination in soils, making them an effective amendment for soil remediation (Querol et al., 2006).

Mechanisms of PTE Immobilization

The effectiveness of soil amendments depends on several physicochemical processes, which govern the immobilization of PTEs in soils. The major mechanisms include:

Precipitation and Co-Precipitation

Soil amendments reduce the mobility of potentially toxic elements (PTEs) through various chemical and physical mechanisms. One key process is precipitation and co-precipitation, where PTEs react with soil amendments to form stable, insoluble compounds that cannot easily dissolve in water. For example, phosphate-based amendments help immobilize lead (Pb) by converting it into pyromorphite, a mineral that is highly stable and does not pose a risk to plants or groundwater (Cao et al., 2020). Similarly, adding lime (CaO) to contaminated soils increases soil pH, which leads to the precipitation of metal hydroxides, making them less bioavailable (Bolan et al., 2021).

Complexation and Adsorption

Another important mechanism for immobilizing PTEs is complexation and adsorption. Organic amendments like compost and biochar contain functional groups (such as carboxyl and hydroxyl) that bind with metal ions, forming stable complexes that prevent metals from leaching into groundwater (Beesley et al., 2017). Additionally, clay minerals and zeolites, which have a high surface area and negative charge, can trap metal ions through ion exchange and electrostatic interactions, further reducing their mobility (Park et al., 2019). These processes are highly effective for stabilizing metals like cadmium (Cd), zinc (Zn), and copper (Cu) in contaminated soils. By combining different amendments, soil remediation efforts can be optimized for greater efficiency and long-term sustainability.

Redox Reactions

Redox reactions play a key role in the immobilization of potentially toxic elements (PTEs) in contaminated soils. Amendments like biochar and compost can change the oxidation state of PTEs, making them less mobile and less harmful. For example, chromium (Cr) in its toxic form, Cr(VI), can be reduced to the less toxic Cr(III) by these amendments. Cr(III) then forms solid compounds that do not easily move in the soil, reducing the risk of contamination (Zhou et al., 2018). This process of altering the oxidation state helps to stabilize the metals and prevent them from spreading further in the environment.

Ion Exchange and Electrostatic Forces

Ion exchange and electrostatic forces are also important mechanisms for immobilizing PTEs in soils. Certain amendments, such as clay minerals and zeolites, can capture heavy metals by exchanging their cations (positively charged ions) with metal ions in the soil. This process helps to remove the metals from the soil solution, making them less available for plant uptake (García et al., 2020). Additionally, negatively charged soil amendments attract positively charged metal ions, binding them to the surface of the amendments. This electrostatic attraction also reduces the mobility of the PTEs, preventing them from moving through the soil and potentially harming plants or animals (Liu et al., 2019).

Conclusion and Future Perspectives

Soil amendments offer a promising strategy for the in-situ immobilization of PTEs, reducing their bioavailability and mitigating environmental risks. Biochar, clay minerals, organic matter, and industrial by-products have demonstrated high efficiency in stabilizing heavy metals through adsorption, complexation, and precipitation mechanisms. However, soil characteristics, amendment selection, and sustainability factors must be carefully evaluated for successful field application. Future research should focus on optimizing amendment combinations, assessing long-term stability, and integrating soil amendments with other remediation techniques for enhanced effectiveness and sustainability.

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