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[1.] Gianina DAMIAN

FACTORS AFFECTING THE PERFORMANCE AND APPLICABILITY OF SOIL WASHING FOR HEAVY METAL–CONTAMINATED SOIL REMEDIATION

[1.] Department of Cadastre, Civil Engineering and Environmental Engineering, "1 Decembrie 1918", University of Alba Iulia, Alba–Iulia 510009, ROMANIA

Abstract: Soil contamination by heavy metals, largely resulting from mining and industrial activities, represents a major environmental challenge at local, regional, national, and global scales. Among the technologies available for the remediation of heavy metal–contaminated soils, soil washing is one of the most widely applied methods due to its relatively high removal efficiency, short treatment time, applicability to a broad range of soil types, and comparatively lower operating costs. However, the effectiveness of the process depends on a complex interplay of factors related to soil properties, the type and extraction capacity of the washing solution, and operational parameters such as pH, contact time, liquid–to–solid ratio, temperature, and agitation intensity. Based on a review of the relevant literature, this paper examines the main factors influencing the efficiency and practical applicability of soil washing for the remediation of heavy metal–contaminated soils. Particular attention is given to soil characteristics, the extraction performance of acids, chelating agents, surfactants, and humic substances used as washing agents, as well as to the operational parameters governing the process.

Keywords: heavy metals, soil washing, ex situ soil remediation, washing solution, chelating agents

INTRODUCTION

Soil contamination with heavy metals, largely resulting from intensive industrial development and mining activities, has become a major environmental concern worldwide (Levei et al., 2010). The environmental significance of this issue arises from the toxicity of heavy metals to both terrestrial and aquatic ecosystems, as well as from their potential to accumulate in agricultural crops and food products. Due to their persistence and non-biodegradable nature, heavy metals can be transferred to humans through the food chain and may cause a wide range of adverse health effects (Gămăneci & Căpățână, 2011). Consequently, several heavy metals, including lead (Pb), mercury (Hg), arsenic (As), and cadmium (Cd), are classified as priority pollutants by regulatory agencies such as the United States Environmental Protection Agency (USEPA) (Singh & Prasad, 2015).

The restoration of degraded and contaminated soils, particularly those affected by historical mining activities, has become a priority from legislative, technical, economic, and social perspectives. The ultimate objective is to enable the safe reuse of these lands for agricultural, forestry, or other productive purposes. As the number and extent of contaminated sites continue to increase, the demand for effective soil remediation technologies is growing accordingly.

Although numerous remediation technologies have been developed for contaminated soils, many of them suffer from important technical and economic limitations. Their performance is often strongly dependent on soil properties, they may require long treatment periods, involve substantial capital and operating costs, or generate undesirable environmental impacts. As a result, the large-scale application of some conventional remediation methods remains economically challenging (Mathew, 2005).

In this context, soil washing has become one of the most widely investigated and applied technologies for the remediation of heavy metal-contaminated soils at laboratory, pilot, and industrial scales (Wuana & Okieimen, 2011). Soil washing is a physicochemical remediation technique that employs water, either alone or supplemented with chemical additives, to extract contaminants adsorbed onto soil particles. The widespread use of this technology is mainly attributed to its high heavy-metal removal efficiency, relatively short treatment time compared with biological remediation methods, applicability to a wide range of contaminated soils, and comparatively low operating costs (Szanto et al., 2011). Consequently, soil washing is considered one of the best available technologies for the remediation of heavy metal-contaminated sites (Wuana & Okieimen, 2011). In addition, it represents a potentially permanent remediation solution because the treated soil can often be returned to the site and reused at relatively low cost (Begum et al., 2016).

Although soil washing can be implemented both *in situ* and *ex situ*, *ex situ* applications are generally preferred (Begum et al., 2016). The effectiveness

of *in situ* soil washing is often limited by the low mobility of extraction agents within the soil matrix and by the risk of contaminant migration toward groundwater systems (Begum et al., 2016). In contrast, *ex situ* soil washing involves excavation, particle separation, and chemical extraction under controlled operating conditions, which facilitates process control and generally improves treatment efficiency (Micle V., 2014).

Despite its advantages, soil washing also presents several limitations. These include the need to treat the generated washing effluent, the costs associated with excavation and transport of contaminated soil, and the large space requirements of treatment facilities. Additional challenges arise from the risk of contaminant dispersion and dust generation during excavation and handling operations, as well as from the complexity of soil physicochemical properties, which may significantly affect treatment performance (Begum et al., 2016).

To overcome these limitations and to improve the effectiveness and practical applicability of soil washing, careful optimization of the remediation process is required. The success of *ex situ* soil washing depends on the interaction between soil characteristics, the properties of the washing solution, and the operational conditions under which the process is conducted. An inadequate selection of these parameters may result in reduced removal efficiencies, increased operating costs, equipment corrosion, or undesirable alterations of soil properties. Therefore, a thorough understanding of the factors controlling the process is essential for the successful implementation of soil washing as a sustainable remediation technology.

Although several reviews addressing soil washing have been published, recent advances regarding biodegradable chelating agents, humic substances and combined washing strategies have not been comprehensively integrated. Furthermore, the interaction between soil characteristics, washing-agent selection and operational parameters remains insufficiently synthesized. This review seeks to address these aspects by providing an updated and integrated assessment of the factors controlling soil washing performance.

Therefore, the aim of this paper is to review the main factors governing the efficiency and practical applicability of soil washing for the remediation of heavy metal-contaminated soils. Based on the available literature, particular attention is given to soil characteristics, the type and extraction capacity of washing agents, and the operational parameters that influence the performance of the process.

This review was conducted through a structured analysis of the scientific literature concerning soil washing for heavy metal-contaminated soils. Relevant publications were identified using scientific databases including Scopus, Web of Science and Google Scholar. The literature search focused on studies addressing the influence of soil properties, washing agents and operational parameters on heavy metal removal efficiency. Both classical and recent publications were included to provide a comprehensive overview of current knowledge and emerging developments in the field.

FACTORS INFLUENCING THE EFFICIENCY AND APPLICABILITY OF THE SOIL WASHING PROCESS

Soil washing of heavy metal-contaminated soils relies on the ability of water, alone or combined with specific additives, to mobilize heavy metals present in the soil. Therefore, it is necessary to understand the factors that influence metal mobility in soil, their extraction, and consequently the efficiency of the soil washing remediation process.

Soil Characteristics and Co-occurring Pollutants

The efficiency of heavy metal removal by soil washing is strongly influenced by soil properties and by the presence of co-occurring contaminants. Factors affecting metal extraction include soil composition and texture, pH, organic matter content, contaminant distribution, and other physicochemical characteristics that govern metal mobility and retention within the soil matrix.

Several factors may limit the effectiveness of soil washing, including soil particle size distribution, organic matter content, the presence of hydrophobic contaminants, and the occurrence of non-metallic pollutants. For example, the application of soil washing may become economically unattractive when the fine soil fraction exceeds approximately 50% of the total soil mass. In addition, the performance of certain washing agents may be adversely affected by specific soil constituents. Surfactant-based washing, for instance, may show limited effectiveness in soils containing more than 20–30% clay or high levels of organic matter (Begum et al., 2016).

In contaminated soils, heavy metals are preferentially associated with the finer soil fractions through physical adsorption and chemical binding processes. As particle size decreases, heavy metal concentrations generally increase because fine particles possess a larger specific surface area and a greater abundance of reactive mineral and organic constituents. These constituents contain functional groups, particularly hydroxyl and carboxyl groups, that contribute to the development of surface charge and provide binding sites for metal ions, thereby enhancing metal retention in the soil matrix (Mohanty &

Mahindrakar, 2011). As a result, heavy metals tend to accumulate in the finest soil fractions, as illustrated in Figure 1, where chromium and lead concentrations increase markedly with decreasing particle size.

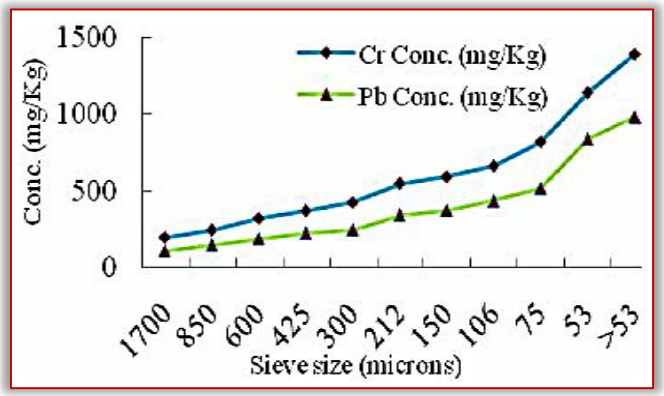

Figure 1. Cr and Pb concentration as a function of soil particle size (Mohanty & Mahindrakar, 2011)

Accordingly, soil washing aims to treat the entire volume of contaminated soil by separating fine particles from coarser fractions and transferring the associated heavy metals into the washing solution (Begum et al., 2016). The objective of the particle separation stage is to maximize the recovery of a coarse soil fraction with a low contamination level that can be safely reused at relatively low cost (Stegmann et al., 2001).

Additionally, high levels of soil organic matter, particularly humic substances, may reduce metal extraction efficiency by providing additional sorption sites for heavy metals. Similarly, soils containing significant amounts of hydrophobic contaminants often require the addition of supplementary extraction agents, which may introduce additional challenges related to their recovery or disposal after treatment (Begum et al., 2016). The chemical speciation of heavy metals is another key factor because it determines their mobility, solubility, and availability for extraction (Lestan et al., 2008). Furthermore, the volume of washing solution required, and the operating conditions applied depend on both the type and concentration of contaminants present in the soil, and variations in these parameters may significantly influence process performance (Begum et al., 2016).

Type and Extraction Capacity of the Washing Solution

The effectiveness of the soil washing technology for heavy metal-contaminated soils is closely related to the ability of the extraction solutions to mobilize and remove metallic contaminants from the soil. For the remediation of heavy metal-contaminated soils by washing, acids, bases, surfactants, alcohols, reducing agents and chelating agents are among the most commonly used washing agents reported in the literature.

— Acid Washing

Acid-assisted soil washing relies on the ability of acidic solutions to mobilize heavy metals from the soil matrix. Metal removal may occur through ion-exchange reactions, in which hydrogen ions displace metal cations from adsorption sites, or through the dissolution of metal-bearing compounds and mineral phases that contain the target contaminants (Begum et al., 2016). The acids most frequently used for the remediation of heavy metal-contaminated soils and sediments include hydrochloric acid (HCl), sulfuric acid (H_2SO_4), nitric acid (HNO_3), and phosphoric acid (H_3PO_4).

Acid washing can achieve very high heavy-metal removal efficiencies, in some cases approaching complete extraction under optimized operating conditions. A comparison of metal removal efficiencies reported in the literature for different acid washing agents is presented in Table 1.

Table 1. Metal–ion removal efficiencies (%) achieved by soil washing with different acids (data reported by Moutsatsou et al., 2006)

Metal/ acid washing agent	HNO_3 (6 M)	H_2SO_4 (6 M)	HCl (1 M)	HCl (2 M)	HCl (3 M)	HCl (6 M)
Fe	14	47	37	55	63	72
Cu	10	30	41	42	51	46
Zn	45	78	67	67	65	97
Mn	42	93	68	70	75	80
Pb	44	6	35	57	79	83
As	11	80	64	92	77	73

The data presented in Table 1 indicate that the efficiency of acid washing depends strongly on both the type and concentration of the acid used. Considerable differences in removal efficiency can be observed even for the same target metal. For example, HCl (6 M) achieves very high Zn removal efficiencies, whereas H_2SO_4 (6 M) performs particularly well in the extraction of Mn. In contrast, Pb removal is relatively poor when H_2SO_4 is used but increases substantially in the presence of concentrated HCl. These results highlight the difficulty of selecting a single acid capable of efficiently removing all contaminants from soils affected by multi-metal pollution.

Despite their high extraction efficiency, strong acids may adversely affect the physical, chemical, and biological properties of the treated soil. For example, increasing acid concentration has been reported to alter soil engineering properties, including its compressibility and expansion behaviour (Zhu et al., 2012). In addition, highly acidic washing solutions may accelerate equipment corrosion and contribute to secondary environmental impacts. Consequently, the use of strong acids is often limited in practical

applications despite their excellent extraction performance (Wang et al., 2013).

To reduce the drawbacks associated with strong mineral acids, several weak organic acids, including acetic, oxalic, succinic, and malic acid, have been investigated as alternative washing agents. Their extraction performance is generally lower because of their weaker dissolution capacity, although they are often considered more environmentally compatible. After 6 h of extraction, the removal efficiencies obtained for As and Cr were below 50%, while Cu removal remained below 65% when these organic acids were used (Uwumarongie-Ilori & Okieimen, 2010). Nevertheless, under optimized operating conditions, such as increased contact time or higher reagent concentrations, removal efficiencies comparable to those achieved with strong acids may be obtained, as shown in Figure 2.

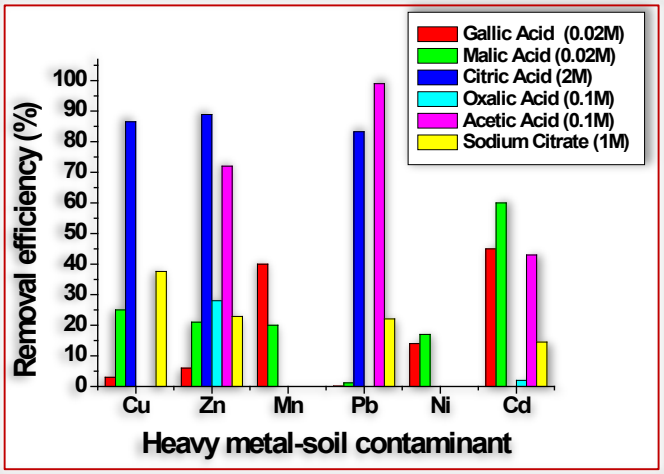

Figure 2. Comparison of heavy metal removal efficiencies from soil through washing with various weak (organic) acids (compiled from data reported by Lubna, 2015; Park et al., 2013; Oustan et al., 2011; Gzar et al., 2014; Oudghiri et al., 2015)

As an alternative to both highly concentrated mineral acids and weak organic acids, mildly acidic chloride-based solutions, such as $CaCl_2$ and NaCl, have been proposed for soil washing applications. Metal removal by these solutions may occur through ion-exchange reactions, in which Ca^{2+} or Na^{+} ions replace adsorbed metal ions such as Pb^{2+} and Cd^{2+}, as well as through the formation of soluble metal-chloride complexes. According to the literature, saline washing solutions, either alone or combined with mild acidification, can reduce dissolution of the soil matrix while preserving the physicochemical and microbiological properties of the treated soil at levels comparable to those of uncontaminated soils (Begum et al., 2016).

Chelating agents are generally regarded as a more environmentally compatible alternative to strong acids and saline washing solutions, owing to their ability to form strong and stable metal complexes while maintaining high extraction efficiencies (Lestan et al., 2008; Jiang et al., 2011). Their capacity to selectively mobilize heavy metals has led to their extensive investigation as soil-washing agents for contaminated soils.

— **Chelating Agents**

Chelating agents promote the desorption of heavy metals from soil particles through the formation of water-soluble metal complexes. These complexes are generally highly stable, reduce the likelihood of metal precipitation, and retain the associated metal ions over a broad range of environmental conditions. Their stability may decrease only under strongly acidic conditions, where complex dissociation can occur (Lestan et al., 2008).

A wide range of chelating agents, particularly aminopolycarboxylic acids, have been investigated as soil-washing agents because of their strong affinity for many toxic metals commonly found in contaminated soils. A comparison of the heavy-metal removal efficiencies reported in the literature for several chelating agents is presented in Figure 3.

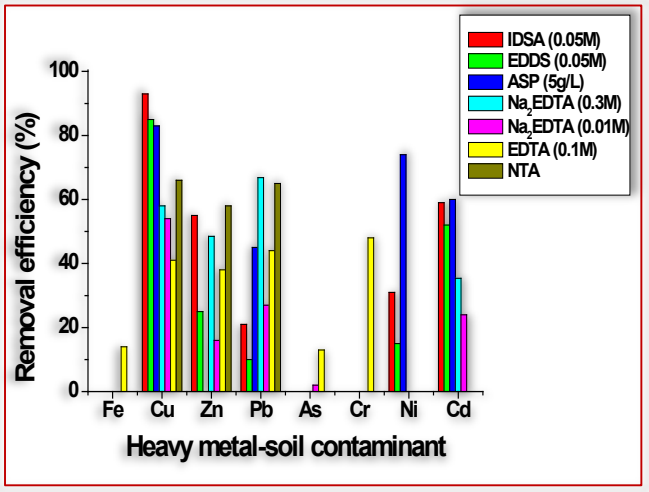

Figure 3. Comparison of heavy metal removal efficiencies from soil through washing with various chelating agents (compiled from data reported by Houser, 2003; Begum et al., 2012; Liu et al., 2015; Oudghiri et al., 2015; Qiu et al., 2010; Moutsatsou et al., 2006; Mohanty & Mahindrakar, 2011)

Among the chelating agents reported in the literature, Na_2EDTA (disodium ethylene-diamine-tetraacetate) is the most widely used for heavy-metal extraction because of its high efficiency, availability, and relatively low cost (Lestan et al., 2008). However, naturally occurring soil constituents may compete with heavy metals for complexation, increasing the amount of chelating agent required to achieve high removal efficiencies. For example, Pb removal efficiencies exceeding 95% have been reported when an EDTA:Pb ratio of 2:1 was applied (Elliot & Brown, 1989).

The large quantities of chelating agents often required during soil washing, together with the poor biodegradability of compounds such as EDTA, have stimulated interest in more environmentally friendly alternatives. Consequently, several biodegradable chelating agents, including nitrile-

triacetic acid (NTA), [S,S]-ethylene-diamine-disuccinic acid (EDDS), and imino-disuccinic acid (IDSA), have been evaluated as potential substitutes for EDTA in soil-washing applications (Begum et al., 2012).

In recent years, however, the use of NTA has become increasingly restricted because of concerns regarding its potential carcinogenicity (Jiang et al., 2011).

A more recent extraction agent, ASP (2-amino-3-sulfanylpropanoic acid, cysteine), was investigated for the remediation of soils contaminated by mining activities in the RuCheng area of China. The reported results demonstrated effective removal of Cu, Ni, Cd, and Pb, with extraction efficiency increasing as temperature increased. Under the investigated conditions, removal efficiencies exceeded 80% for Cu, 75% for Ni, 60% for Cd, and 45% for Pb (Liu et al., 2015).

Despite their effectiveness, several of the chelating agents investigated to date have been associated with environmental and health concerns related to toxicity, persistence, or potential carcinogenic effects (Jiang et al., 2011).

In response to these concerns, attention has increasingly shifted toward biodegradable and environmentally benign chelating agents such as chitosan. Although relatively few studies have investigated its application in soil washing, the available results are promising. Jiang et al. (2011) reported higher removal efficiencies for Cu and Ni when chitosan (0.2 g L^{-1} pH 3.2) was used compared with EDTA under identical experimental conditions.

Several criteria should be considered when selecting a chelating agent for the remediation of heavy metal-contaminated soils (Lestan et al., 2008; Begum et al., 2016). These include:

- the ability to form stable complexes with the target metals;
- selectivity toward the contaminants requiring removal;
- the potential for recovery and reuse after the washing process;
- low adsorption affinity of the formed complexes for soil particles;
- low toxicity and minimal environmental impact; and
- economic feasibility.

An effective chelating agent should therefore be capable of forming strong and stable metal complexes over a wide pH range while maintaining high selectivity for the target contaminants. The nature of the donor atoms present in the chelating molecule plays an important role in determining this selectivity. For example, chelating agents containing sulfur donor groups exhibit a strong affinity for transition metals such as Cu and Ni, as well as for Zn, Cd, Pb, and Hg ions.

Surfactants

Surfactants have also been investigated as washing agents for the remediation of heavy metal-contaminated soils. These compounds possess an asymmetric molecular structure, composed of two parts, one strongly polar (ionizable or non-ionizable) and the other non-polar or weakly polar (hydrocarbon-based). The polar part is hydrophilic, while the non-polar part is insoluble in water (hydrophobic). Depending on the nature of the hydrophilic group, surfactants may be classified as cationic, anionic, non-ionic, or amphoteric (Avram et al., 2004).

Numerous studies have evaluated the effectiveness of different surfactants for soil-washing applications. In general, surfactants are particularly effective in soils contaminated with organic pollutants and may therefore be especially suitable for sites affected by mixed organic-inorganic contamination. Heavy-metal removal is achieved primarily through ion-exchange and complexation mechanisms. Among the surfactants investigated, the cationic surfactant DPC, the non-ionic surfactant Ammonyx KP, and the anionic surfactant JBR-425 have been applied to heavy metal-contaminated soils, with JBR-425 exhibiting the highest removal efficiencies for Zn, Cu, Pb, and Cd (Begum et al., 2016).

Natural surfactants are often considered attractive alternatives to synthetic compounds because their complex molecular structures contain multiple functional groups capable of interacting with metal ions. Among the natural surfactants investigated for soil washing are rhamnolipids, saponins, and tannic acid. A comparison of the extraction efficiencies reported for saponin and tannic acid is presented in Figure 4.

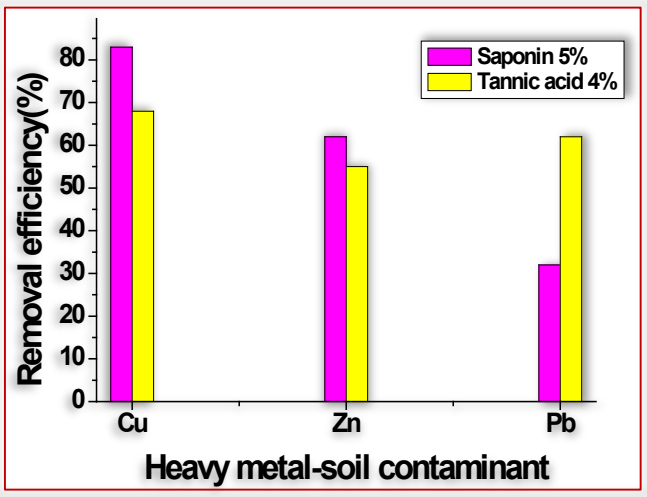

Figure 4. Comparison of copper, zinc and lead removal efficiencies from soil through washing with different surfactants (compiled from data reported by Gusiatin et al., 2014)

As observed for other categories of washing agents, the effectiveness of surfactants depends on both the target metal and the surfactant employed. According to the available literature, tannic acid

appears to be more effective for Pb removal, whereas saponin achieves higher extraction efficiencies for Cu and Zn.

Given that many conventional soil-washing agents are synthetic and may generate environmental concerns, increasing research efforts have been directed toward the development of natural and environmentally friendly alternatives capable of achieving comparable heavy-metal removal efficiencies.

Humic Substances

Humic substances are naturally occurring organic materials that are widely distributed in terrestrial and aquatic environments (Perminova & Hatfield, 2005). They are generally classified into three major fractions: humic acids, fulvic acids, and humin (Mohamed et al., 2010). Humic acids are insoluble under acidic conditions (pH < 2) but become soluble at higher pH values, whereas fulvic acids remain soluble throughout the entire pH range. In contrast, humin is insoluble regardless of pH (Perminova & Hatfield, 2005). Although their composition varies depending on their origin (*e.g.*, lignite, leonardite, plant composts, and sewage sludge), humic substances generally consist predominantly of carbon, oxygen, hydrogen, nitrogen, and minor quantities of other elements (Boguta & Sokołowska, 2013; White, 2013).

Humic substances can interact with a wide variety of environmental contaminants, including heavy metals, chlorinated compounds, petroleum hydrocarbons, pesticides, dyes, and actinides (Perminova & Hatfield, 2005). Their ability to influence metal mobility and bioavailability is primarily related to the presence of carboxylic, phenolic, and alcoholic functional groups, which participate in complexation and sorption processes (Boechat et al., 2016). Through these interactions, humic substances can significantly affect the transport, retention, and plant uptake of heavy metals in soils. Metal ions are retained mainly through the formation of stable complexes with the functional groups present in humic substances (Wit, 1992).

The extraction potential of humic substances has been demonstrated in several studies. For example, Soleimani et al. (2010) reported removal efficiencies of 44% for Cd, 53% for Cu, and 4% for Pb following ten successive soil-washing cycles using soluble humic acids at a concentration of 0.1 M.

The replacement of conventional synthetic washing agents with humic substances represents a promising strategy for sustainable soil remediation. In addition to their capacity to mobilize heavy metals, humic substances may contribute to improvements in soil structure and promote plant growth (Meng et al., 2017).

Unlike EDTA and NTA, humic acids are generally considered environmentally benign and do not present the same concerns regarding persistence, toxicity, or risks to human health (Soleimani et al., 2010). Furthermore, humic acids derived from *Leonardite* have been reported to increase the solubility of Cu, Zn, Ni, Cr, Cd, Pb, As, and Ba without causing significant reductions in soil pH (Boechat et al., 2016).

A comparison of the removal efficiencies achieved for Cd, Cu, and Pb using humic substances, NTA, and EDTA at a concentration of 0.05 M after a single extraction cycle is presented in Figure 5.

Although humic substances have demonstrated considerable potential for the extraction of heavy metals from contaminated soils and may represent viable alternatives to conventional chelating agents such as EDTA and NTA, their application in soil-washing remediation has received comparatively limited research attention. Nevertheless, the available studies consistently indicate that humic substances can effectively mobilize a wide range of heavy metals while offering important environmental advantages associated with their natural origin and biodegradability (Steponkaite et al., 2008; Soleimani et al., 2010; Borggaard et al., 2009, 2011; Shaker & Albishri, 2014; Kulikowska et al., 2015a,b; Boechat et al., 2016; Meng et al., 2017; Yang & Hodson, 2019; Wang et al., 2023; Piccolo et al., 2021; Meignant et al., 2025). Additional evidence supporting the applicability of humic substances as soil-washing agents has been provided by studies investigating the mobilization and removal of Pb, Cu, and Ni from multi-metal contaminated soils using humic substances extracted from *Leonardite* (Damian et al., 2018; Damian et al., 2019a, 2019b, 2019c, 2019d).

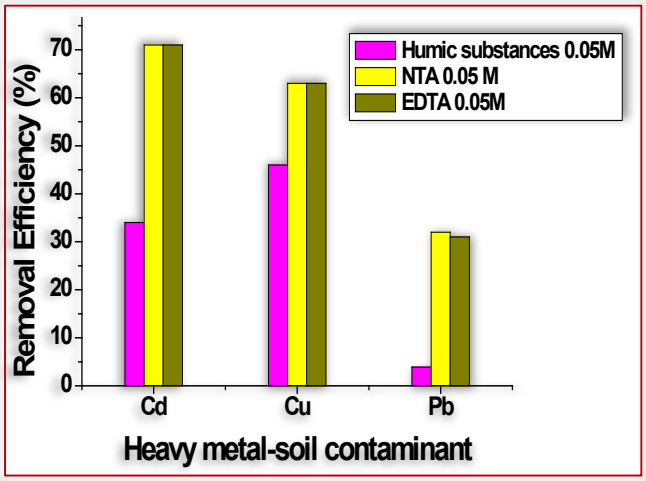

Figure 5. Comparison of copper, cadmium and lead removal efficiencies from soil through washing with humic substances, NTA and EDTA (concentration 0.05 M, single extraction, contact time 24 hours) (compiled from data reported by Soleimani et al., 2010)

Nevertheless, the extraction efficiency of humic substances may vary considerably depending on their origin, molecular composition, concentration

and the characteristics of the contaminated soil. In some cases, multiple extraction cycles may be required to achieve removal efficiencies comparable to those obtained with synthetic chelating agents.

Because each washing agent exhibits a specific affinity and extraction capacity for different heavy metals, selecting a single reagent capable of efficiently removing all contaminants present in a soil is often difficult. This challenge is particularly relevant because contaminated sites are rarely affected by a single metal and frequently contain complex mixtures of inorganic and organic pollutants.

Consequently, multi-stage or combined washing strategies may offer significant advantages. Sequential washing approaches, in which different extraction agents are applied successively, or combined washing systems employing mixtures of reagents, may improve overall remediation performance. For example, the use of a combined washing solution consisting of 0.2 M Na_2EDTA, 1.0 M citrate, 0.5 M oxalate, and 1% SDS (sodium dodecyl sulphate) resulted in removal efficiencies of 96% for Cr, 88.24% for Ni, 85% for Cd, and 82% for Mn (Olusegun & Oluwafemi, 2012).

It should be noted that the removal efficiencies presented throughout this review originate from independent studies performed under different experimental conditions, soil characteristics, contaminant concentrations, and operating parameters. Consequently, direct quantitative comparisons should be interpreted with caution and should be regarded primarily as an indication of the relative extraction potential of the investigated washing agents.

Other Operational Variables Influencing the Efficiency of the Soil Washing Process

In addition to the selection of the washing agent, the performance of soil washing is strongly influenced by several operational parameters, including solution pH, reagent concentration, application method, liquid-to-solid ratio, contact time, and washing technique (Lestan et al., 2008).

Contact time is one of the key parameters governing heavy-metal extraction during soil washing. Moutsatsou et al. (2006) investigated the effect of washing duration using HCl (1 M) and EDTA (0.1 M) as extraction agents and observed substantial differences among metals.

Maximum extraction efficiencies were achieved after 4 h for Zn, Cu, and Pb when HCl was used, whereas Fe and As required 8 hours, and Mn was extracted almost completely after only 2 hours. Similar variations were observed for EDTA-assisted washing. EDTA-assisted soil washing led to maximum extraction rates for Mn and Zn after 4 hours, for Pb and Cu after 2 hours, and for Fe after 8 hours, whereas, in the case of As, maximum removal efficiency was obtained after 24 hours. These results indicate that the optimum contact time is strongly dependent on both the target metal and the extraction agent employed.

The concentration of the washing solution is another critical factor influencing metal removal efficiency. According to Moutsatsou et al. (2006), most of the investigated metals were extracted most effectively when HCl concentrations approached 6 mol L^{-1}, although lower optimum concentrations were reported for specific contaminants such as As (2 mol L^{-1}) and Cu (3 mol L^{-1}). These findings highlight the importance of reagent concentration optimization for each contamination pattern.

Agitation intensity also affects the efficiency of the soil-washing process. Mohanty & Mahindrakar (2011) reported that increasing the mixing speed enhanced heavy-metal extraction, leading to improved removal efficiencies for both Pb and Cr. Thus, the Pb removal efficiency varied between 49.77% and 62.21% as the speed increased from 50 to 100 rpm, while the Cr removal efficiency varied from 34.47% to 39.21% as the speed increased from 50 to 150 rpm. However, the beneficial effect was observed only up to a threshold value, beyond which further increases in agitation intensity did not result in significant improvements in metal removal.

Temperature is another operational variable that may significantly influence extraction kinetics and metal removal efficiency, although its effect varies depending on the metal and washing agent employed. For example, Liu et al. (2015) observed increasing removal efficiencies with increasing temperature when cysteine (ASP) was used as the extraction agent under controlled experimental conditions (ASP concentration: 2 g L^{-1}; pH: 7.5; contact time: 48 hours).

Solution pH is one of the most influential parameters governing heavy-metal extraction during soil washing because it affects metal speciation, solubility, adsorption-desorption equilibria, the stability of metal complexes, and ultimately metal retention within the soil matrix. Under acidic conditions, increased concentrations of hydrogen ions compete with metal cations for sorption sites, thereby promoting metal desorption and enhancing their transfer into the washing solution. Consequently, lower pH values generally result in higher extraction efficiencies, although excessively acidic conditions may increase reagent consumption, accelerate equipment corrosion, and adversely affect soil properties (Lestan et al., 2008; Begum et al., 2016). Numerous studies have confirmed the importance of pH in controlling metal removal efficiency, although the observed trends depend strongly on the washing agent employed. Zhan et al. (2012) reported that metal

extraction efficiency generally decreases with increasing pH. However, Jiang et al. (2011) observed that Cu removal using saponin was largely independent of pH, whereas the extraction efficiency of chitosan decreased as solution pH increased. In contrast, Moutsatsou et al. (2006) found that the removal efficiencies of Cd and As increased at pH values above 10, while the extraction efficiencies of Cu, Pb, and Zn decreased when EDTA was used as the washing solution. Similarly, Karthika et al. (2016) reported that, at a pH of 13 of Na_2EDTA solution, 40.6% of As and 41.1% of Cd were removed, whereas Pb and Zn removal was almost negligible. The same study showed that Pb removal exhibited little dependence on pH within the range of 5–9 and identified pH 4 as the optimum value for Na_2EDTA-assisted extraction.

The liquid-to-solid ratio is another important operational parameter because it determines the amount of washing solution available for contaminant mobilization. Increasing the volume of extraction solution generally enhances contact between the reagent and contaminated soil particles, thereby improving metal removal. An increase in the liquid-to-solid ratio from 5 to 20 when chitosan was used as the washing agent for heavy metal-contaminated soil led to an improved removal efficiency from 26.34% to 47.22%, and from 41.75% to 66.13% in the case of copper and nickel, respectively (Jiang et al., 2011). However, excessively high liquid-to-solid ratios increase reagent consumption and generate larger volumes of wastewater requiring subsequent treatment. Therefore, the optimum ratio should be selected by balancing extraction efficiency against operational and environmental costs.

DISCUSSION

The literature reviewed in this study clearly demonstrates that the effectiveness of soil washing cannot be attributed to a single factor. Instead, remediation performance results from the interaction between soil characteristics, contaminant properties, washing-agent chemistry, and operational conditions. Consequently, the selection of an appropriate remediation strategy requires a site-specific evaluation of all these parameters rather than the application of a universal treatment approach.

A critical comparison of the washing agents reviewed in this study indicates that remediation performance must be evaluated together with environmental sustainability and potential impacts on soil quality. Strong mineral acids generally provide the highest extraction efficiencies and are capable of mobilizing a broad range of heavy metals from contaminated soils. Their practical application is often limited by adverse effects on soil physicochemical properties, equipment corrosion, and the generation of acidic effluents requiring further treatment.

Comparison among studies remains difficult because experimental conditions, soil characteristics and contamination levels differ substantially. Consequently, removal efficiencies reported in the literature cannot always be directly compared.

Chelating agents, particularly EDTA-based systems, offer high extraction efficiencies and are especially suitable for soils contaminated with multiple metals. Nevertheless, concerns regarding the persistence and limited biodegradability of some synthetic chelants have encouraged the development of more environmentally compatible alternatives. Surfactants constitute a valuable option for soils co-contaminated with organic and inorganic pollutants, although their effectiveness may depend strongly on soil characteristics and may require additional recovery or wastewater-treatment steps.

Among the alternative washing agents reviewed, humic substances appear particularly promising because they combine metal-complexation capacity with low toxicity, biodegradability, and the potential to preserve or even improve soil quality after treatment. Although their extraction efficiencies do not always match those achieved by strong acids or synthetic chelating agents, they may provide a more favourable balance between remediation effectiveness and environmental sustainability. Consequently, the selection of a washing agent should not be based solely on metal-removal efficiency but should also consider long-term soil quality, environmental risks, reagent consumption, wastewater generation, and overall treatment costs.

To facilitate a general comparison among the main categories of washing agents discussed in this review, Table X summarizes their relative performance with respect to extraction efficiency, environmental impact, cost, and major practical limitations. The comparison is intended to provide a qualitative overview based on the literature reviewed and should not be interpreted as a direct quantitative ranking, since the reported performances depend strongly on soil properties, contaminant characteristics, and operating conditions.

The comparison presented in Table 2 highlights the trade-off between extraction efficiency and environmental sustainability. While strong mineral acids generally provide the highest metal removal efficiencies, they may adversely affect soil quality and generate secondary environmental impacts. Conversely, humic substances and biodegradable chelating agents offer more environmentally sustainable alternatives, although their performance may be more variable and site-

specific. Therefore, the optimal washing agent should be selected based on both remediation objectives and long-term environmental considerations.

Table 2. Qualitative comparison of the main washing agents used for remediation of heavy metal–contaminated soils

Washing agent	Typical extraction efficiency	Environmental impact	Relative cost	Main limitation
Strong mineral acids (e.g., HCl, H_2SO_4)	Very high	High	Low–Moderate	Soil degradation, corrosion, acidic wastewater generation
EDTA	High	Moderate–High	Moderate	Poor biodegradability and environmental persistence
Biodegradable chelating agents (e.g., EDDS)	High	Low	High	Higher reagent cost
Surfactants	Moderate	Moderate	Moderate	Strong dependence on soil characteristics and contaminant type
Humic substances	Moderate–High	Low	Moderate	Variable composition and extraction performance

Furthermore, the operational parameters of the process (pH, concentration, contact time, agitation speed, temperature, and the liquid-to-solid ratio) interact with the choice of washing agent in metal- and soil-specific ways, meaning that the optimal operating window for one metal-soil-agent combination cannot generally be extrapolated to another. This is particularly relevant when, as is most often the case in real contaminated sites, several heavy metals co-occur, requiring either a compromise single-step washing solution or a more complex sequential/combined washing strategy.

Future research should increasingly focus on the development of environmentally sustainable washing agents capable of combining high extraction efficiency with low environmental impact. Particular attention should be directed toward biodegradable chelating agents, natural surfactants, humic substances, and combined extraction systems that exploit the complementary advantages of different reagents. In addition, more studies conducted under comparable experimental conditions are needed to facilitate direct performance comparisons among washing agents. The integration of soil washing with other remediation technologies, including stabilization, phytoremediation, and electrokinetic treatment, may also offer promising opportunities for improving remediation efficiency while minimizing adverse impacts on soil quality.

The reviewed studies collectively demonstrate that successful soil-washing remediation depends on balancing extraction efficiency, environmental sustainability, and soil-quality preservation. Differences in contaminant composition, soil properties, and treatment objectives require the careful adaptation of washing strategies to site-specific conditions. In this context, combined extraction systems and environmentally sustainable washing agents appear to represent particularly promising directions for future research and practical implementation.

The present review is based on published studies conducted under highly variable experimental conditions. Differences in soil properties, contamination levels, washing protocols and performance indicators limit direct quantitative comparisons among studies. Therefore, the conclusions should be interpreted primarily as general trends rather than universally applicable performance estimates.

CONCLUSIONS

The efficiency of soil washing for the remediation of heavy metal-contaminated soils is governed by a complex interaction between soil properties, contaminant characteristics, washing-agent chemistry, and operational conditions.

Among the factors influencing remediation performance, soil texture, organic matter content, contaminant speciation, washing-agent type, solution concentration, pH, contact time, agitation intensity, temperature, and liquid-to-solid ratio play particularly important roles.

Strong mineral acids generally provide the highest extraction efficiencies; however, their application may adversely affect soil quality and increase environmental risks. Chelating agents offer an effective alternative, although concerns remain regarding the persistence and biodegradability of certain compounds.

Humic substances have emerged as promising environmentally friendly washing agents due to their ability to mobilize heavy metals while minimizing the environmental concerns associated with conventional synthetic extractants. Although additional research is required to fully evaluate their large-scale applicability, the available evidence highlights their potential for sustainable soil remediation.

The successful implementation of soil washing requires the optimization of both the extraction agent and the operational parameters according to site-specific conditions. Future advances in the

field are likely to rely on the development of environmentally sustainable washing agents and integrated remediation strategies capable of achieving high extraction efficiencies while preserving soil quality.

The future of soil washing is likely to depend on the development of environmentally sustainable extraction agents and integrated remediation systems capable of balancing contaminant removal efficiency with long-term soil quality preservation.

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