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Review

Remediation techniques for heavy metal-contaminated soils: Principles and applicability

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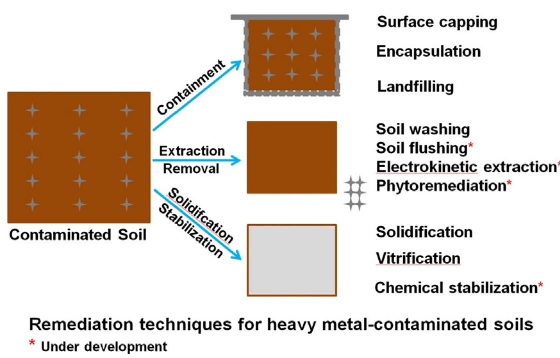
HIGHLIGHTS

- Various remediation methods have been developed for heavy metal-contaminated soils.
- In-situ, contaminant removal/extraction remediation techniques are more favorable.
- The methods landfilling, soil washing, and solidification are well established.
- Electrokinetic extraction, chemical stabilization, and phytoremediation are immature.
- Treatability studies are crucial to selecting feasible soil remediation techniques.

GRAPHICAL ABSTRACT



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ABSTRACT

Globally there are over 20 million ha of land contaminated by the heavy metal(loid)s As, Cd, Cr, Hg, Pb, Co, Cu, Ni, Zn, and Se, with the present soil concentrations higher than the geo-baseline or regulatory levels. In-situ and ex-situ remediation techniques have been developed to rectify the heavy metal-contaminated sites, including surface capping, encapsulation, landfilling, soil flushing, soil washing, electrokinetic extraction, stabilization, solidification, vitrification, phytoremediation, and bioremediation. These remediation techniques employ containment, extraction/removal, and immobilization mechanisms to reduce the contamination effects through physical, chemical, biological, electrical, and thermal remedy processes. These techniques demonstrate specific advantages, disadvantages, and applicability. In general, in-situ soil remediation is more cost-effective than ex-situ treatment, and contaminant removal/extraction is more favorable than immobilization and containment. Among the available soil remediation techniques, electrokinetic extraction, chemical stabilization, and phytoremediation are at the development stage, while the others have been practiced at full, field scales. Comprehensive assessment indicates that chemical stabilization serves as a temporary soil remediation technique, phytoremediation needs improvement in efficiency, surface capping and landfilling are applicable to small, serious-contamination sites, while solidification and vitrification are the last remediation option. The cost and duration of soil remediation are technique-dependent and site-specific, up to \$500 ton^{-1} soil (or \$1500 m^{-3} soil or \$100 m^{-2} land) and 15 years. Treatability studies are crucial to selecting feasible techniques for a soil remediation project, with considerations of the type and degree of contamination, remediation goals, site characteristics, cost effectiveness, implementation time, and public acceptability.

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Contents

1. Introduction

Soil contamination by heavy metals is a worldwide problem for human health and safe food production. Except for uncommon geogenic origins, heavy metal contaminants are inadvertently introduced to soils through anthropogenic activities such as mining, smelting, warfare and military training, electronic industries, fossil fuel consumption, waste disposal, agrochemical use, and irrigation. For example, the common fossil fuel coal contains an array of heavy metals including Hg, Pb, Cd, Cr, Cu, Co, Zn, and Ni in the concentration range of 0.1 to 18 mg kg^{-1}; these heavy metals are discharged into the environment in vapor, flue gas particulate matter, fly ash, and bottom ash upon coal combustion (Nalbandian, 2012). Inappropriate soil disposal of mine spoils, industrial waste, and construction waste frequently causes heavy metal contamination (USDA, 2000; He et al., 2005). Land application of phosphorus (P) fertilizers, Cu-based pesticides, biosolids, and animal manure and crop irrigation with sewage water and poorly-treated industrial wastewater are major pathways for heavy metals to enter into agricultural soils (USDA, 2000; Sharma et al., 2007; Bolan et al., 2014).

Globally there are >5 million sites covering 20 million ha of land in which the soils are contaminated by different heavy metal(loid)s (Wuana and Okieimen, 2011; He et al., 2015). In China alone, >1.0 million km^2 (100 million ha) of land are heavy metal-polluted (He et al., 2015). The heavy metals in contaminated soils impair the natural ecosystem services and eventually damage human health via the food chain (Tchounwou et al., 2012; Jaishankar et al., 2014). Over the years various in-situ and ex-situ remediation techniques have been developed to contain, clean up, or restore heavy metal-contaminated soils, such as surface capping, soil flushing, electrokinetic extraction, solidification, vitrification, and phytoremediation (Fig. 1). These techniques can be classified into five categories: physical, chemical, electrical, thermal, and biological remediation or three divisions: containment-based (e.g., capping/encapsulation), transformation-based (e.g., stabilization/immobilization), and transport-based (e.g., extraction/removal) methods. In general, these soil remediation methods employ different working mechanisms and demonstrate specific application advantages and limitations. More important, these techniques vary significantly in effectiveness and cost in field practices (Khalid et al., 2017). There are a number of literature documents overviewing the soil heavy metal remediation technologies (Khan et al., 2004; Bradl and Xenidis, 2005; Jankaite and Vasarevičius, 2005; Dermont et al., 2008; Wuana and Okieimen, 2011; Yao et al., 2012; Meuser, 2013; Shammas, 2016; Khalid et al., 2017), yet few are comprehensive to compare all the existing technologies and provide instructive evaluations on the practical feasibility of the technologies. This paper was aimed to systematically review the available remediation techniques for heavy metal-contaminated soils in terms of their working principles, technical procedures, applicability, advantages and limitations, and application status. The information is expected to assist in selecting appropriate remediation technology for treatment of heavy metal-contaminated agricultural and urban soils within particular scenarios.

2. Assessment of soil heavy metal contamination

In soil, heavy metals exist in different forms: dissolved ions (e.g., Cu^{2+}, Cd^{2+}, CrO_4^{2-}, $Cr_2O_7^{2-}$, and MoO_4^{2-}) and organic complexes (e.g., Cu^{2+}, Pb^{2+}, and Hg^{2+} binding to dissolved organic matter) in soil solution, exchangeable ions (e.g., Cu^{2+}, Zn^{2+}, Cd^{2+}, Ni^{2+}, and Pb^{2+}) adsorbed on soil solid particles, and (co-)precipitates as part of soil solids (e.g., $Cd_3(PO_4)_2$, ZnS, $PbCO_3$, and $HgSO_4$). These three broad forms maintain a thermodynamic equilibrium in activity and concentration between each other, with insoluble precipitates as the predominant species (Roberts et al., 2005). Research has clearly shown that it is not the total concentration but the reactive fraction of heavy metals in soil

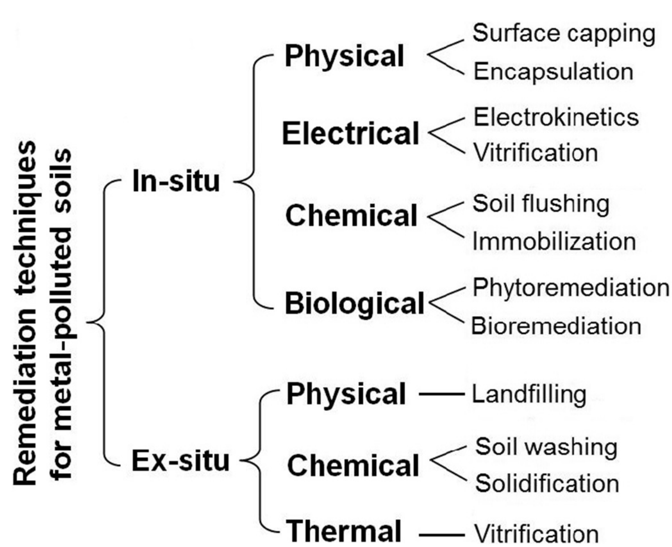

Fig. 1. Common remediation techniques for heavy metal-contaminated soils.