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VIEWS & COMMENTS

# Stabilization-based soil remediation should consider long-term challenges

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**Abstract** Soil remediation is of increasing importance globally, especially in developing countries. Among available remediation options, stabilization, which aims to immobilize contaminants within soil, has considerable advantages, including that it is cost-effective, versatile, sustainable, rapid, and often results in less secondary pollution. However, there are emerging challenges regarding the long-term performance of the technology, which may be affected by a range of environmental factors. These challenges stem from a research gap regarding the development of accurate, quantitative laboratory simulations of long-term conditions, whereby laboratory accelerated aging methods could be normalized to real field conditions. Therefore, field trials coupled with long-term monitoring are critical to further verify conditions under which stabilization is effective. Sustainability is also an important factor affecting the long-term stability of site remediation. It is hence important to consider these challenges to develop an optimized application of stabilization technology in soil remediation.

**Keywords** Stabilization, Soil remediation, Long-term, Trace metals

Globally, approximately 1 in 4 human deaths are due to unhealthy environmental conditions created by anthropogenic activity. Soil contamination is one of the most concerning global environmental problems, and has been attracting increasing attention in developing countries such as China, India, Pakistan and Ghana. Considerable recent efforts have been made in these regions to remediate contaminated land, because of public health concerns and in order to move toward sustainable land use practices and economic growth. For instance, China recently released the "Action Plan on Prevention and Control of Soil Pollution" aiming to arrest the worsening soil contamination situation by 2020, to move positively toward improved soil quality including a comprehensive plan to control risk by 2030, and ultimately to develop a virtuous ecosystem cycle by 2050 [1]. These urgent targets demand the large-scale remediation of contaminated land, as it is estimated that 16.1% of China's land area has been contaminated [1]. In the short-term, effective and sustainable remediation technologies are required.

Stabilization, a promising technology to remediate contaminated soil, aims to immobilize contaminants by adding binding materials (e.g., MgO and industrial wastes (fly ash and slag)), minerals (e.g., zeolite, palygorskite, kaolinite, bentonite, apatite), activated carbon, biochar, compost and agriculture wastes (manure and straws) to soil. The contaminants remain in the soil; however, their mobility and bioavailability are significantly reduced by stabilization. Stabilization is often conducted in the case of trace metals contamination [2], as they are not degradable. In comparison, organic pollutants can be thoroughly removed from soil by microbial decomposition, thermal combustion or chemical oxidation. Typical stabilization methods include stabilization/solidification (S/S), soil amendment and permeable reactive barriers (PRB). The advantages of stabilization technology include (Fig. 1): 1) they are cost-effective, as compared with, e.g., soil washing, one of the most conventional remediation technologies used to achieve thorough clean-up of metals-contaminated sites, which may cost up to \$ 1717 $m^{-3}$ [3]. Stabilization is considerably less costly (e.g. \$ 50–330 $m^{-3}$ for S/S) (USEPA); 2) they are versatile; stabilization technologies are generally flexible in terms of site size and contaminant type; 3) they are sustainable; adsorptive materials can come from or be produced from waste materials such as fly ash, slag and waste biomass (e.g., straws, grass, rice and wheat husks, sludge, compost);

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4) they can often be rapidly implemented as stabilization technologies enable rapid redevelopment of previously contaminated sites; and 5) they result in less secondary contamination due to reduced exposure of contaminated materials at the surface during remedial activities. Therefore, stabilization technologies are promising for application in developing countries due to their ease of implementation, effectiveness, and relatively low cost.

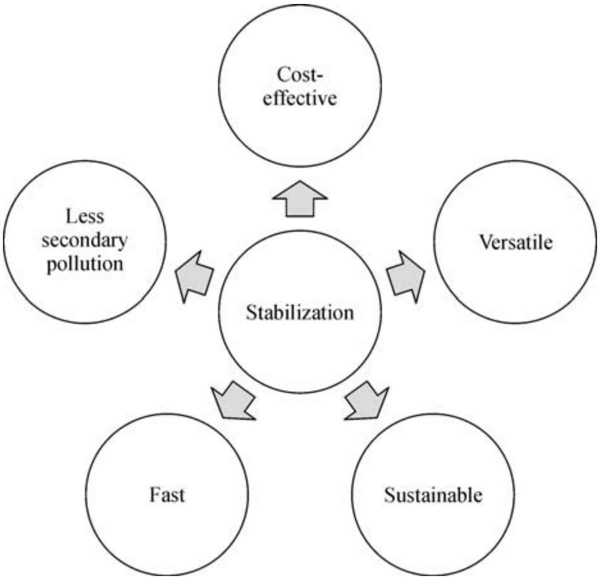

**Fig. 1** Advantages of stabilization-based soil remediation

The application of stabilization technologies to a contaminated site typically includes three stages: 1) characterization of the remedial materials for both physicochemical and adsorptive properties; 2) laboratory studies to quantify treatability of the contaminated soil in question; and 3) field application and long-term monitoring. Despite extensive studies into these three stages, few studies integrate across all three stages. Thus, challenges exist regarding the long-term performance of stabilization technologies in the field. Integrated studies as a critical future research direction are addressed below (Fig. 2).

**1) Long-term effectiveness.** The long-term effectiveness is a major concern of stabilization-based soil remediation. Short-term stabilization of trace metals is usually achievable (e.g., to comply with Toxicity Characteristic Leaching Procedure (TCLP) regulatory limits) when binding materials are added into soils. However, environmental factors such as acid rain, groundwater flow, wet–dry cycles, thawing-freezing cycles, plant growth and soil microbes may affect immobilization in the long-term. For instance, acid rain may diminish the liming effect of MgO, lime and other alkaline binders, or, due to pH alternation, result in the desorption of trace metals bound to biochar and zeolite. Microbial degradation of organic amendments such as compost and manure may also result in the release of previously immobilized contaminants. Furthermore, additives themselves (e.g., compost, manure, biochar, slag and fly ash) may contain metal contaminants, which may be slowly released under field aging. Finally, the flow of groundwater may deliver contaminants to the region of stabilization after site remediation operations have finished. Relatively few studies show the long-term effectiveness of in situ stabilization (exceptions include, e.g., five-year effectiveness for biochar treatment [4] and seventeen-year effectiveness for S/S [5]). Generally, field trials with long-term monitoring are scantly, and these studies are needed to verify conditions under which stabilization will be effective.

**2) Accelerated aging to simulate long-term condition**. Laboratory accelerated aging is one short-term method to

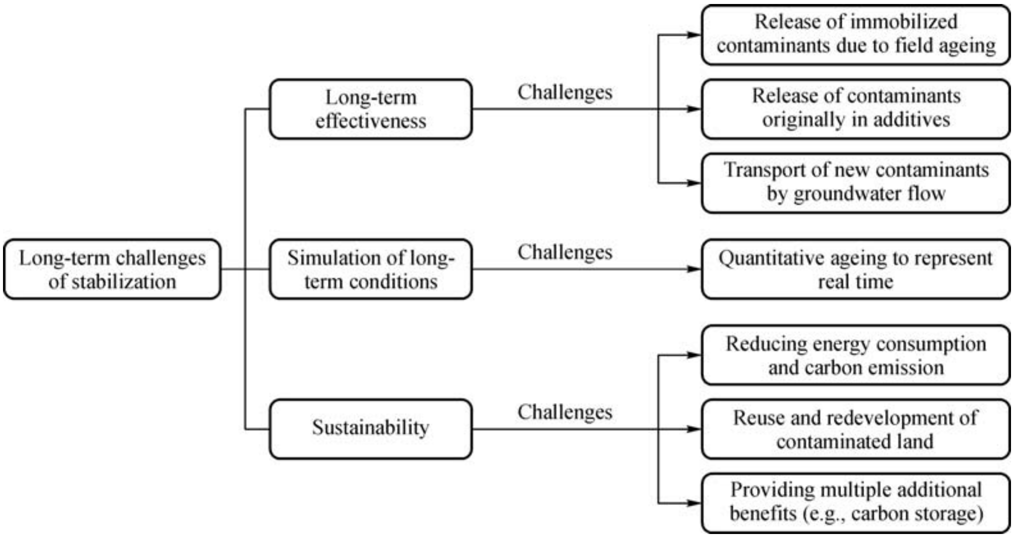

**Fig. 2** Long-term challenges of stabilization-based soil remediation

simulate long-term field conditions and assess the performance of stabilization technologies. Numerous physical, chemical and biological aging methods have been used in extant research. However, the correlations between artificial short-term aging and actual aging in the field remain poorly constrained. For instance, when a stabilized soil is aged using wet–dry cycles by acidic rain water, it is unclear how many of these cycles equate to field aging for one decade or for one century. Thus, since standardized aging methods are not well-developed, predictions of field aging based on laboratory accelerated aging experiments cannot be successfully achieved. In [6], the amount of $H^+$ received by the soil per unit mass through annual rainfall was determined, and the total amount of $H^+$ the soil receives from rain water after 100 years was calculated. Based on that calculation, an acidic solution containing the same amount of $H^+$ was prepared and used for leaching tests of $Pb^{2+}$ from a contaminated soil, to represent the influence of 100-year field aging. This study is one of the few to attempt the normalization of laboratory accelerated aging methods to real field conditions.

**3) Sustainability**. The reuse and redevelopment of a contaminated site is, in itself, a sustainable outcome [7,8]. One option for heavily contaminated industrial land (e.g., mining and steelmaking sites) is to use S/S to treat the soil and reuse the resulting solidified material for construction. However, the manufacture of cement, which is conventionally used in S/S, consumes considerable energy, and it also produces large amounts of $CO_2$ during mixing and curing. The usage of green cement, which aims to replace cement with more sustainable materials such as MgO, slag and fly ash, may be a low-carbon approach for future S/S treatment of industrial land. For lightly contaminated agricultural land, revegetation or enhancement of crop production offers a sustainable and long-term site treatment option. The amendments into soils alter the soil environment, including its microbial community, organic matter composition and structure, over the long-term. Therefore, eco-friendly materials such as biochar, clay minerals and organic amendments may be preferred for agricultural land stabilization. Biochar, one of the most popular and recent sorbents in soil and water treatment [9,10], offers carbon storage benefits for hundreds to thousands of years in addition to the more immediate goal of site remediation, and thereby is regarded as a promising sustainable material for remediation of agricultural land.

Considering the explosion of research and engineering projects on soil remediation recently initiated in China and other developing countries, a focus on stabilization technologies should be a high priority due to its low cost and relative ease of application. Carefully considering the challenges associated with linking short-term laboratory studies with long-term field results is critical in developing optimized applications of this promising technology.

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