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REVIEW PAPER

# Binder-Based Remediation of Heavy Metal Contaminated Soils: A Review of Solidification/Stabilization Methods

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**Abstract**

Heavy metal contaminants are posing serious threats to the ecosystem and human beings. Such contaminants are produced by different human activities, including industry, farming, and mining. Treatment of heavy metal contaminants must be implemented by regulatory bodies to preserve the environment. Due to the stable form of metal contaminants, the solidification and stabilization treatment method is a proven technique to decrease the harm and stability of these pollutants. Stabilization can be achieved chemically using binders or mechanically by controlling the drainage conditions of contaminated land. Different binders to stabilize heavy metals are proposed in the literature, including Portland cement, calcium oxide, and fly ash. It is very important to classify stabilization binders based on their chemical class as organic or inorganic. Such classification facilitates a better evaluation of the binder efficiency with different metal contaminants. The current study provides an overall review of the different types of binders that can be used to stabilize the soil.

**Keywords:** Stabilization; Solidification; Toxic metals; Stabilizing agent.

## 1. Introduction

Soil contamination caused by heavy metals is a recognized environmental issue globally. It is widely accepted that farming, industrial, and mining practices are the primary anthropogenic contributors to heavy metal contamination [1], [2]. Metal pollutants from various sources are believed to severely harm the environment. Studies have proved that excessive heavy metal deposition in soils frequently endangers public health, food security, and soil environment [3], [4]. Therefore, strong pollution control regulations must be enforced to preserve the environment. For example, the heavy metal contamination produced by different industries, factories, or other sources must be treated to specific tolerance levels before disposal. In such cases, effective wastewater treatment for the effluent released from different industries, and factories is becoming increasingly important. That is because stains, washing chemicals, and other poisons found in wastewater alter chemical and biotic activities, use dissolved oxygen, destroy aquatic species, and jeopardize human health, clothing factory effluents are a major origin of water pollution. Another issue with treatment plants and industries is synthetic sludge, which is not disposable. Furthermore, in another study, it was found that salinity and the presence of sodium can also limit the growth of vegetation [5]. Pollutants including pesticides, plastics, and other fine sediments also contaminate the soil [6]. Solidification and stabilization (S/S) treatment has been used for a long time as the last stage in the treatment process before contaminated and chemically unsafe materials are disposed of. Solidification processes contain the waste in a solid mass that has a high degree of structural stability. Solidification is not only a chemical process, but it can be a physical process when the waste is mechanically bonded to the lithosphere. Furthermore, by controlling the surface drainage and/or covering the surface with an impermeable cap, the flow of contamination is decreased. Stabilization solutions entail changing pollutants from their least soluble, mobile, or poisonous states to a more stable and less dangerous state. Sludge, contaminated soils with dangerous metals and organic materials, boiler remains, and heavy garbage from incinerators are all treated with S/S regularly [7]. Due to their straightforward operation, low cost, and attractive qualities, S/S is a popular method [8].

Fly ash, fine particles generated from coal combustion, comprises silicates, unburned char (carbon) as well as mineral forms like feldspar, quartz, hematite, ettringite, and Thomasite, and metal fragments exist in considerable amounts [9]-[11]. For many years, fly ash has been the main ingredient in soil stabilization and ground improvement [12]-[15]. Fly ash was eventually used less often and disposed of in open spaces or, in some rare cases, landfills as it became evident how damaging fly ash was over time. Based on the survey, almost 100 million tonnes of fly ash are fabricated every year, and the disposal of this waste presents significant environmental challenges for developing countries like India [16]. Different researchers used different kinds of materials to stabilize the soil including organic, inorganic, and cement-based stabilizers.

The current manuscript revises different materials utilized as a binder in the S/S process. Furthermore, the ability of these binders to remediate contaminated soils, particularly those contaminated with heavy metals, is investigated.

### 1.1 Stabilization and Solidification

Stabilization and solidification (S/S) are a soil remediation method that fixes contaminants in place by chemical reactions or mechanical actions. Pollutants may be chemically bounded or anchored into a matrix during the S/S procedure, which is also known as immobilization, fixation, or encapsulation. According to the Environmental Protection Act, solidification and stabilization are processes that attain the following [2].

1) Decrease the dissolvability of toxic elements.
2) Reduce the permeability of waste.
3) Stabilized very toxic chemicals like heavy metals and organic contaminants.

Some organic and inorganic binders may affect the soil's properties and limit the growth of plants and other species. In this work, a detailed model is proposed to provide comprehensive information regarding the use of an appropriate binder that leads to soil decontamination without compromising soil qualities as shown in Figure 1. During a feasibility study to remediate contaminated land, the selection of a remedial method depends on the land's characteristics. If the S/S method is opted for, it is crucial to evaluate the effect of the binder on the soil properties. The binder should not negatively alter soil properties; otherwise, an alternative binder must be chosen.

## 2. Procedures of Solidification and Stabilization Method

Even without extra additives, cement-based solidification and stabilization technology is successful in deactivating toxic metals [17]. For example, researchers stabilized lead (Pb) contaminated soil with Ordinary Portland Cement (OPC) and examined the leachability of lead. They found that at a high acidity environment, i.e., a pH of 2.0, a greater amount of Pb has leached [3]. The investigators showed that OPC has a prolonged capacity for stabilizing polluted soils. They conducted a Toxicity Characteristic Leaching Procedure (TCLP) test on 17-year-old stabilized soils. Copper, nickel,

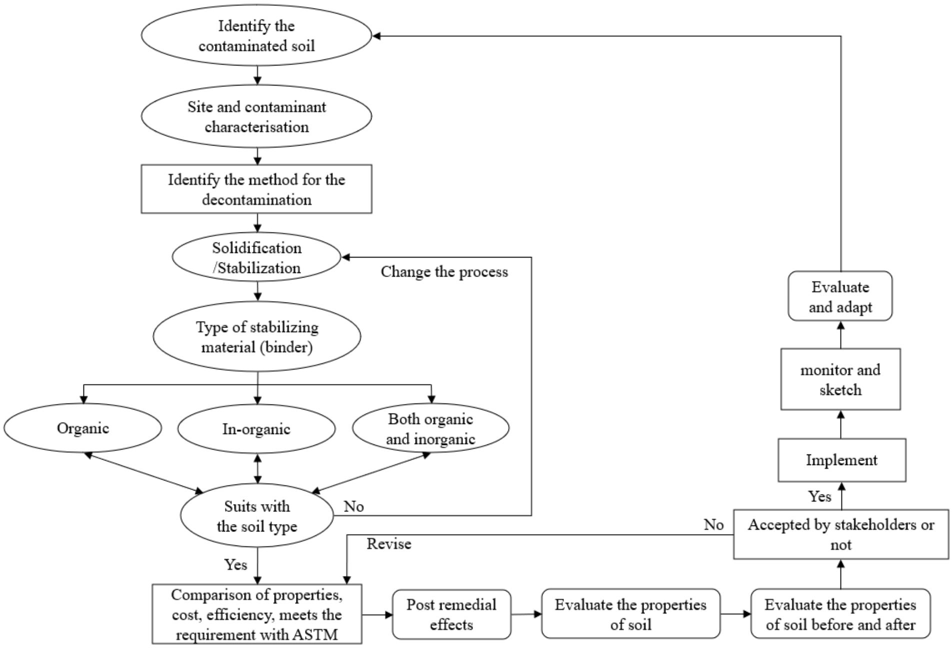


**Figure 1:** *A detailed illustration for selecting an appropriate binder for the solidification/stabilization process.*

zinc, lead, and cadmium levels in the leachate met the portable water safety levels [4]. Researchers employed OPC to treat soil polluted with lead, zinc, copper, iron, and manganese. They claimed that samples treated with OPC leached a small amount of lead at a pH of 12 [18]. Furthermore, the concentrations of other metals such as zinc, copper, iron, and manganese in the leachate are lower in an alkaline environment, showing the importance of pH in metal leaching properties. Comparable findings were outlined [19]. Moreover, investigators used calcium aluminate cement (CAC) and pozzolanic cement (PC) as S/S binders [20]. The results showed that soil leachability of cadmium, lead, zinc, copper, nickel, and arsenic in mineralized water is significantly reduced beneath the quantification standard. Similarly, another researcher reported that utilizing calcium aluminate cement in S/S treatment for soil samples results in increased application of mechanical strength of up to 7.65 $N/mm^2$ [7]. They also claim that combining solidification stabilization with calcium aluminate cement lowers the leachability of cadmium, lead, zinc, copper, nickel, and arsenic. Some researchers observed the absorbent capabilities of calcium aluminate cement for poisonous metals and discovered that total absorption of lead, zinc, and copper could be found at up to 3% by weight [8]. However, some investigators focused on replacing the cement component with alternative additives such as pulverized fuel ash, calcium oxide, and pozzolan minerals. Researchers used OPC, fly ash, and calcium oxide and examined lead leachability in the solidification and stabilization technique, and found that specimens containing 10% calcium oxide showed a significant lead concentration depletion of 43 mg/L compared to samples containing 10% OPC alone, which had a value of 699 mg/L at 28 curing days [21]. Furthermore, the researcher examined the results with different combinations of lime and fly ash and discovered that after 28 days of curing the reduction in lead intensity was best at 8 mg/L. The treatment of polluted soil using various binders is shown in Table 1.

**Table 1:** *Relationship between climatic and hydrological parameters.*

| Binding materials | Heavy Metal contaminants | Observation | Country | Reference |
|---|---|---|---|---|
| Ordinary Portland Cement (OPC), CaO and fly ash | Lead | According to TCLP, Pb's final pH is categorized as acidic, neutral, or alkaline. It was observed that the lead was percolated out in a mean aggregation of 4.8 mg/l. | United States of America | [21] |
| OPC | Lead, zinc, copper, iron, manganese | All metals examined have diffusion coefficients greater than 11.5, specifying low potency in the cement casting. | India | [18] |
| Cao, Fly ash | Lead | The leaching test results showed that the S/S method was successful in deactivating Pb. | United States of America | [22] |
| Rice husk ash and OPC | Lead | The results show that using OPC in conjunction with rice husk ash to rectify lead levels in the S/S technique showed better results than OPC alone. | Malaysia | [9] |
| OPC | Cadmium, lead, copper, nickel, arsenic | Cd, Pb, Zn, and Ni concentrations were generally reduced by toxicity characteristics leaching procedure, whereas arsenic concentrations stayed unchanged while Cu concentrations increased. | Slovenia | [19] |
| OPC, CAC) and pozzolanic cement | Cadmium, lead, zinc, copper, nickel, arsenic | With the utilization of OPC and CAC, the leachability of soil was reduced, and the mechanical strength was increased up to 12 N/mm2 | Slovenia | [20] |
| Rice husk ash and OPC | Chromium | The compressive strength was improved, and the maximum strength was obtained with mixed samples of 20% rice husk ash. | India | [10] |
| OPC, Bottom ash, fly ash | Chromium, iron, nickel, copper, cadmium, barium | Cement-based S/S had an unconfined compressive strength ranging from 0.55 to 16.12 MPa -ultimate stress of concrete (UCS) declined as cement content decreased - S/S UCS reduced with partial addition of fly ash and bottom ash. | Greece | [23] |
| CAC, and sulphate-resistant Portland cement (SRC) | Zinc, copper, lead, arsenic, cadmium, nickel | CAC enhanced the mechanical strength of S/S soil to 7.65 N/mm2 - TCLP results reveal that S/S with CAC reduced leachability more than SRC. | Slovenia | [7] |

| Binding materials | Heavy Metal contaminants | Observation | Country | Reference |
|---|---|---|---|---|
| Calcium alite cement | Lead, zinc, copper | Calcium elite cement demonstrated good sorbent capabilities for hazardous metals, with metals entirely retained when applied at less than 3% (w/w) by cement. | Spain | [8] |
| OPC | Lead | At the pH of 2.0, the acidic leachate influenced the soil's leaching behavior in a semi-dynamic leaching test. | China | [3] |
| OPC | Lead | Lead was leached from 109, 83, and 71 mg to 37, 30, and 25 mg in a semi-dynamic leaching test, respectively. | China | [11] |
| OPC | Copper, nickel, zinc, lead cadmium | The results demonstrate that S/S treatment met the TCLP standard level after 17 years of stabilization, with Ni being the most stable, with around 40% remaining in the soil. | UK | [4] |
| Fly ash, sepiolite, lime, diatomite, OPC, montmorillonite | Lead | According to the results, the additions with the cement to fly ash ratio: quicklime is the most effective. A lead pollution level of 10,000 mg/kg may be successfully rectified. | China | [12] |

### *2.1 Various Applications of S/S Methods [2].*

The S/S approach can be used in situ as well as ex-situ. In situ, treatment entails injecting s/s indicators into the earth utilizing soil-mixing appliances or force injection. Ex situ processes are those that are implemented to excavate the soil and treat it either on-site or off-site.

1) The S/S treatment approach can be utilized on a variation of materials involving soils, mud, and residues.

2) Metals, radioactive, other synthetic chemicals, and vaporous or non-vaporous organic components can be stabilized using the S/S method.

3) The S/S technique can encapsulate organic and inorganic pollutants in a network and impending their potency.

## 3. Utilisation of Inorganic Materials for Heavy Metal Stabilization and Solidification

Because of their remarkable ability to store heavy metals through varied methods, several inorganic elements, such as mud, lime (CaO) materials, phosphate (PO3), oxides of metals, iron/aluminum content, and waste from industry, are globally consumed as coherent stabilizing factors in the soil restoration. Recent case studies, as indicated in Table 2, explored the impact of several inorganic stabilizers on heavy metals in damaged soils.

### *3.1 Clay mineral binder*

Clay minerals have long been recognized as intrinsic hunters of hazardous heavy metal contaminants in the soil [14]. Clay minerals such as bentonite are used widely due to their lower cost and high performance. Researchers found that as a waste–struvite/diatomite compound's functional rates and soil development time rose, the hydrochloric acid extractable lead content declined considerably [16]. Another researcher used physisorption, complexation, and electrostatic contact in stabilization mechanisms. Tetramethylammonium (TMA) and dodecyl trimethylammonium (DTMA) amended bentonites [26].

These modified bentonites exhibit lower stability efficiencies for heavy metals like cadmium, zinc, and copper. Furthermore, some researchers modified the bentonite with struvite-supported palygorskite (S-PAL) and found it effective for copper, lead, and cadmium retention in polluted soil [27]. That is because phosphate groups may react directly with these metals to generate metal-phosphate precipitates. According to a group researcher rising hexadecyltrimethylammonium (HDTMA) filling-up concentrations resulted in a notable rise in zeta potential and an apparent improvement in the stabilization of chromium function, also the montmorillonite was modified with HDTMA for the adsorption of hydrogen chromate [30].

### 3.2 Utilization of CaO for S/S

For the stabilization of harmful metals in polluted soil, different types of calcium oxide were implemented. Lime is considered the most ancient and commonly used metal stabilizer. Different researchers found that the experimental implication of lime to the soil not only raises the pH but also reduces the solubility of metals present in the soil [31], [32]. Several environmentally friendly lime-based stabilizer minerals have been generated in recent years to improve metal stabilization efficiency, with additional public, financial, and environmental benefits [33], [34]. For example, in a recent study arsenate-bearing gypsum was successfully proven as a safe stabilizer for contaminated soil and provided sufficient calcium to the soil and vegetation [35]. Research group did a similar investigation and they discovered, during a 754-day development period, a novel metal sorbent called FIXALL. It is mostly made of ferrihydrite and gypsum which could consistently lower arsenate and lead levels that are water soluble in polluted soil [36].

### 3.3 Phosphate ($PO_3$) compounds are consumed as stabilizers.

Phosphate ($PO_3$) compounds have lately been demonstrated to be well-organized stabilizing material for metal-contaminated soils [30], [37]-[39]. Natural phosphate rock, calcium dihydrogen phosphate, superphosphate, and hydroxyapatite are the most prevalent phosphate minerals [40]-[42]. Some researchers checked the suitability of phosphate-based stabilizers in treating lead-bearing soils collected from different sources, i.e., Schlepp Farm and Black Rock Slough near Rose Lake, Idaho [41]. They found that the concentration of lead was reduced to 3-10 mg/kg and 52-200 mg/kg, respectively. Researchers checked the lead stabilization in the polluted soil by comparing two stabilizing agents: rock phosphate (RP) and phosphate solubilizing bacteria (PSB) [43]. At 800 mg/kg dosage of RP, the stabilization rate of RP and PSB was found to be 13.7% and 26.4%, respectively. Some researchers investigated the mechanochemical stabilisation of mono-chemical phosphate for lead in polluted soils using mechanochemical ball milling trials, and the outcome showed that the concentration of lead in the soil was 4.36 mg/L under maximum conditions, whereas 54.96% of lead was present in the residual fraction [44]. Due to the higher amounts of lead stabilizing agents, the chances of eutrophication increases by dumping an excessive amount of P into the water bodies [45].

### 3.4 Metal oxides as a stabilizer

Decontamination of soil using diverse types of metal oxides as a stabilizing agent is widely practiced because of their higher absorption capability. However, most metal oxides may degrade the environment [46],[47]. For example, research decontaminated the arsenate-polluted soil by employing an efficient stabilizing agent, i.e., amorphous manganese oxide (AMO), and found that it has a maximum adsorption capacity of 1.79 mmol/g at pH equal to 7 and 8 [48]. However, some researchers reported that a nanoscale carbon black (CB) was modified with magnesium oxide (MgO) coated corncob biochar and found that it reduced the toxicity characteristics of leaching procedure (TCLP) leached

**Table 2:** *Stabilization of heavy metals in soil using clay minerals.*

| Type of clay mineral | Type of experiment | Type of soil | Type of mineral | Heavy metal immobilization efficiency | References |
|---|---|---|---|---|---|
| Sepiolite (Sep) in its natural state | Experiment in the field | Rice soil | Cadmium | The effluent fractions rose even though the cadmium fraction fell in sepiolite-amended soil. | [24] |
| Bentonite (Bn) | Incubation in soil | A type of agricultural soil | Cadmium | CO3 fraction of cadmium increased because of the addition of bentonite. | [25] |
| TMA-Ben and DTMA-Ben organo-bentonites | Incubation in soil | Soil that has been tainted artificially | Chromium, zinc, copper, arsenic, cadmium and magnesium | Because of the involvement of bentonite-DTMA and bentonite-TMA leachability of heavy metals was improved. | [26] |
| Palygorskite (Pal) and struvite (S-Pal) were used to support palygorskite. | Incubation in soil | Soil that has been tainted artificially | Cadmium, lead, and copper | 1)For 10% of S-Pal Copper (0.77 mg/kg), lead (0.24 kg), and cadmium (0.24 kg), and 10% of PAL copper (1.45mg/kg), lead (0.32kg) and cadmium (2.06 mg/kg) were reduced by calcium chloride extractable concentrations in amended soils. 2)With the increase in S-Pal and Pal from 1% to 10%, the acid solubility of these metals reduced. | [27] |
| Modified attapulgite (ATTP) (ZVI-Attp) and Clay containing zero-valent iron (ZVI) | Experiment with a pot | Soil from the suburbs | Chromium, cadmium, and lead | 1)The ZVI-Attp therapy outperformed the nFe0 and ATTP treatments in terms of Cd, Cr, and Pb immobilization.With the increase in fractions of ZVI, Attp, and ZVI-Attp, the TCLP extractable amounts of these examined metals were reduced. | [28] |

| Type of clay mineral | Type of experiment | Type of soil | Type of mineral | Heavy metal immobilization efficiency | References |
|---|---|---|---|---|---|
| Montmorillonite based humic acid (HA-Mont) and montmorillonite (Mont) | Experiments in batch adsorption and leaching | A type of agricultural soil | Cadmium and mercury | HA-Mont at 5% dosage reduced TCLP leached cadmium and mercury concentrations by 94.1%, 93.0%, and 69.5%, 65.9%, respectively, when compared to no and Mont-treated soils. | [29] |
| TMA-Mont and HDTMA-Mont organo-montmorillonites | Experiments with immobilization and leaching | Soil that has been tainted artificially | Chromium and cadmium | Cadmium leachability decreased significantly in HDTMA-Mont and TMA-Mont treated soils chromium leachability maintained 17.3% for the control using the new TCLP method. | [30] |

lead concentration in the soil from 10.63 to 5.24 mg/L [49]. Furthermore, research employed an electrochemical method to deactivate amorphous Fe-oxide from wastewater can stabilize arsenate-based polluted soil [50]. After implementing column studies, it was found that the concentration of arsenic in the leachate was much lower than in the control sample.

### 3.5 Utilisation of silicon-based content as stabilizers

Different silicate-based wastes such as steel slag, tailings, and blast furnaces are effective soil stabilizers [51]–[53]. Through co-precipitating interactions between silicate ions and heavy metals, silicon content is not only reducing heavy metal bioavailability but offering nutrients for crop growth [51], [54]. Some researchers used the steel slag-based silicon stabilizer and found that the exchangeable amount of cadmium in crop soil was reduced [55]. Research outcomes discovered that due to the modification of magnesium silicate (MS-C), there was a reduction in the pH That is because of the reaction of the MS-C with heavy metals [52].

### 3.6 Industrial waste as a stabilizer

Industrial waste proved as an efficient stabilizer for contaminated soils [56], [57]. Moreover, the utilization industrial waste in stabilization is a sustainable approach to reducing waste mass and treating contaminated lands. Researchers worked on the treatment of chromium base contaminated soil by using fly ash as a stabilizer and found that the leached chromium concentration decreased by increasing the fly ash content [58]. In another study, combined steel slag, vinegar, and weathered coal for the treatment of lead in polluted soil [59]. They found that with the increase in the amount of the mentioned combination, the extractable lead concentration decreased. Furthermore, researchers discovered that basic oxygen furnace (BOF) slag treatment enhanced metal stabilization of the polluted soil at low pH [60]. Furthermore, silicon-iron modified from copper tailings was efficient in reducing the heavy metals from the polluted soil [61].

## 4. Utilization of Organic Material for the Stabilization and Solidification of Heavy Metals.

Various organic content such as sludge, biochar, and other organic waste can enhance the soil properties and reduce the toxicity in the contaminated soil [62], [63].

### 4.1 Biochar

Biochar is an organic material that has high porosity and is originally composed of biomass products [64]. Animal dung, farmland residues, bamboo, cultivation residues, and bio composites are the most common types of biomass [65]. Biochar is mainly preferred because of its effective physical properties due to which it is considered an efficient stabilizer to decontaminate polluted soils [66]-[68]. Furthermore, biochar also can improve the physical, chemical, and biological properties of the soil [69], [70]. For example, researchers used the ammonia functionalized hydro char (NH2-HCS) modified from the pinewood sawdust for the treatment of heavy metals (i.e., copper, lead, and cadmium) in the contaminated soil [71]. They found that at 5% of NH2-HCS, the concentration of copper, lead, and cadmium was reduced to 63.8, 24.7 and 22.6% respectively, and noted that the application of NH2-HC in soil remediation is effective [72], [73]. Furthermore, the alkalinity, composition, microporous structure, surface area, and surface functional groups of biochar all have a significant impact on its metal stabilisation efficacy. Biochar has recently been employed as a transporter for degrading bacteria in soil stabilisation remediation research [74].

### 4.2 Utilization of sewage/sludge, composite and arsenate-based stabilizer.

Researchers have found that the waste from municipal sewage, and other bio composite can be effectively used as a stabilizer for the decontamination of soil [75]. Another group of researchers used the agriculture composite and conducted a pot experiment for the treatment of cadmium in the soil [76]. Researchers used different stabilizers including cow dung, sewage sludge from urban areas, vermicompost, and the sludge-derived biochar, and conducted the experiment and found after two months, because of the addition of a natural stabilizing agent, leachability was significantly decreased [77]. Investigators used the composite made from the eggshell and concluded that leachability decreased by more than 95% for lead and zinc and it was observed with the increase in pH the mobility was reduced [78].

### 4.3 Polymer-based compounds are used as stabilizers.

Polymer-based materials have attracted widespread attention as a novel form of stabilizing material with numerous advantages such as water solubility, low cost, and high strength [79]. Some researchers used three different polymer-based stabilizers, namely carboxymethyl cellulose, lignin, and sodium alginate, for the decontamination of soil close to zinc and lead mines for the reduction of leaching concentration of cadmium and lead in the decontaminated soil by 4.25-49.6% and 5.46-71%, respectively [80]. These results came from the efficient chelation actions of copious oxygen-containing groups. In a recent work, discovered that basic lignin may be used to effectively stabilize the cadmium and lead by increasing phosphorus in the soil and increasing the unconfined compressive strength [81].

## 5. Evaluating the Efficacy of Heavy Metal Stabilization in Polluted Soil

Following the remediation process, a specific site evaluation incorporating site monitoring must be evaluated. The goal is to assess the treatment methods and to determine the success of the cleanup. The assessment of heavy metal stabilization effects focuses primarily on four perspectives: soil transformation characteristics, physical testing, chemical extraction, and environmental toxicity as shown in Figure 2. Furthermore, the mentioned evaluation process is being used widely, where only one method was typically used. This may pose difficulty to the decision-makers in finding the best methodologies to assess metal immobilization efficacy based on different remedial scenarios. However, it is necessary to understand the advantages and disadvantages of different methods used for the decontamination of soil.

### 5.1 Changes in Soil Properties

Soil properties such as the texture of the soil, cation exchange capacity, and anion exchange capacity are affected by decontaminating the heavy metals present in the soil [82], [83]. The pH of the soil is an important factor in controlling heavy metals absorption and accumulation by plants [84]. For instance, researchers used the triple super phosphate (TSP) for the decontamination of heavy metals in the soil and found that because TSP lowered soil pH, it increased the exchangeable and bound to carbonate fractions of zinc and nickel [85]. Some researchers found that due to the increase in pH in the soil, mobility of cadmium in the soil was decreased. Soil enzyme activity may be used as a biomarker of soil biological properties to evaluate soil remediation impacts due to their critical roles in nutrient mineralization and fertility management in soils [86], [87]. The microbial species present in soil are enough to decompose the organic matter present in the soil [31], [88], [89]. The influence of various stabilisers on the different properties of soil is illustrated in Table 3.

### 5.2 Physical Method

To assess the soluble quantities of heavy metals at the water-soil interface that did not change chemical forms during the collecting period, soil pore water speciation analysis was used [37]. Some researchers compared the untreated soil with the treated after giving treatment by using various stabilizers such as residue of marble and composite. They found a significant reduction in the concentration of heavy metals in the contaminated soil [98].

### 5.3 Chemical Method

In many countries, according to the requirements of the environment, focus on heavy metal concentration. To avoid overestimating the bio-availability of heavy metal concentration must be more than the overall content. Various chemical techniques such as toxicity leaching have been employed in most environmental programs [99].

### 5.4 Bioassays for Environmental Toxicity

The examination of stabilization therapy effects includes changes in the risk of ecotoxicity as well as other possible concerns. Very little data can be found about heavy metal bioavailability by using the chemical extraction method [100]. Some researchers found that the arsenate fractions were decreased after employing the iron-based sorbent but arsenate toxicity was increased [101]. To strengthen cleanup decisions, chemical information should be supplemented with ecotoxicological testing [25], [102]. Ecotoxicological experiments utilizing wild organisms have been established to acquire ecological indicators for soil remediation assessment [103].

## 6. Limitations of solidification and stabilization

The most important drawback of the S/S method is that it alters both the physical as well as chemical properties of the soil. From the literature, it was found that the different stabilizers that are used for the decontamination of soil are unable to permanently eliminate or destroy contaminants for the long term. S/S effectiveness in certain contaminants especially some organic compounds, which include volatile organic, may necessitate taking extra precautions during testing and design. Furthermore, for the decontamination of heavy metals such as chromium (VI), the cement-based stabilizer does not show high efficiency. Because of mixing and adding material in the S/S method, the volume of soil usually increases which requires to be managed.

**Table 3:** *Variation in the soil's various properties.*

| Type of stabilizer | Kind of soil | Soil Property | Outcome | References |
|---|---|---|---|---|
| Sludge from sewage | Soil from the repossessed area | Structure | By using sewage from the sludge the stability of soil improved. | [90] |
| CaO, steel slag, acid mine | Soil was damaged by a mine. | Electrical Conductivity of Soil | CaO, and slag steel amine acids treatments decreased electrical conductivity in subsurface soil by 20.24%, 58.21%, and 50%, respectively. | [88] |
| Biochar | Paddy soil | Capacity for cation exchange | 10% and 20% biochar increased cation exchange capacity by 13.6% and 22.4%, respectively. | [91] |
| Mud composite | A practical location | Organic matter concentration | No significant change in the organic matter composition of the sludge amendment during the trial. | [92] |
| Biochar made from rice hulls and vermicompost | Agriculture soil | Organic matter concentration | When compared to the control, organic matter content increased as organic amendment rates increased. | [93] |
| Potassium dihydrogen phosphate | Paddy soil | Soil redox potential | Oxidation/reduction potential fell gradually in all potassium dihydrogen treatment-treated soils during the flooding stage (0-30 days) but increased dramatically following the drying-wetting cycle (60-90 days). | [94] |
| $FeSO_4$ with olive mill waste compost (OMWC). | Smelting contaminated soil | Nutrients | The addition of iron (1%) and oil mill waste compost (3%), respectively, raised the extractable P, K, and TN contents significantly. | [95] |
| Natural sepiolite | A Mining polluted soil | Enzyme activity | The addition of 5% sepiolite increased the activity of dehydrogenase and alkaline phosphatase by up to 138 and 42%, respectively. | [96] |
| Wood residue | Mining and smelting | Microbial community | Wood residue treatments lowered $CO_2$ output by 12-21% over a 60-day incubation period. | [97] |

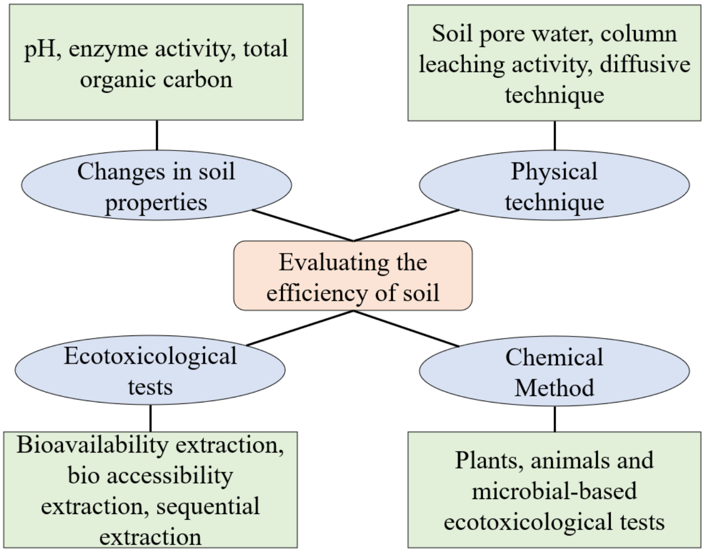


**Figure 2:** *The evaluating efficiency of soil.*

### 6.1 Future scope

The stabilization method is simple and cost-effective and considered one of the most sustainable methods. The stabilizers modified with some agriculture-based products (e.g. biochar) can be implemented to stabilize heavy metals. For low-plasticity soils, cement and cementitious blends have shown superior cost-to-strength, energy-to-strength, and CO2 emission-to-strength ratios; however, lime-blended stabilisers appeared to be successful for high-plasticity soils.

## 7. Conclusion

In summary, the versatile applications of the S/S method extend to both in situ and ex-situ treatments. The effectiveness of S/S is evident across various barriers, encompassing soils, mud, and residues, with a primary focus on addressing heavy metals, radioactive elements, synthetic chemicals, and organic components. The S/S technique, encapsulating pollutants in a network, proves successful in mitigating the mobility of both organic and inorganic pollutants. Investigating the use of inorganic materials for heavy metal stabilization, the paper delves into the efficacy of clay minerals, lime materials, phosphates, metal oxides, iron/aluminum materials, and industrial wastes as stabilizing agents. Each material is examined for its distinct mechanisms, including cation exchange, physisorption, precipitation, complexation, and electrostatic interaction.

Furthermore, the comprehensive exploration of organic materials, including biochar, compost, sewage sludge, and natural wastes, showcases their potential in not only improving soil physicochemical and biological qualities but also in reducing metal bioavailability and toxicity. The porous structure, alkaline characteristics, and active functional groups of biochar contribute to its cost-effectiveness as a carbonic material for soil remediation. These attributes influence various soil properties and microbial activities. The assessment of the efficacy of heavy metal stabilization in polluted soils is crucial, requiring a multifaceted approach. The evaluations incorporate changes in soil properties, physical testing, chemical extraction, and environmental toxicity assessments. The vital indicators such as soil pH, enzyme activity, and microbial species reveal how stabilization treatments affect the ecological stress and health of the soil.

In conclusion, the journey through various stabilization methods and materials highlights the complexity and interconnectedness of the remediation process. The need for a holistic evaluation approach becomes apparent while considering the soil transformation characteristics, physical methods, chemical analyses, and bioassays. As the scientific community strives to better understand the benefits and limitations of these assessment methodologies, this research contributes to the ongoing dialogue on effective heavy metal stabilization in contaminated soils.

**Conflicts of Interest: The authors declare no conflict of interest.**

**References**

[1] H. Yuanan, K. He, Z. Sun, G. Chen, and H. Cheng, "Quantitative source apportionment of heavy metal (loid) s in the agricultural soils of an industrializing region and associated model uncertainty," J. Hazard. Mater., vol. 391, p. 122244, 2020.
[2] U. EPA, "A Citizens Guide to Solidification and Stabilization." Response, 2012.
[3] Y.-J. Du, M.-L. Wei, K. R. Reddy, Z.-P. Liu, and F. Jin, "Effect of acid rain pH on leaching behavior of cement stabilized lead-contaminated soil," J. Hazard. Mater., vol. 271, pp. 131–140, 2014.
[4] F. Wang, H. Wang, and A. Al-Tabbaa, "Leachability and heavy metal speciation of 17-year old stabilized/solidified contaminated site soils," J. Hazard. Mater., vol. 278, pp. 144–151, 2014.
[5] A. Mohanavelu, S. R. Naganna, and N. Al-Ansari, "Irrigation induced salinity and sodicity hazards on soil and groundwater: An overview of its causes, impacts and mitigation strategies," Agriculture, vol. 11, no. 10, p. 983, 2021.
[6] A. Mohanavelu, S. Shrivastava, and S. R. Naganna, "Streambed pollution: A comprehensive review of its sources, eco-hydro-geo-chemical impacts, assessment, and mitigation strategies," Chemosphere, vol. 300, p. 134589, 2022.
[7] G. E. Voglar and D. Leštan, "Equilibrium leaching of toxic elements from cement stabilized soil," J. Hazard. Mater., vol. 246, pp. 18–25, 2013.
[8] I. Navarro-Blasco, A. Duran, R. Sirera, J. M. Fernández, and J. I. Alvarez, "Solidification/stabilization of toxic metals in calcium aluminate cement matrices," J. Hazard. Mater., vol. 260, pp. 89–103, 2013.
[9] C.-Y. Yin, H. Bin Mahmud, and M. G. Shaaban, "Stabilization/solidification of lead-contaminated soil using cement and rice husk ash," J. Hazard. Mater., vol. 137, no. 3, pp. 1758–1764, 2006.
[10] N. Jain, "Solidification and Leachability of Cr (VI) in rice husk ash-blended cement," Int. Sch. Res. Not., vol. 2011, 2011.
[11] J.-S. Li, Q. Xue, P. Wang, Z.-Z. Li, and L. Liu, "Effect of drying-wetting cycles on leaching behavior of cement solidified lead-contaminated soil," Chemosphere, vol. 117, pp. 10–13, 2014.
[12] Y. Xi, X. Wu, and H. Xiong, "Solidification/stabilization of Pb-contaminated soils with cement and other additives," Soil Sediment Contam. An Int. J., vol. 23, no. 8, pp. 887–898, 2014.
[13] D. S. S. Raj, C. Aparna, P. Rekha, V. H. Bindhu, and Y. Anjaneyulu, "Stabilisation and solidification technologies for the remediation of contaminated soils and sediments: an overview," L. Contam. Reclam., vol. 13, no. 1, pp. 23–48, 2005.
[14] X. Cao et al., "Effects of a natural sepiolite bearing material and lime on the immobilization and persistence of cadmium in a contaminated acid agricultural soil," Environ. Sci. Pollut. Res., vol. 25, pp. 22075–22084, 2018.
[15] Q.-H. Zhu, D.-Y. Huang, S.-L. Liu, B. Zhou, Z.-C. Luo, and H.-H. Zhu, "Flooding-enhanced immobilization effect of sepiolite on cadmium in paddy soil," J. Soils Sediments, vol. 12, pp. 169–177, 2012.
[16] H.-P. Jing, X. Wang, P. Xia, and J. Zhao, "Sustainable utilization of a recovered struvite/diatomite compound for lead immobilization in contaminated soil: potential, mechanism, efficiency, and risk assessment," Environ. Sci. Pollut. Res., vol. 26, pp. 4890–4900, 2019.

[17] C. Napia, T. Sinsiri, C. Jaturapitakkul, and P. Chindaprasirt, "Leaching of heavy metals from solidified waste using Portland cement and zeolite as a binder," Waste Manag., vol. 32, no. 7, pp. 1459–1467, 2012.
[18] R. Malviya and R. Chaudhary, "Factors affecting hazardous waste solidification/stabilization: A review," J. Hazard. Mater., vol. 137, no. 1, pp. 267–276, 2006.
[19] G. E. Voglar and D. Leštan, "Solidification/stabilisation of metals contaminated industrial soil from former Zn smelter in Celje, Slovenia, using cement as a hydraulic binder," J. Hazard. Mater., vol. 178, no. 1–3, pp. 926–933, 2010.
[20] G. E. Voglar and D. Leštan, "Efficiency modeling of solidification/stabilization of multi-metal contaminated industrial soil using cement and additives," J. Hazard. Mater., vol. 192, no. 2, pp. 753–762, 2011.
[21] C. Jing, X. Meng, and G. P. Korfiatis, "Lead leachability in stabilized/solidified soil samples evaluated with different leaching tests," J. Hazard. Mater., vol. 114, no. 1–3, pp. 101–110, 2004.
[22] D. H. Moon and D. Dermatas, "An evaluation of lead leachability from stabilized/solidified soils under modified semi-dynamic leaching conditions," Eng. Geol., vol. 85, no. 1–2, pp. 67–74, 2006.
[23] K. Anastasiadou, K. Christopoulos, E. Mousios, and E. Gidarakos, "Solidification/stabilization of fly and bottom ash from medical waste incineration facility," J. Hazard. Mater., vol. 207, pp. 165–170, 2012.
[24] X. Liang et al., "Two-year stability of immobilization effect of sepiolite on Cd contaminants in paddy soil," Environ. Sci. Pollut. Res., vol. 23, pp. 12922–12931, 2016.
[25] Y. Sun, G. Sun, Y. Xu, W. Liu, X. Liang, and L. Wang, "Evaluation of the effectiveness of sepiolite, bentonite, and phosphate amendments on the stabilization remediation of cadmium-contaminated soils," J. Environ. Manage., vol. 166, pp. 204–210, 2016.
[26] K. Yu, J. Xu, X. Jiang, C. Liu, W. McCall, and J. Lu, "Stabilization of heavy metals in soil using two organo-bentonites," Chemosphere, vol. 184, pp. 884–891, 2017.
[27] H. Wang et al., "Comparison of palygorskite and struvite supported palygorskite derived from phosphate recovery in wastewater for in-situ immobilization of Cu, Pb and Cd in contaminated soil," J. Hazard. Mater., vol. 346, pp. 273–284, 2018.
[28] C. Xu et al., "Immobilization of heavy metals in vegetable-growing soils using nano zero-valent iron modified attapulgite clay," Sci. Total Environ., vol. 686, pp. 476–483, 2019.
[29] L. Wang, X. Li, D. C. W. Tsang, F. Jin, and D. Hou, "Green remediation of Cd and Hg contaminated soil using humic acid modified montmorillonite: Immobilization performance under accelerated ageing conditions," J. Hazard. Mater., vol. 387, p. 122005, 2020.
[30] J. Yang, K. Yu, and C. Liu, "Chromium immobilization in soil using quaternary ammonium cations modified montmorillonite: Characterization and mechanism," J. Hazard. Mater., vol. 321, pp. 73–80, 2017.
[31] L. Shi et al., "Immobilization of cadmium and improvement of bacterial community in contaminated soil following a continuous amendment with lime mixed with fertilizers: a four-season field experiment," Ecotoxicol. Environ. Saf., vol. 171, pp. 425–434, 2019.
[32] L. Gong et al., "Immobilization of exchangeable Cd in soil using mixed amendment and its effect on soil microbial communities under paddy upland rotation system," Chemosphere, vol. 262, p. 127828, 2021.
[33] M. Lian et al., "Highly effective immobilization of Pb and Cd in severely contaminated soils by environment-compatible, mercapto-functionalized reactive nanosilica," J. Clean. Prod., vol. 235, pp. 583–589, 2019.
[34] W. Zhai et al., "Simultaneous immobilization of the cadmium, lead and arsenic in paddy soils amended with titanium gypsum," Environ. Pollut., vol. 258, p. 113790, 2020.
[35] D. Yang, A. Sasaki, and M. Endo, "Reclamation of a waste arsenic-bearing gypsum as a soil

conditioner via acid treatment and subsequent Fe (II) As stabilization," J. Clean. Prod., vol. 217, pp. 22–31, 2019.
[36] K. Kameda, Y. Hashimoto, S.-L. Wang, Y. Hirai, and H. Miyahara, "Simultaneous and continuous stabilization of As and Pb in contaminated solution and soil by a ferrihydrite-gypsum sorbent," J. Hazard. Mater., vol. 327, pp. 171–179, 2017.
[37] G. Zeng et al., "Precipitation, adsorption and rhizosphere effect: the mechanisms for phosphate-induced Pb immobilization in soils—a review," J. Hazard. Mater., vol. 339, pp. 354–367, 2017.
[38] M. R. Baker, F. M. Coutelot, and J. C. Seaman, "Phosphate amendments for chemical immobilization of uranium in contaminated soil," Environ. Int., vol. 129, pp. 565–572, 2019.
[39] F. Kastury et al., "Relationship between Pb relative bioavailability and bioaccessibility in phosphate amended soil: Uncertainty associated with predicting Pb immobilization efficacy using in vitro assays," Environ. Int., vol. 131, p. 104967, 2019.
[40] Y. Cui, X. Du, L. Weng, and W. H. Van Riemsdijk, "Assessment of in situ immobilization of lead (Pb) and arsenic (As) in contaminated soils with phosphate and iron: solubility and bioaccessibility," Water, Air, Soil Pollut., vol. 213, pp. 95–104, 2010.
[41] L. R. Osborne, L. L. Baker, and D. G. Strawn, "Lead Immobilization and Phosphorus Availability in phosphate-amended, mine-contaminated soils," J. Environ. Qual., vol. 44, no. 1, pp. 183–190, 2015.
[42] G. Huang, X. Su, M. S. Rizwan, Y. Zhu, and H. Hu, "Chemical immobilization of Pb, Cu, and Cd by phosphate materials and calcium carbonate in contaminated soils," Environ. Sci. Pollut. Res., vol. 23, pp. 16845–16856, 2016.
[43] J. H. Park, N. Bolan, M. Megharaj, and R. Naidu, "Isolation of phosphate solubilizing bacteria and their potential for lead immobilization in soil," J. Hazard. Mater., vol. 185, no. 2–3, pp. 829–836, 2011.
[44] X. Zhang, X. Lou, H. Zhang, W. Ren, and M. Tang, "Effects of sodium sulfide application on the growth of Robinia pseudoacacia, heavy metal immobilization, and soil microbial activity in Pb–Zn polluted soil," Ecotoxicol. Environ. Saf., vol. 197, p. 110563, 2020.
[45] J. H. Park, N. Bolan, M. Megharaj, and R. Naidu, "Comparative value of phosphate sources on the immobilization of lead, and leaching of lead and phosphorus in lead contaminated soils," Sci. Total Environ., vol. 409, no. 4, pp. 853–860, 2011.
[46] V. Ettler, Z. Tomášová, M. Komárek, M. Mihaljevič, O. Šebek, and Z. Michálková, "The pH-dependent long-term stability of an amorphous manganese oxide in smelter-polluted soils: implication for chemical stabilization of metals and metalloids," J. Hazard. Mater., vol. 286, pp. 386–394, 2015.
[47] X. Ouyang et al., "Immobilization and release risk of arsenic associated with partitioning and reactivity of iron oxide minerals in paddy soils," Environ. Sci. Pollut. Res., vol. 27, pp. 36377–36390, 2020.
[48] Z. Michálková, M. Komárek, V. Veselská, and S. Číhalová, "Selected Fe and Mn (nano) oxides as perspective amendments for the stabilization of As in contaminated soils," Environ. Sci. Pollut. Res., vol. 23, pp. 10841–10854, 2016.
[49] Z. Shen et al., "Temporal effect of MgO reactivity on the stabilization of lead contaminated soil," Environ. Int., vol. 131, p. 104990, 2019.
[50] M.-S. Ko, J.-Y. Kim, H.-S. Park, and K.-W. Kim, "Field assessment of arsenic immobilization in soil amended with iron rich acid mine drainage sludge," J. Clean. Prod., vol. 108, pp. 1073–1080, 2015.
[51] Y. Ding, Y. Wang, X. Zheng, W. Cheng, R. Shi, and R. Feng, "Effects of foliar dressing of selenite and silicate alone or combined with different soil ameliorants on the accumulation of As and Cd and antioxidant system in Brassica campestris," Ecotoxicol. Environ. Saf., vol. 142, pp.

207–215, 2017.
[52] X. Yuan et al., "Immobilization of heavy metals in two contaminated soils using a modified magnesium silicate stabilizer," Environ. Sci. Pollut. Res., vol. 25, pp. 32562–32571, 2018.
[53] H. Yang, G. Zhang, P. Fu, Z. Li, and W. Ma, "The evaluation of in-site remediation feasibility of Cd-contaminated soils with the addition of typical silicate wastes," Environ. Pollut., vol. 265, p. 114865, 2020.
[54] C. Lei, T. Chen, Q.-Y. Zhang, L.-S. Long, Z. Chen, and Z.-P. Fu, "Remediation of lead polluted soil by active silicate material prepared from coal fly ash," Ecotoxicol. Environ. Saf., vol. 206, p. 111409, 2020.
[55] D. Ning, Y. Liang, Z. Liu, J. Xiao, and A. Duan, "Impacts of steel-slag-based silicate fertilizer on soil acidity and silicon availability and metals-immobilization in a paddy soil," PLoS One, vol. 11, no. 12, p. e0168163, 2016.
[56] Y. Wang et al., "Characteristics and in situ remediation effects of heavy metal immobilizing bacteria on cadmium and nickel co-contaminated soil," Ecotoxicol. Environ. Saf., vol. 192, p. 110294, 2020.
[57] S. Zhang et al., "Differential effects of three amendments on the immobilisation of cadmium and lead for Triticum aestivum grown on polluted soil," Environ. Sci. Pollut. Res., vol. 27, pp. 40434–40442, 2020.
[58] S. B. K. Kanchinadham, L. M. Narasimman, V. Pedaballe, and C. Kalyanaraman, "Diffusion and leachability index studies on stabilization of chromium contaminated soil using fly ash," J. Hazard. Mater., vol. 297, pp. 52–58, 2015.
[59] G. Pei, Y. Li, Y. Zhu, W. Shi, and H. Li, "Immobilization of lead by application of soil amendment produced from vinegar residue, stainless steel slag, and weathered coal," Environ. Sci. Pollut. Res., vol. 24, pp. 22301–22311, 2017.
[60] T. Wen, L. Yang, C. Dang, T. Miki, H. Bai, and T. Nagasaka, "Effect of basic oxygen furnace slag on succession of the bacterial community and immobilization of various metal ions in acidic contaminated mine soil," J. Hazard. Mater., vol. 388, p. 121784, 2020.
[61] J. Mu, Z. Hu, L. Huang, Z. Xie, and P. E. Holm, "Preparation of a silicon-iron amendment from acid-extracted copper tailings for remediating multi-metal-contaminated soils," Environ. Pollut., vol. 257, p. 113565, 2020.
[62] A. Yao et al., "Simultaneous attenuation of phytoaccumulation of Cd and As in soil treated with inorganic and organic amendments," Environ. Pollut., vol. 250, pp. 464–474, 2019.
[63] Å. R. Almås, E. Pironin, and G. Okkenhaug, "The partitioning of Sb in contaminated soils after being immobilization by Fe-based amendments is more dynamic compared to Pb," Appl. Geochemistry, vol. 108, p. 104378, 2019.
[64] H. P. Lu, Z. A. Li, G. Gasco, A. Mendez, Y. Shen, and J. Paz-Ferreiro, "Use of magnetic biochars for the immobilization of heavy metals in a multi-contaminated soil," Sci. Total Environ., vol. 622, pp. 892–899, 2018.
[65] M. Simiele et al., "Assisted phytoremediation of a former mine soil using biochar and iron sulphate: Effects on As soil immobilization and accumulation in three Salicaceae species," Sci. Total Environ., vol. 710, p. 136203, 2020.
[66] N. H. Matin, M. Jalali, and W. Buss, "Synergistic immobilization of potentially toxic elements (PTEs) by biochar and nanoparticles in alkaline soil," Chemosphere, vol. 241, p. 124932, 2020.
[67] R. Van Poucke, J. Ainsworth, M. Maeseele, Y. S. Ok, E. Meers, and F. M. G. Tack, "Chemical stabilization of Cd-contaminated soil using biochar," Appl. Geochemistry, vol. 88, pp. 122–130, 2018.
[68] J. Lin, M. Sun, B. Su, G. Owens, and Z. Chen, "Immobilization of cadmium in polluted soils by phytogenic iron oxide nanoparticles," Sci. Total Environ., vol. 659, pp. 491–498, 2019.
[69] L. Trakal, I. Raya-Moreno, K. Mitchell, and L. Beesley, "Stabilization of metal (loid) s in

two contaminated agricultural soils: comparing biochar to its non-pyrolysed source material," Chemosphere, vol. 181, pp. 150–159, 2017.
[70] S. Mandal et al., "Synergistic construction of green tea biochar supported nZVI for immobilization of lead in soil: A mechanistic investigation," Environ. Int., vol. 135, p. 105374, 2020.
[71] Y. Xia et al., "Efficient immobilization of toxic heavy metals in multi-contaminated agricultural soils by amino-functionalized hydrochar: Performance, plant responses and immobilization mechanisms," Environ. Pollut., vol. 261, p. 114217, 2020.
[72] M. Lebrun, F. Miard, R. Nandillon, G. S. Scippa, S. Bourgerie, and D. Morabito, "Biochar effect associated with compost and iron to promote Pb and As soil stabilization and Salix viminalis L. growth," Chemosphere, vol. 222, pp. 810–822, 2019.
[73] Y. Wang, Y. Xu, X. Liang, Y. Sun, Q. Huang, and Y. Peng, "Leaching behavior and efficiency of cadmium in alkaline soil by adding two novel immobilization materials," Sci. Total Environ., vol. 710, p. 135964, 2020.
[74] T. Sun, J. Miao, M. Saleem, H. Zhang, Y. Yang, and Q. Zhang, "Bacterial compatibility and immobilization with biochar improved tebuconazole degradation, soil microbiome composition and functioning," J. Hazard. Mater., vol. 398, p. 122941, 2020.
[75] M. Černe et al., "The effect of stabilization on the utilization of municipal sewage sludge as a soil amendment," Waste Manag., vol. 94, pp. 27–38, 2019.
[76] Y. Li et al., "Remediation of hexavalent chromium in contaminated soil using amorphous iron pyrite: Effect on leachability, bioaccessibility, phytotoxicity and long-term stability," Environ. Pollut., vol. 264, p. 114804, 2020.
[77] S. Hazrati, M. Farahbakhsh, G. Heydarpoor, and A. A. Besalatpour, "Mitigation in availability and toxicity of multi-metal contaminated soil by combining soil washing and organic amendments stabilization," Ecotoxicol. Environ. Saf., vol. 201, p. 110807, 2020.
[78] M. A. R. Soares, M. J. Quina, and R. M. Quinta-Ferreira, "Immobilisation of lead and zinc in contaminated soil using compost derived from industrial eggshell," J. Environ. Manage., vol. 164, pp. 137–145, 2015.
[79] N. Hataf, P. Ghadir, and N. Ranjbar, "Investigation of soil stabilization using chitosan biopolymer," J. Clean. Prod., vol. 170, pp. 1493–1500, 2018.
[80] X. Tao, A. Li, and H. Yang, "Immobilization of metals in contaminated soils using natural polymer-based stabilizers," Environ. Pollut., vol. 222, pp. 348–355, 2017.
[81] L. He, Z. Dai, X. Liu, C. Tang, and J. Xu, "Effect of alkaline lignin on immobilization of cadmium and lead in soils and the associated mechanisms," Chemosphere, vol. 281, p. 130969, 2021.
[82] L. Meng et al., "Decreasing cadmium uptake of rice (Oryza sativa L.) in the cadmium-contaminated paddy field through different cultivars coupling with appropriate soil
[83] R. G. Lacalle, C. Garbisu, and J. M. Becerril, "Effects of the application of an organic amendment and nanoscale zero-valent iron particles on soil Cr (VI) remediation," Environ. Sci. Pollut. Res., vol. 27, no. 25, pp. 31726–31736, 2020.
[84] A. H. Lahori et al., "Residual effects of tobacco biochar along with different fixing agents on stabilization of trace elements in multi-metal contaminated soils," J. Environ. Sci., vol. 87, pp. 299–309, 2020.
[85] R. Wang et al., "Effect of amendments on contaminated soil of multiple heavy metals and accumulation of heavy metals in plants," Environ. Sci. Pollut. Res., vol. 25, pp. 28695–28704, 2018.
[86] X. Yang, L. Liu, W. Tan, C. Liu, Z. Dang, and G. Qiu, "Remediation of heavy metal contaminated soils by organic acid extraction and electrochemical adsorption," Environ. Pollut., vol. 264, p. 114745, 2020.

[87] Z. Qiu, J. Tang, J. Chen, and Q. Zhang, "Remediation of cadmium-contaminated soil with biochar simultaneously improves biochar's recalcitrance," Environ. Pollut., vol. 256, p. 113436, 2020.
[88] S. C. Kim et al., "Effect of chemical amendments on remediation of potentially toxic trace elements (PTEs) and soil quality improvement in paddy fields," Environ. Geochem. Health, vol. 39, pp. 345–352, 2017.
[89] cadmium and lead immobilization in contaminated soil under rice-wheat cropping system," Chemosphere, vol. 214, pp. 259–268, 2019.
[90] W. Zuo et al., "Sewage sludge amendment improved soil properties and sweet sorghum yield and quality in a newly reclaimed mudflat land," Sci. Total Environ., vol. 654, pp. 541–549, 2019.
[91] F. Jing et al., "Potentially hazardous element accumulation in rice tissues and their availability in soil systems after biochar amendments," J. Soils Sediments, vol. 19, pp. 2957–2970, 2019.
[92] H. Liu, "Relationship between organic matter humification and bioavailability of sludge-borne copper and cadmium during long-term sludge amendment to soil," Sci. Total Environ., vol. 566, pp. 8–14, 2016.
[93] N. Liu, Z. Jiang, X. Li, H. Liu, N. Li, and S. Wei, "Mitigation of rice cadmium (Cd) accumulation by joint application of organic amendments and selenium (Se) in high-Cd-contaminated soils," Chemosphere, vol. 241, p. 125106, 2020.
[94] Q. Xu et al., "Lead was mobilized in acid silty clay loam paddy soil with potassium dihydrogen phosphate (KDP) amendment," Environ. Pollut., vol. 255, p. 113179, 2019.
[95] P. Saengwilai, W. Meeinkuirt, J. Pichtel, and P. Koedrith, "Influence of amendments on Cd and Zn uptake and accumulation in rice (Oryza sativa L.) in contaminated soil," Environ. Sci. Pollut. Res., vol. 24, pp. 15756–15767, 2017.
[96] T. Fresno, J. M. Peñalosa, M. Flagmeier, and E. Moreno-Jiménez, "Aided phytostabilisation over two years using iron sulphate and organic amendments: Effects on soil quality and rye production," Chemosphere, vol. 240, p. 124827, 2020.
[97] M. Pukalchik, F. Mercl, M. Panova, K. Břendová, V. A. Terekhova, and P. Tlustoš, "The improvement of multi-contaminated sandy loam soil chemical and biological properties by the biochar, wood ash, and humic substances amendments," Environ. Pollut., vol. 229, pp. 516–524, 2017.
[98] V. González, M. Simón, I. García, J. A. Sánchez, and F. Del Moral, "Effectiveness of amendments to restore metal-arsenic-polluted soil functions using Lactuca sativa L. bioassays," J. Soils Sediments, vol. 13, pp. 1213–1222, 2013.
[99] S. Bagherifam, A. Lakzian, A. Fotovat, R. Khorasani, and S. Komarneni, "In situ stabilization of As and Sb with naturally occurring Mn, Al and Fe oxides in a calcareous soil: bioaccessibility, bioavailability and speciation studies," J. Hazard. Mater., vol. 273, pp. 247–252, 2014.
[100] P. Alvarenga et al., "Ecotoxicological assessment of the potential impact on soil porewater, surface and groundwater from the use of organic wastes as soil amendments," Ecotoxicol. Environ. Saf., vol. 126, pp. 102–110, 2016.
[101] J. An, B. Jeong, and K. Nam, "Evaluation of the effectiveness of in situ stabilization in the field aged arsenic-contaminated soil: Chemical extractability and biological response," J. Hazard. Mater., vol. 367, pp. 137–143, 2019.
[102] F. Guo et al., "Assessment of the immobilization effectiveness of several amendments on a cadmium-contaminated soil using Eisenia fetida," Ecotoxicol. Environ. Saf., vol. 189, p. 109948, 2020.
[103] H. Zhang, X. Yuan, T. Xiong, H. Wang, and L. Jiang, "Bioremediation of co-contaminated soil with heavy metals and pesticides: Influence factors, mechanisms and evaluation methods," Chem. Eng. J., vol. 398, p. 125657, 2020.