

Review

# Application of Soil Washing and Thermal Desorption for Sustainable Remediation and Reuse of Remediated Soil

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**Abstract:** Global governance of soil resources as well as revitalizations and remediation of degraded areas seem to be necessary actions for sustainable development. A great deal of effort has gone into developing remediation technologies to remove or reduce the impact of these contaminants in the environment. However, contaminated soil remediations in stringent conditions deteriorate soil properties and functions and create the need for efficient soil revitalization measures. Soil washing (SW) and thermal desorption (TD) are commonly used to remediate contaminated soil and can significantly reduce the contaminant, sometimes to safe levels where reuse can be considered; however, the effects of treatment on soil quality must be understood in order to support redevelopment after remediation. In this review, we discussed the effects of SW and TD on soil properties, including subsequent soil quality and health. Furthermore, the importance of these techniques for remediation and reclamation strategies was discussed. Some restoration strategies were also proposed for the recovery of soil quality. In addition, remediated and revitalized soil can be reused for various purposes, which can be accepted as an implementation of sustainable remediation. This review concludes with an outlook of future research efforts that will further shift SW and TD toward sustainable remediation.

**Keywords:** amendments; revitalization; soil remediation; soil reuse; sustainability



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## 1. Introduction

Soil is an irreplaceable natural resource that plays essential roles in the natural environment and human society [1]. However, human activities, such as industrial emissions, mining, and sewage irrigation, pollute soil and produce numerous contaminated sites, which threaten soil health worldwide [2]. Thus, management of contaminated land is a global challenge that has prompted a wide array of remediation techniques and management options [3]. The growing demand for its reuse indicates the significance of soil remediation. To facilitate the reuse of remediated soil, both remediation efficiency and soil characteristics related to soil quality and health must be carefully considered. However, to date, studies have focused on the development of remediation techniques that can be applied to specific contaminants or sites, as well as on techniques to increase remediation efficiency or reduce remediation time [4–6]. Remediation of contaminated soil often provides net benefits, and no intervention can lead to significantly greater environmental impacts than those associated with pollution. Integration of sustainable practices for remediation of contaminated land provides an opportunity to consider and optimize the social, ecological, and economic aspects of the process.

Environmental remediation has primarily aimed to manage or prevent risks to humans and the environment through control or removal of pollutants, but the restoration of soil ecological functions and productivity and reclamation of sediments, groundwater, and

surface water allowing post-remediation land use increase the sustainability of the soil remediation interventions. Although environmental remediation has advanced with the development of more sophisticated remedial technologies, the remedial actions currently applied tend to be energy-intensive, and to emit pollutants and disturb neighboring communities. Furthermore, these actions often require several years for implementation and long-term monitoring, with the potential for long-term impacts. Therefore, remediation must be conducted using a more environmentally, socially, and economically sustainable approach [7]. Recently, interest in the concept of “sustainable remediation” has grown [8–10]. Sustainable remediation has various definitions, but there is a consensus regarding its broad aims, which include reducing the impacts and maximizing the long-term benefits of remediation projects while ensuring an overall net benefit in terms of social, economic, and biophysical conditions [11]. Sustainable remediation is not only a cost-cutting measure, but also has long term implications [12]. Holland et al. [7] advocated the integration of sustainability principles into remediation activities, which is described as a holistic approach to remediation. This approach aims to balance impacts and influences on social, environmental, and financial sustainability while protecting human and ecosystem health. They suggested that sustainable remediation frameworks should critically consider the preferred end use or future use, and that all planning, activities, and resources dedicated to remediating a site should align and add value to the preferred end or future uses, beginning from the inception of the project.

Since the mid-to-late 2000s, growing interest for sustainable remediation has emerged in initiatives from several international and national organizations as well as other initiatives from networks and forums [13]. SuRF-UK is a framework especially developed for sustainable contaminated land and groundwater management. Criteria suggested by SuRF-UK are divided into five indicator categories and each of these categories contains several issues that can be considered for selecting the optimum land-use design, determining remedial objectives, and selecting a remediation strategy and technique [14]. Ellis and Hadley [15] stated that land reuse is a key indicator of sustainable remediation of contaminated soil.

The world is currently facing a serious agricultural crisis due to issues including climate change, global warming, soil degradation, reduction of agricultural land area, and food insecurity. Hence, recognition of remediated soil as a valuable resource and strategies for its agricultural reuse are essential. To promote the reuse of remediated soil, careful attention should be paid to the efficiency of remediation, as well as to changes in soil properties during the remediation process. However, much of the research on soil remediation has focused on increasing remediation efficiency for specific sites or pollutants [4,5].

The association between remediation efficacy and soil function is vital to subsequent reclamation or restoration processes [16]. Soil function is defined as the ability of the soil to provide the following types of services: regulatory, supportive, provisioning, and cultural services [17].

The concept of green and sustainable remediation focuses on minimizing the environmental impacts of remediation activities, and covers a wide range of impacts and benefits, including long-term land use and soil management. This concept aims to address the following questions in the design of remediation strategies. Which remediation technologies can improve soil conditions, and which might result in reduced soil quality? How can soil quality be restored after remediation? Which soil properties can and cannot be restored? At present, systematic review of soil quality deterioration due to SW and TD treatment, deteriorated soil recovery technology, and evaluation methods that can evaluate deteriorated soil revitalization are insufficient.

The aims and conditions of remedial projects, and their effects on soil function, determine their relevance for long-term project management [18]. For example, some projects may aim to return the land to commercial or industrial use; in such cases, soil productivity will likely have low priority. However, soil strength and stability are essential for its use as

an engineering medium. Conversely, remediation projects on agricultural land or natural areas may aim to restore the land to a pre-disturbance state, and their reclamation goals may focus on functions that support habitat, biomass, productivity, water management, and nutrient cycling [19]. The main aims of this study were to assess the effects of soil washing (SW) and thermal desorption (TD) on the physicochemical and biological properties of soil, and to determine the feasibility of improving deteriorated soil for reuse through the remediation process.

## 2. Deterioration of Soil Quality during Remediation and Revitalization of Remediated Soil for Sustainable Soil Management

### 2.1. Deterioration of Soil Quality during Soil Remediation

Directly assessing changes in soil health or quality resulting from the soil remediation process is virtually impossible, as such changes are driven by dynamic interactions of numerous soil properties and environmental processes. Nonetheless, identifying changes specific to soil properties is valuable for estimating the effects of remediation on overall soil function [20].

#### 2.1.1. Soil Washing (SW)

SW is considered a permanent remediation technology for the removal of organic and inorganic pollutants (Figure 1). The pollutants are removed from the soil through physical separation and chemical leaching, using various reagents and extractants [21].

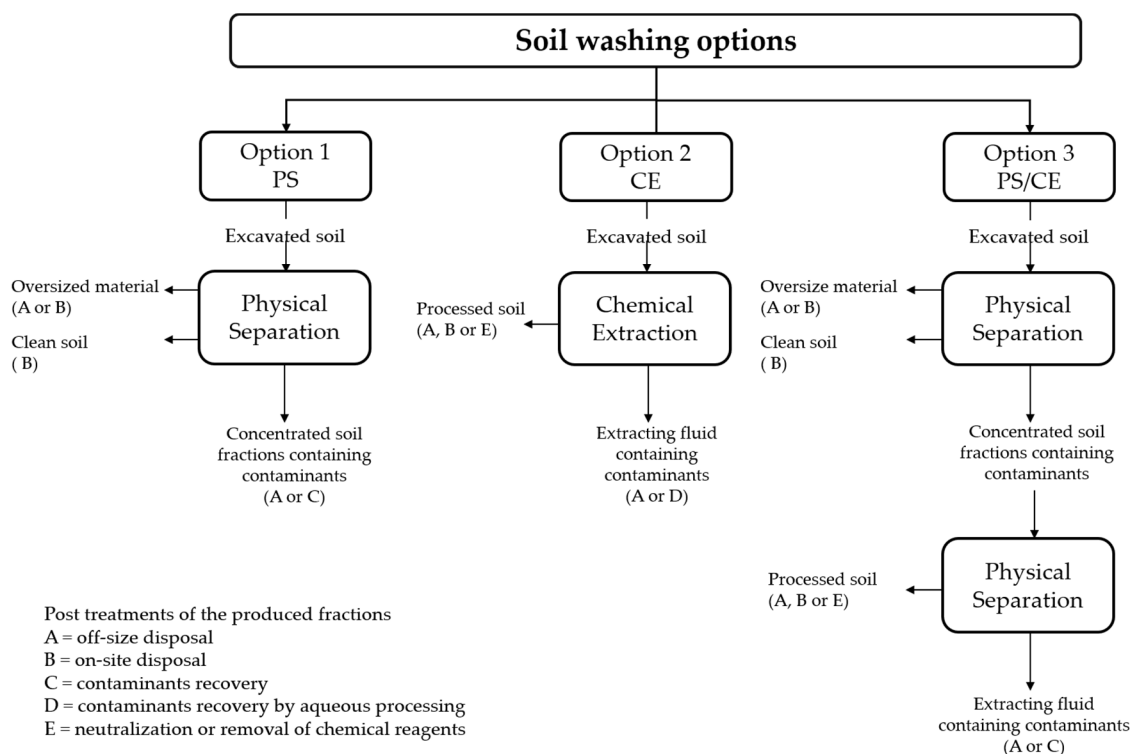


Figure 1. Typical techniques used for soil washing (modified from Dermont et al. [22]).

Typical processes used for SW include physical separation, chemical extraction, and combinations of those two techniques. Soil texture may be affected by the physical separation process, and its chemical properties can be altered by reagents such as acids, bases, surfactants, chelating agents, salt, and redox agents, which are used to transfer pollutants from soil solids to the aqueous phase [23].

Conversely, these processes can reduce soil quality during soil remediation due to deterioration of soil physical properties caused by the loss of fine particles during physical separation, changes to soil chemical properties due to extractants, and damage to soil

quality caused by residual extractants [24]. Examples of soil degradation during SW are summarized in Table 1.

**Table 1.** Effects of soil washing on soil quality indicators.

Soil Quality Indicators	Deterioration	Ref.
Physical	Decrease in water and nutrient holding capacities	[24,25]
Chemical	Loss of soil organic matter, cation exchange capacity, micro- and macronutrients	[26–28]
	Increase in bioavailability and mobility of residual pollutants	[29,30]
	Toxicity of residual extractants	[23,31,32]
Biological	Changes in DNA content and microbial population structure Reduced enzyme activities Reduced germination and growth rates of plants (crops)	[24,27,33,34]

The physical separation process involves reducing the volume of contaminated soil by utilizing physical properties to separate ordinary particles from particles where pollutants are concentrated. Gautam et al. [25] suggested that finer soils (particle diameters < 0.075 mm) act as degrading media during SW and should be separated after washing all of the soil. Fine soil particles that contain a high concentration of contaminants are separated for further treatment or disposal [26]. The loss of fine particles during the physical separation process alters soil physical properties, such as water- and nutrient-holding capacities.

Chemical extraction involves techniques for solubilizing pollutants from the soil using an extraction solution containing inorganic acids (e.g., HCl, HNO<sub>3</sub>, or H<sub>2</sub>SO<sub>4</sub>), organic acids (e.g., acetic acid, citric acid, or oxalic acid), chelating agents (e.g., ethylenediaminetetraacetic acid (EDTA)), bases (e.g., NaOH), and inorganic salts (e.g., potassium phosphate). Strong acids are often used, especially for the removal of toxic trace elements (TTEs) from soils.

Ko et al. [26] reported significant loss of soil organic matter (SOM) from the fine particle fraction after leaching of soil with acids (HCl, H<sub>2</sub>SO<sub>4</sub>, and H<sub>3</sub>PO<sub>4</sub>). Because acids are non-selective extractants, cation exchange capacity (CEC) as well as micro- and macronutrients are removed along with pollutants. Udovic and Lestan [35] reported that leaching with HCl dissolved carbonates in soils. Both the carbonate and SOM contents decreased significantly, likely due to mechanical extraction of small organic soil constituents during the leaching process. Hu et al. [28] reported that CEC, total P, total K, and available K all decreased after leaching with EDTA.

After SW, residual pollutants with high mobility, which were detected mainly in the highly available fraction, were affected by the redistribution of TTEs, showing increased bioavailability [29,30,36,37]. Hazrati et al. [38] observed increases in exchangeable Cd, Pb, and Zn concentrations after washing with hydroxylamine hydrochloride and citric acid, which had a toxic effect on plant growth. Barona et al. [39] and Lei et al. [40] found that TTEs remaining in the soil after chelation-based remediation showed enhanced mobility and weak associations with soil components. Enhanced mobility of residual metals likely occurs due to metal detachment, chelator attack, soil dissolution, or cation exchange between chelated complexes and soil particles.

Washing with chelating agents and synthetic surfactants leads to health and safety concerns due to their slow degradation and the inability to recover these extraction agents [31,32]. The extraction efficiency of synthetic surfactants is optimal for organic pollutants [33,41]. However, some synthetic surfactants have low biodegradability and are affected by precipitation or sorption onto soil, thus requiring larger volumes that may further damage the soil [42]. Moreover, surfactants may form emulsions with high

viscosities that are difficult to manage and remove. EDTA is poorly photo-, chemo-, and biodegradable, and persists in the environment [43]. EDTA has been used as an extractant, and is reported to decompose by only 14% over 20 days, with the rest remaining in soil [44]. Sub-soil transportation of complex toxic metals and the spread of pollution could therefore pose a long-term environmental hazard [45]. Significant differences in water retention characteristics, aggregate fractionation, and stability exist between the original and remediated soils; a lower yield of white clover was observed from EDTA-washed soil [23]. The introduction of EDTA into soil causes stress in soil microorganisms, and significantly impairs the growth and activity of fungi while also causing necrotic lesions on Chinese cabbage leaves, a lack of development of arbuscular mycorrhizae in red clover, and stress in soil microfauna [46]. EDTA has been shown to reduce soil microbial biomass and inhibit soil enzyme activity [47,48]. Chelated EDTA-TTE complexes pose a potential health risk, as they are poorly biodegradable and persist in the soil environment. HCl is also used as an extractant, and high concentrations of  $\text{Cl}^-$  ions have been reported to cause salinization, with detrimental effects on soil organisms [49].

Remediation changes the physical and chemical characteristics of soil, thereby influencing its microbial activities. The structure and activity of the soil microbial community can serve as a major indicator of changes in soil quality. The Shannon index, which indicates the richness and evenness of soil bacteria and fungi, significantly decreased due to changes in soil pH and nutrient contents after washing [50]. Soil pH is critical to microbial activity, affecting the integrity and function of microbial cell membranes, as well as biomass and community structure [51,52]. Under low-pH conditions, TTEs are easily converted into more mobile or bioavailable forms [51]. Mühlbachova [47] reported a negative relationship between microbial biomass (soil microbial carbon) and available ( $\text{NH}_4\text{NO}_3$ -extractable) heavy metal fractions in EDTA-treated arable soils. Jelusic et al. [27] reported that remediation initially reduced soil DNA content and altered the microbial population structure. Chae et al. [34] reported significantly lower enzyme activities in washed soil due to improper conditions, including high pH, low nutrient levels, and high sand content in the washed soil. The ecological properties of soil evaluated based on the activities of soil enzymes, such as dehydrogenase (DH), phosphatase (PHO), and  $\beta$ -glucosidase (GLU), did not recover fully after remediation to a healthy state despite pollutants being removed through remediation, with many reports of lower soil enzyme activities due to changes in soil properties, such as soil pH and nutrient concentrations [24,33,34]. In another case, Kaulin et al. [53] reported that remediation had a positive effect on DH and GLU activities, whereas urease (UR) activity decreased after washing with EDTA. They suggested that enzyme activity is sensitive to both soil remediation and transient soil conditions, such as substrate addition.

Yi and Sung [24] confirmed that the germination and growth rates of *Brassica juncea* decreased after soil cleaning due to changes in soil pH and electrical conductivity (EC). Increased mobility and bioavailability of residual soil pollutants after SW has been reported to increase the absorption of toxic elements by plants [27,54]. Available potassium in soil promotes good soil fertility and high crop yields [55]. Kwak et al. [56] confirmed that the biomass and photosynthetic activity of *Chlorococcum infusionum* and *Chlamydomonas reinhardtii* were reduced with changes in pH, EC, and nutrient contents, while the survival, appearance, and burrowing behavior of *Eisenia andrei* were impacted in remediated soils; therefore, follow-up measures were needed to restore habitat quality and function.

Im et al. [34] confirmed ecotoxicological effects, in terms of the germination rate, shoot growth, and soil enzyme activities in remediated soil, using a bioassay, and noted that these effects were caused by rapid changes in pH and nutrient contents. They suggested that proper management of ecotoxicological effects and changes in soil properties is essential for the reuse of remediated soil.

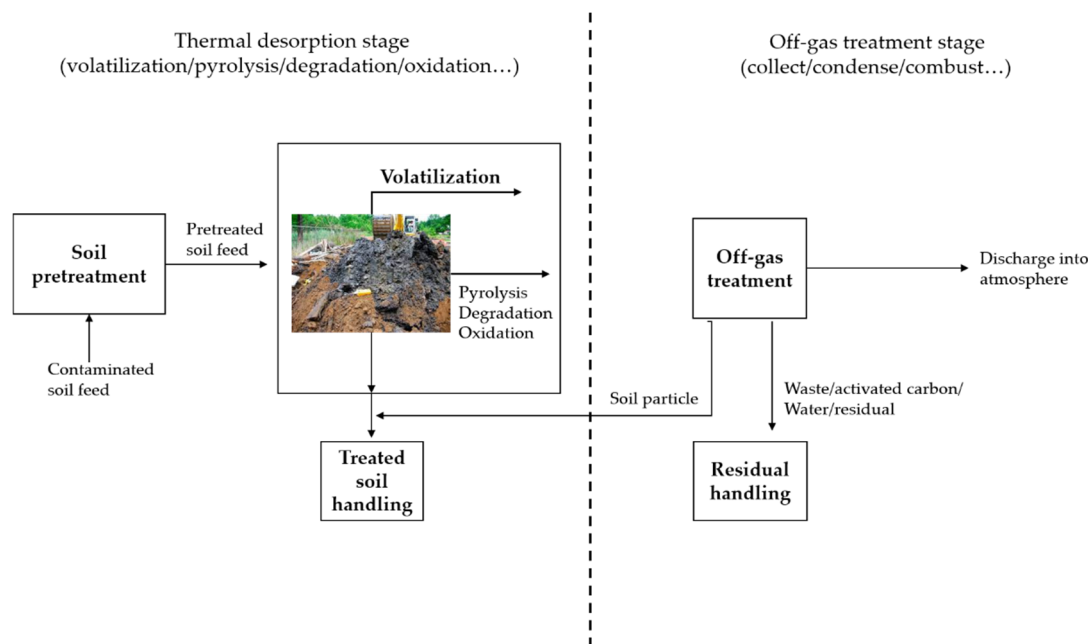
With increasing awareness of remediated soil quality, the following considerations related to SW should receive greater attention in future research: controlling the increased activity of pollutants during SW; preventing changes in certain soil physicochemical



properties after washing (e.g., pH, macro- and micronutrients); alleviating decreases in soil enzyme activities and microbial diversity after washing; and selecting milder chemical reagents for SW and neutralization. The ideal extraction agent should have the following properties: high extraction efficiency for the target pollutant at low extractant volume, low soil sorption, minimal influence on soil health, little mobilization of SOM, little effect on the efficiency of the process used for degradation of the target pollutant, and limited degradation during SW.

### 2.1.2. Thermal Desorption (TD)

TD is a prominent remediation technique that is highly effective for removing most volatile and semi-volatile contaminants, including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT), total petroleum hydrocarbon (TPH), and Hg. TD treatment has the advantages of processing a wide range of pollutants, rapid treatment, high efficiency, safety, and little production of secondary products (pollutants). For these reasons, TD has been widely used for remediating highly contaminated small areas and has often been applied to sites needing urgent treatment. TD is a physical remediation technology that removes contaminants primarily through volatilization and desorption mechanisms. However, reactions such as pyrolysis, degradation, and oxidation are dependent on temperature and oxygen concentrations in the local atmosphere, with the intensity of these reactions enhanced by increases in temperature and oxygen (Figure 2). In terms of the temperature used for removal of contaminants, TD can be divided into low-temperature thermal desorption (LTTD) and high-temperature thermal desorption (HTTD) processes. The boundary between the two technologies is unclear, but 300 °C–350 °C is generally considered a critical temperature distinguishing HTTD from LTTD.



**Figure 2.** Basic process of TD (modified from Zhao et al. [57]).

LTTD is widely used for processing volatile organic compounds with low boiling points, such as gasoline and benzene, while HTTD is suitable for semi-volatile organic compounds (such as PAHs and PCBs) with high boiling points and for inorganic pollutants (such as Hg). Regardless of temperature, the heating applied for desorption of contaminants affects SOM, clay content, pH, and water holding content (WHC), and can also decrease CEC [58,59], which may impair soil health [60].

Examples of soil quality deterioration during TD are summarized in Table 2.

**Table 2.** Effect of thermal desorption on soil quality indicators.

Soil Quality Indicators	Deterioration	Ref.
Physical	Clay-sized particles are cemented with Fe- and Al-hydroxides, altering the distribution of soil particle sizes	[58]
Chemical	Can decrease clay content, soil pH, WHC, and CEC	[58,59,61]
Biological	Genotoxic effects on coelomocytes of <i>Eisenia fetida</i> Microbial activity (including soil enzyme activities) decreases at higher temperature due to thermal denaturation	[58,62,63]

TD treatment can cause changes in soil texture and mineral contents, as the structure of the mineral clay lattice is dehydrated and decomposed [62]. Following the denaturation of these mineral structures, amorphous clay-sized particles are cemented with Fe- and Al-hydroxides released during the decomposition of SOM, resulting in larger particle sizes [58]. As a result, large soil particles, i.e., sand grains, are formed, which have low water and nutrient holding capacities and poor structure, increasing susceptibility to wind erosion [60]. O'Brien et al. [61] reported that after oil-contaminated soil had been TD-treated at 350 °C, soil physical characteristics and hydraulic processes related to agricultural productivity were significantly altered, with increased saturated hydraulic conductivity, reduced water retention, and caused a higher permanent wilting point.

During TD processing, SOM is affected by volatilization, charring, oxidation, and pyrolysis reactions [64,65]. Such decomposition and reduction of SOM are affected by heating time and temperature [19]. Incineration at 620 °C for 180 min reduces SOM by more than 90% [64], while smoldering for 60 min can almost completely remove SOM [58]; however, when heated to 300 °C, the SOM level is not significantly reduced [17,58,66]. Ren et al. [67] reported that LTTD of diesel produced biochar-like pyrolytic carbon, which buffered heat-induced changes and created favorable soil conditions, such as elevating the soil pH to reduce Al phytotoxicity [68], improving soil fertility due to increases in surface area and negatively charged functional groups [69], and enhancing the soil nutrient content to facilitate wheat growth [70].

Changes in soil pH due to TD are affected by temperature and time, with many studies showing little or no change in soil pH, especially at lower temperatures (<250 °C). Decreases in pH are likely caused by oxidation reactions and the formation of  $\text{HCO}_3^-$  following the mineralization of  $\text{CO}_2$  [63]. Changes in pH have also been attributed to the displacement of  $\text{H}^+$  from exchange sites on clay and SOM by basic cations released during heating. SOM is mineralized, which releases  $\text{CO}_2$  that is readily transformed into  $\text{HCO}_3^-$ . At high temperatures (>250 °C), pH rises due to the removal of organic acids and substitution of hydrogen ions in soil solutions with various cations formed during the combustion of SOM [63,71]. In soils with high SOM content, TD treatment causes large pH fluctuations, while pH shifts are less pronounced in soils with low SOM or high  $\text{CaCO}_3$  contents, as  $\text{CaCO}_3$  buffers against pH changes.

Thermal treatment can lead to changes in plant-available nutrient contents, particularly in the major components of SOM, C, and N, which are lost through volatilization. However, during LTTD (<220 °C), organic N is mineralized into either  $\text{NO}_3^-$  or  $\text{NH}_4^+$  (predominantly  $\text{NH}_4^+$ ), which does not affect the total nitrogen content [72]. Soil phosphorus is reported to have significantly higher volatilization temperatures than C and N, resulting in minimal losses through volatilization, but in some cases plant-available P interacts with newly formed highly reactive minerals following rehydroxylation, which may adsorb additional P and thus reduce the plant-available fraction [73,74]. Huang et al. [75] reported that thermal treatment led to repartitioning of trace elements. Trace elements in Fe/Mn oxides were transformed into acid-extractable, organic-matter bound, and residual forms

after thermal treatment of Hg-contaminated soil at 550 °C; meanwhile, Cr, Cu, and Ni became less mobile.

Bonnard et al. [60] studied the effect of TD on genotoxicity in *Eisenia fetida* worms using the comet assay and found that up to 94% of the contaminants were treated with TD, but the genotoxicity of soil pollutants to earthworms increased. The concentration of nonvolatile metals remained unchanged after TD. Among trace elements found in the treated soil, Cd, Cr, and Ni could explain the genotoxicity of contaminated soil after TD. Treatment could increase the bioavailability and genotoxicity of TTEs via modification of SOM.

The recovery of soil microorganisms after TD occurs in distinctly different ways depending on the desorption temperature. After LTTD (<300 °C), recovery occurs within a few days, while HTTD (>300 °C) does not support recovery of the number and activity of microorganisms, even after hundreds of days. Therefore, additional measures, such as supplying nutrients or organic amendments, are needed to restore the activity of soil microorganisms [58,76,77]. Low-temperature heating can lead to the release of dissolved organic carbon (DOC), initiating a short-lived recovery that is ephemeral due to the rapid mineralization of DOC. High-temperature heating destroys DOC, which inhibits recovery. According to Mataix-Solera et al. [78], recovery is related to microbial community composition and heating temperature. In particular, fungi are more sensitive to heating than bacteria. Moreover, vegetation can favor the recovery of microbial biomass [77,79], likely due to the close relationships between microorganisms and plants (e.g., mycorrhiza or N-fixing rhizobia).

Soil enzymes exhibit increased activity during LTTD treatment due to the release of nutrients and cell lysis, while during HTTD their activity is greatly suppressed due to the denaturation of enzymes [58,63,80].

The factors discussed above can facilitate the reuse of remediated soil if heat treatment is conducted at an appropriate temperature. Ding et al. [81] reported that the effect of low-temperature (<250 °C) heat desorption on soil properties was minimal, and that the availability of nutrients and DOC increased during TD, thereby promoting the growth of microorganisms and plants. Yi et al. [66] confirmed that LTTD can improve overall soil health related to biological productivity and environmental functions and suggested that LTTD be used as an alternative to harsher remediation methods. Sierra et al. [60] confirmed that LTTD-treated soil can be reused as farmland soil, despite some nutrient losses due to treatment. However, to fully recover the function of damaged soil after thermal treatment, the addition of SOM and nutrients, individually or in combination, may be needed.

## 2.2. Revitalization of Disturbed Soil

Among the remediation technologies developed and utilized to date, SW and TD are efficient techniques that permanently remove soil pollutants, but they also impair soil quality. Although SW and TD are efficient and permanent methods of removing pollutants from contaminated soils, these treatments adversely impact soil microorganisms and their function, as well as other soil properties. Serious changes in soil properties during the remediation process can irreparably damage the health of the remediated soil, despite decreasing the pollutant concentration below the target level [27]. Barona et al. [39] and Lei et al. [40] reported that effective revitalization approaches are essential for restoring soil health and reclaiming remediated soil as a fertile and safe plant substrate.

Revitalization of soil health during the remediation of disturbed soils is essential for the reuse of remediated soil. Understanding the soil functions that can be disrupted during the remediation process provides information for the establishment of remediation strategies and restoration plans that minimize disturbance.

Soil pH that is significantly outside the normal range (typically <5.5 or >8.5), due to extraction with acid or alteration of SOM during TD, reduces the availability of nutrients and inhibits microbial activity. Acid washing can cause problems, such as increased mobility and bioavailability of TTEs remaining in the soil, which must be addressed



through reduction of the mobility and availability of TTEs by raising the pH above 7. Conversely, a rapid increase of soil pH significantly reduces P availability and increases the solubility of As, thereby inhibiting plant growth and microbial activity. P and N deficiencies limit plant and microbial growth; hence, maintaining sufficient levels of available or labile N, P, and K is crucial to survival for most species.

Soil amendments, such as clay minerals (e.g., vermiculite and zeolite), lime, biochar, and organic amendments are commonly used to effectively stabilize residual pollutants and restore soil quality in remediated soils [37,51,53,82]. Jelusic et al. [37] used vermiculite to improve soil structure, as it contributes numerous exchange sites for retaining nutrients added to the soil; they also assessed apatite and a commercial mixture of absorbent amendments in terms of their capacity to reduce leachability and plant-available TTE levels remaining in the soil after remediation. Guo et al. [83] reported that inorganic amendments (zeolite and  $\text{CaCO}_3$ ) increased seed germination in Chinese cabbage.

The bioavailability of TTEs (Cd, Cu, Pb, and Zn) in  $\text{FeCl}_3$ -washed soil decreased significantly with the addition of 1% (w/w) lime [51]. Wang et al. [50] reported that  $\text{Ca}(\text{OH})_2$  treatment of acidic soil after washing resulted in increased available P and total N contents, and that the chemical forms of Cd and Pb in neutralized soil shifted toward the residual and Fe–Mn oxide fractions. Additionally, although  $\text{HNO}_3$  reduced soil quality to some extent, the normal growth of *Mentha haplocalyx* was unaffected, and the Pb, Cu, and As concentrations in its aboveground parts decreased significantly when grown in neutralized soil. Therefore,  $\text{Ca}(\text{OH})_2$  neutralization is necessary to improve the quality and ecological safety of washed soils. Kim et al. [52] reported that barley growth in acid-washed and CaO-neutralized sediment was comparable to that observed in untreated and water-washed sediments. This result indicates the protective effect of residual calcium against sodium and chloride toxicity. The combined application of SW (with  $\text{FeCl}_3$ ) and immobilization (with lime, biochar, and black carbon) reduces the toxicity of residual trace elements, with significant recovery of microbial activity seen compared with soil that had only been washed, thus confirming the necessity of immobilization with stabilizers after SW [51].

Organic amendments such as biochar, compost, and organic fertilizer are frequently used for supplying essential nutrients, such as N and P, increasing SOM content and restoring microbial activity. The introduction of organic amendments affects the composition of SOM, CEC, and the microbial community, ultimately improving overall soil quality [84]. Yoo et al. [84] revealed that sludge-derived biochar enhanced acid PHO activity, but only marginally improved DH and UR activities in the remediated soil. Guo et al. [83] reported that the combined application of  $\text{CaCO}_3$  and chicken manure reduced the bioavailability of TTEs in acid-washed soil.

The use of specific combinations of plants and microbes to reintroduce nutrients and organic matter through semi-natural succession [85] is an economical restoration strategy that could provide long-term sustainable results. For example, red clover improved biological activity in nitrogen-deficit soils when specific bacterial symbionts were present, thereby facilitating nitrogen fixation. This process could complement or follow a short-term amendment strategy. Developing the most appropriate combination of treatments for local remediation must be conducted on a case-by-case basis. Comprehensive biological restoration would provide long-term, sustainable site rehabilitation after remediation and reduce the requirements for external inputs into the system.

Maček et al. [85] studied the revitalization of a remediated soil by inoculation with arbuscular mycorrhizal (AM) fungi, and reported that the native fungal community established in soil owing to its trophic relation with plants, thus highlighting a potential sustainable strategy for revitalizing soils after remediation.

Changes in chemical properties, including significant reductions in essential nutrients, such as N and P, in soil after HTTD ( $>500\text{ }^\circ\text{C}$ ) result in poor plant growth and limit microbial recolonization. Soils showing severely deteriorated quality require intensive rehabilitation processes, such as amendment with organic matter and nutrients, stabilization,

or inoculation of nitrogen-fixing assemblages. O'Brien et al. [20] reported that the effects of TD are heavily dependent on the nature and origin of the treated soil. Nonetheless, until recovery of SOM and soil respiration, treated soils may be susceptible to nutrient and water stresses. Despite substantially reducing crop production, mixing non-contaminated soils with TD soils increased SOC, total N, and respiration, indicating that mixing may enhance the recovery of soil health. Overall, the ability of organisms to recover depends on the soil conditions after treatment, including SOM, available nutrients, and water content. Additionally, organisms must be reintroduced into the treated soil, as most organisms are destroyed during the heating process.

The type, mix, and amounts of soil amendments will vary from site to site in response to the local mix of site contaminants, soil conditions, and type of desired vegetation. Post-revitalization land use also is an important consideration in choosing soil amendments and remedial strategies. Additionally, it is essential that potential soil amendments be carefully characterized for all important physical, chemical, and microbiological properties. Soils are the most complex natural system, and additional research is needed to fully understand the role of factors such as the soil properties and the resilience of the microbial population in soil remediation and revitalization.

### 3. Conclusions

Remediated soil reuse is a key indicator of sustainable remediation. Remediated soil should be acknowledged as a valuable resource, and a feasible solution for its agricultural reuse is urgently needed. To facilitate soil reuse, both remediation efficiency and soil characteristics associated with soil quality and health should be carefully considered. Revitalization of soil health is critical after drastically disturbing a site via remediation. Contaminated soil remediations in stringent conditions, such as SW and TD, necessitate more extensive rehabilitation. By integrating this knowledge with the design of remediation processes, it will be possible to ensure that remediated sites offer environmental and economic benefits in addition to lower environmental hazards. The following aspects should receive more attention in future research regarding SW and TD: (i) the selection of milder chemical reagents and appropriate temperature for SW and TD, respectively, and neutralization; (ii) the control of elevations of availability of contaminants during soil remediation; (iii) the avoidance of decreases in some soil physicochemical properties in soil after soil remediation; and (iv) the alleviation of decreases in soil enzyme activities and soil microbial diversity in the soil after remediation. In most cases, appropriate organic or inorganic soil amendments can be used to regenerate the soil. Research is needed to establish the quantitative relationships between the soil physicochemical properties and microbial activity and the effect of soil remediation and revitalization on the functional recovery of soil quality.

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