

Article

Optimization of a High-Pressure Soil Washing System for Emergency Recovery of Heavy Metal-Contaminated Soil

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Abstract: Recent natural disasters, such as typhoons in South Korea and other countries around the globe, have resulted in loss of human life and damage to property, often causing contamination of nearby soil environments. This study focused on the emergency recovery of soil contaminated by heavy metals following a disaster such as typhoon flooding by applying a soil washing technique that used high-pressure water rather than chemical cleaning agents. Artificially contaminated soil containing 700 mg/kg Cu, 530 mg/kg Pb and 900 mg/kg Zn, was used. All three metals were present at levels higher than the Korean Warning Standards (500 mg/kg Cu, 400 mg/kg Pb, 600 mg/kg Zn) for region 2 (miscellaneous area). A high-pressure soil washing device was designed to treat 0.6 tons/h and optimal treatment was sought for varying levels of pressure (1, 3, 5 MPa), solid to liquid ratios (S/L) (1:1, 1:3, 1:5), and number of washing cycles (1, 2, 3). The high-pressure soil washing results showed that a 5 MPa washing pressure, 1:1 solid-liquid ratio, and one washing cycle were the optimum conditions to generate the highest heavy metal removal rates. Under optimal conditions, high-pressure soil washing attained removal efficiencies of Cu (37.7%), Pb (36.6%), and Zn (45.1%), and the residual concentrations of heavy metals in the remediated soil satisfied the Korean Warning Standard (Region 2). A comparison of the changes in particle size showed that after high-pressure washing, the mass fraction of coarse sand (CS, 2–0.42 mm) decreased by 23.3%, while that of fine sand (FS, 0.42–0.074 mm), silt, and clay (SC, <0.074 mm) increased by 4.2% and 19.1%, respectively. In addition, 31.1–34.6% of the CS heavy metal mass loading shifted to FS and SC fractions after washing. A comparative analysis of the soil surface morphology before and after washing using scanning electron microscopy (SEM) showed that the particles in the remediated soil became noticeably cleaner after high-pressure washing. This study demonstrated the feasibility of emergency recovery of heavy metal-contaminated soil using high-pressure washing without a chemical cleaning agent.



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Keywords: high-pressure soil washing; physical soil washing; physical separation; heavy metal; emergency recovery

1. Introduction

Soil environments are often contaminated by accidental wastewater spills resulting from natural disasters or accidents worldwide [1–3]. Recently, in the Republic of Korea, the occurrence of many typhoons has caused heavy flooding. Once introduced into soils, heavy metals cannot be biodegraded, and may transform to stable forms through a long period of weathering or cause secondary contamination, such as groundwater and air pollution [4,5]. Therefore, spill cleanup and remediation are crucial, especially when heavy metal contamination is a risk. Various remediation technologies have been applied for recovering heavy metal-contaminated soil, including soil washing, solidification/stabilization, electrokinetics, and phytoremediation [6–11]. Among these various alternatives, the soil washing process has been applied successfully in many heavy metal-contaminated soil remediation sites. The process is a well-established technology known for its ability to

permanently remove contaminants at high efficiency in comparatively short remediation times [12]. Soil washing is a representative ex-situ method that uses a cleaning agent to remove contaminants bound to the soil. Depending on the removal method, it can be divided into physical separation (PS) and chemical extraction (CE) [12]. In particular, chemical extraction methods use inorganic agents (e.g., inorganic acids, inorganic salts) or organic chelating agents (e.g., EDTA, citric acid, oxalic acid) to remove heavy metals at high efficiency [13]. However, when used at high concentrations, these chemical agents acidify the soil and may destroy the clay structure. Additionally, concerns arise when cleaning agents (e.g., EDTA) remain in the soil and contaminate groundwater due to low biodegradability [13,14]. The high costs of cleaning agents, the need for post-treatment of washing wastewater streams, as well as greenhouse gas emissions generated during this process, add to the environmental footprint of chemical extraction, posing sustainability concerns for this soil washing method [15]. Obviously, chemical agents may be unavoidable in cleaning chronically contaminated soil. However, for relatively short periods of exposure to contamination such as those linked to natural disasters or accidents, physical washing and separation may be applicable instead of burdensome chemical extraction methods. Therefore, this study considered a high-pressure soil washing technology to remediate short-term contaminated soil. A high-pressure soil washing technique is a physical washing method that uses cavitation flow to promote attrition between soil particles and to separate contaminants bound to the soil into concentrated fine particles and liquid phases [16,17]. The objective of this study was to demonstrate the feasibility of a high-pressure soil washing system for short-term recovery of heavy metals (Cu, Pb and Zn) from contaminated soil. The reason for the selection of Cu, Pb and Zn is because these heavy metals are frequently found in wastewater treatment plant process streams. The optimization of a high-pressure soil washing system was evaluated at various pressures, solid to liquid (S/L) ratios and number of cycles. Following the optimization process, optimal conditions for the high-pressure washing device were determined, removal efficiency was confirmed, and changes in heavy metal mass loading through the process were evaluated. The surfaces of the soil particles before and after soil washing were compared using scanning electron microscopy (SEM). Residual heavy metal concentrations in the treated soil were compared against the Korean Warning Standards (Region 2, miscellaneous area) of 500 mg/kg (Cu), 400 mg/kg (Pb), and 600 mg/kg (Zn).

2. Experimental Methodology

2.1. Soil Collection and Analysis Process

Soil samples were collected from topsoil (0–15 cm) according to soil contamination process test standards at Chosun University. The initial heavy metal concentrations in the soil were 5, 11, and 74 mg/kg for Cu, Pb, and Zn, respectively, which were lower than the Soil Contamination Warning Standards (Region 2) (Ministry of Environment, 2020). This uncontaminated soil was air-dried, passed through a #10 mesh (2.00 mm) sieve, and then contaminated with an aqueous solution made from $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$, $\text{Pb}(\text{NO}_3)_2$, $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (EP, DAEJUNG, Siheung-si, Republic of Korea). Once the soil was spiked with the contaminants of choice, the contaminated soil was left to mellow for 5 days in order to achieve equilibrium. After that, the Aqua Regia digestion technique using nitric and hydrochloric acid at a 1:3 ratio was applied according to the soil contamination process test standards [18]. The final heavy metal concentrations were 700, 530, and 900 mg/kg for Cu, Pb, and Zn, respectively. These concentrations were selected in accordance with sponsor's (Korea Environment Industry and Technology Institute (KEITI) request. In accordance with a previous study, the soil and the heavy metal solution was adsorption equilibrated over 5 days and then naturally dried for at least 48 h to create soil samples contaminated with Cu, Pb, and Zn [19].

2.2. Physicochemical Analyses

To analyze the physicochemical properties of the soil samples, a soil to water weight ratio of 1:5 was used for pH according to the soil contamination process test standards [20]. Organic matter content was measured using a loss on ignition measurement technique [21]. For soil texture, the pipette method [22] was used to determine sand, silt, and clay content, after which the soil texture was determined according to the soil classification triangle of the US Department of Agriculture standards (USDA). To measure the concentration of heavy metals in the soil, the Aqua Regia digestion technique using nitric and hydrochloric acid at a 1:3 ratio was applied according to the soil contamination process test standards [18]. Inductively coupled plasma-optical emission spectrometry (ICP-OES) (Perkin Elmer Optima Model 5300DV, Waltham, MA, USA) was used to analyze the concentration of heavy metals. All the sample analyses were conducted in triplicate and the average values were reported within an error range of 10%. For QA/QC purposes, three different quality control standards were used for every ten samples.

2.3. Scanning Electron Microscopy (SEM) Analyses

Scanning electron microscopy (SEM) analysis was conducted to observe the surface of the soil in detail after each washing process. All samples were fixed to a plate using double-sided carbon tape, coated with platinum, and then analyzed. Field emission scanning electron microscopy (FE-SEM) (HITACHI S-4800, Tokyo, Japan) was used to compare the surface morphology of the soil samples before washing, after washing once, and after washing three times.

2.4. X-ray Powder Diffraction (XRPD) Analysis

X-ray powder diffraction (XRPD) analysis was performed to investigate the mineral phases in the artificially contaminated soil. The XRPD sample preparation was made by pulverizing the sample into a particle size less than 0.075 mm. The XRPD pattern was collected by an X-ray diffractometer (XRD) (X'Pert PRO MPD, PANalytical, Almelo, The Netherlands) equipped with a diffracted beam graphite monochromator with Cu radiation at 40 kV and 40 mA. The XRPD pattern was attained in the 2θ range of 5–65°, step size of 0.02°, and count time of 3 s/step. XRPD patterns were interpreted using the Jade software v. 7.1 [23] and the PDF-2 reference database [24]. As a result of XRPD pattern interpretation, the major phases identified in the artificially contaminated soil were quartz (PDF# 46-1045), microcline (PDF# 19-0932), albite (PDF# 10-0393) and calcite (PDF# 43-0697).

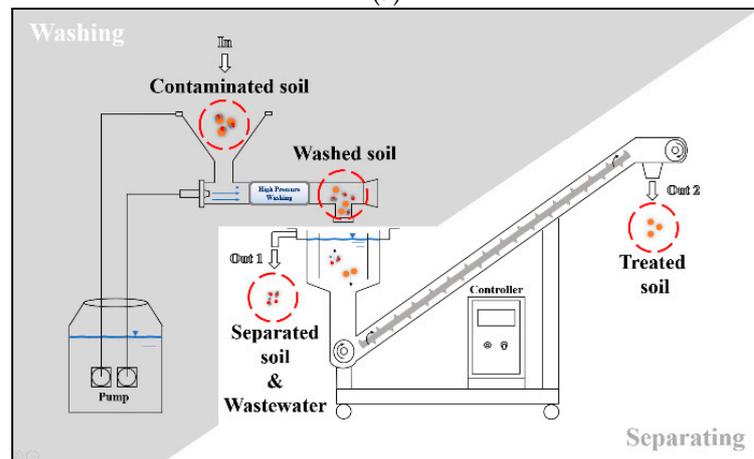
2.5. The High-Pressure Soil Washing Ejector and Solid-Liquid Separator

Figure 1a,b show the front view and a schematic diagram of the high-pressure soil washing device used in this study. In principal, the high-pressure soil washing technique disperses soil aggregates through cavitation flow. The washing device used in this study was designed to treat 0.6 tons/h in accordance with sponsor's (KEITI) request. The device consisted of two parts: a high-pressure washing unit and a solid-liquid separation unit (Figure 1b). Contaminated soil injected into the hopper descended with water supplied from the top and was then mixed with high-pressure water sprayed through a venturi nozzle connected to the left side of the washing pipe. When the high-pressure water was sprayed, the liquid passed through the venturi's nozzle and the pressure dropped due to the structure, producing cavitation [17]. This generated cavitation bubbles, subsequently collapsing, created shockwaves that caused cracks in the soil particles. This led to capillary action that aided the cleaning solution to penetrate further into the particles [25]. Thus, the high-pressure washing device sprayed high-pressure water onto the contaminated soil to disintegrate the soil aggregates into smaller particles and maximized the disintegration effect with cavitation bubbles [16,25]. Soil particles were separated by a solid-liquid separator after high-pressure washing (Figure 1b). Depending on the density of the soil particles, the light, fine soil floated with the washing wastewater and was discharged to Out1, while the heavy coarse soil was deposited into the solid-liquid separator and

discharged to Out2 via a deposited grit screw-conveyor (Figure 1b). Here, only the coarse soil in the device was separated by setting the control unit to 40–50 rpm.



(a)



(b)

Figure 1. (a) High-pressure washing machine (0.6 ton/h); and (b) schematic diagram of high-pressure washing machine.

2.6. High-Pressure Soil Washing Optimization

In the soil washing process, the influencing factors related to washing conditions are the leachate type, concentration, pH, contact time, and solid-to-liquid (S/L) ratio [13]. The high-pressure washing device used tap water for the washing solvent, and pressure, S/L ratio, and the number of washing cycles were considered as influencing factors. To determine the optimal pressure, pressures of 1, 3, and 5 MPa were applied based on the capacity of the high-pressure pump to wash the contaminated soil, after which the concentrations of the washed soil were compared. To determine the optimal input S/L ratio, the soil was washed at three S/L ratios: 1:1 (the minimum S/L ratio without clogging), and 1:3 and 1:5 in consideration of the amount of wastewater generated after washing. The residual heavy metal concentrations in the soil were then compared. Finally, to determine the optimal number of washing cycles, high-pressure washing was performed one, two, or three times, and the change in heavy metal concentrations in the soil for each number of washing cycles was compared.

2.7. Particle Size Fraction and Heavy Metal Mass Loading Analyses

To investigate how the heavy metal contamination load in the soil changed as a result of the washing process, the soil was classified into four types: contaminated, washed,

treated, and separated soil (Figure 1b). Heavy metal mass loading was analyzed for each particle size fraction and soil type (Figure 1b). Mass loading was calculated by multiplying the heavy metal concentration by the mass of the soil (or wastewater). The particle size fractions were classified into three levels: coarse sand (CS, 2–0.42 mm), fine sand (FS, 0.42–0.074 mm), and silt and clay (SC, <0.074 mm), according to the American Association of State Highway and Transportation Officials classification system (AASHTO), and the mass ratio for each particle size fraction was compared.

3. Results and Discussion

3.1. Characterization of Contaminated Soil

Table 1 shows the soil properties used in the experiment. An artificially contaminated soil sample created by adsorption equilibration of soil and heavy metal solutions was used as the sample. The artificially contaminated soil was classified as sandy loam (Table 1 and Figure 2). Based on the results of the contaminated soil concentrations using the Aqua Regia extraction technique [18], all samples exceeded the Soil Contamination Warning Standard (Region 2) and were thus targets for recovery.

Table 1. Soil characterization results.

Soil Properties	Contaminated Soil	Korean Warning Standards (Region 2) ¹
Soil pH	5.03	
Cation exchange capacity (cmol _c /kg)	14.17	
Organic matter content (%) ²	8.01	
Composition (%) ³		
Sand	63.05	
Silt	32.11	
Clay	4.84	
Texture ⁴	Sandy loam	
Heavy metals (mg·kg ⁻¹)		
Cu	700 ± 36	500
Pb	530 ± 10	400
Zn	900 ± 56	600
Major mineral phases ⁵	Quartz, Microcline Albite, Calcite	

¹ Korean warning standards for soils in region 2, ² Organic matter content (%) was calculated from measured loss-on-ignition (LOI), ³ Soil classification based on particle size analysis (PSA); Sand, 20–2000 µm; silt, 2–20 µm; clay, <2 µm, ⁴ Soil texture based on the United States Department of Agriculture (USDA), ⁵ Mineral phases obtained by the Jade software [23].

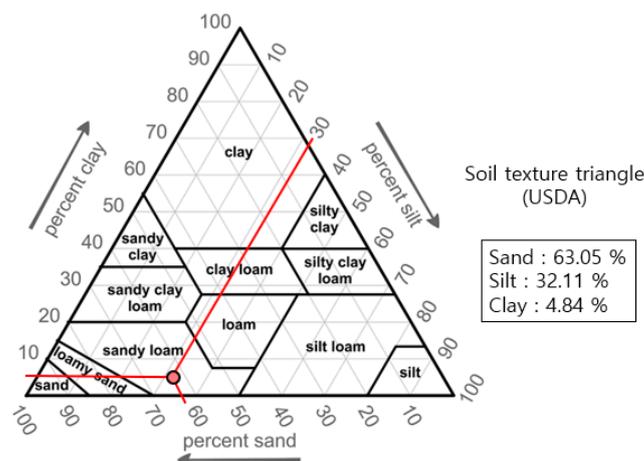


Figure 2. Soil texture triangle (USDA).

3.2. Optimal Washing Pressure

Figures 3–5 show the residual contamination of the soil and removal efficiency after washing at pressures of 1, 3, and 5 MPa based on the applicable pressure range of the high-pressure pump. The highest metal removal efficiency was obtained after washing at 5 MPa, with 44%, 35.9%, and 45.4% removal of Cu, Pb, and Zn, respectively (Figures 3–5). For all three metals (Cu, Pb, Zn), the removal efficiency tended to improve with pressure, as more metals and organic matter bound to the surface of the soil particles were removed by mechanical friction [16]. According to Kim et al. [17], pressure and cavitation intensity are inversely proportional; the difference in cavitation at 3 MPa and 5 MPa was very small because there was a small difference between the flow rates at 3 MPa (2.6 L/min) and 5 MPa (3.0 L/min). Accordingly, this study selected 5 MPa as the optimal pressure, which showed a cavitation effect similar to 3 MPa, with the highest removal efficiency.

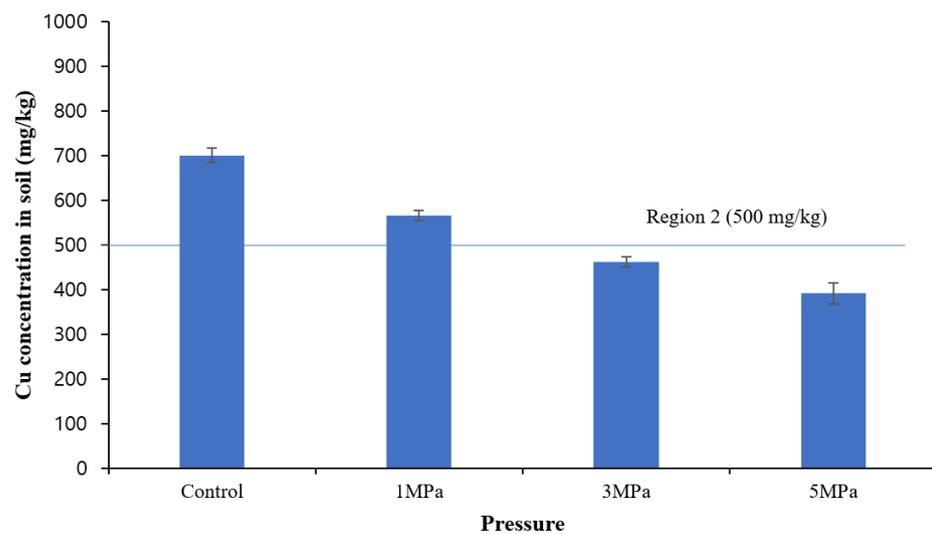


Figure 3. Cu concentrations remaining in the soil after high-pressure washing at 1, 3 and 5 MPa.

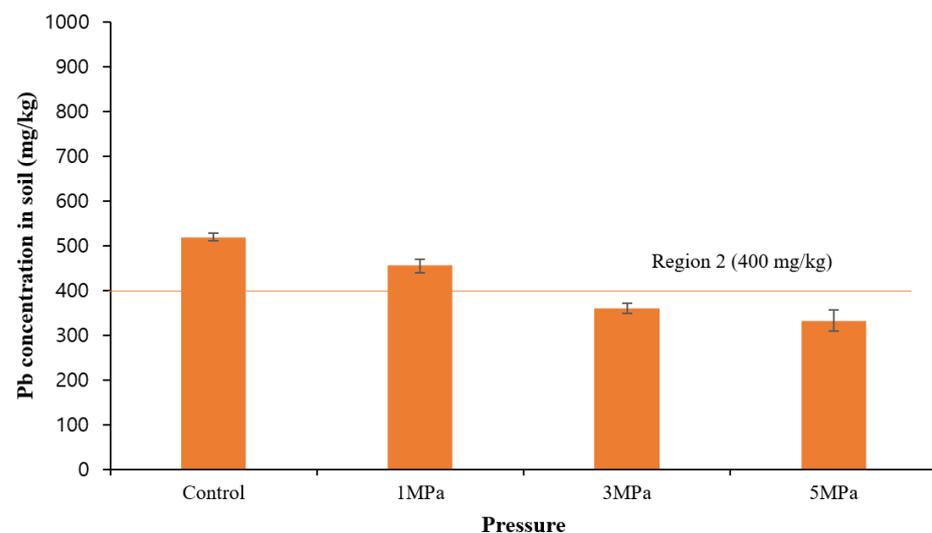


Figure 4. Pb concentrations remaining in the soil after high-pressure washing at 1, 3 and 5 MPa.

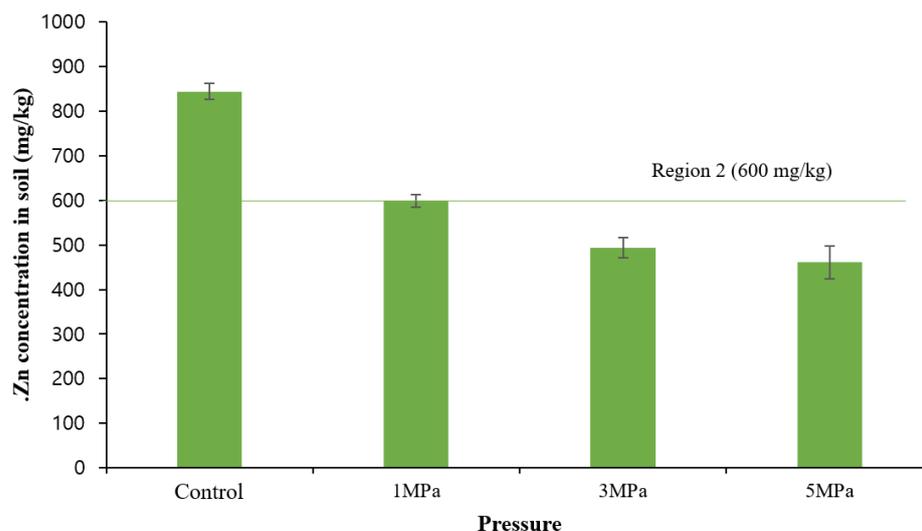


Figure 5. Zn concentrations remaining in the soil after high-pressure washing at 1, 3 and 5 MPa.

3.3. Optimal Solid-to-Liquid Ratio

To determine the optimal input S/L ratio, the pressure was fixed at 5 MPa and S/L ratios of 1:1, 1:3, and 1:5 were applied, and the removal efficiencies were compared (Figures 6–8). The highest removal efficiency, recorded at a S/L ratio of 1:1, corresponded to 37.7%, 36.6% and 45.1% in Cu, Pb, and Zn, respectively. The removal efficiency increased as the S/L input ratio increased. In soil washing, contact between the cleaning agent and soil particles declines as the S/L ratio increases, thus reducing the removal efficiency. It has been reported that suitable S/L ratios range from 1:5 to 10 [13]. However, Feng et al. [26] reported that in attrition washing for diesel-contaminated soil, when the solid concentration was increased from 70% to 80%, effective scrubbing was achieved due to particle friction, and the residual diesel concentration sharply decreased. Even in a high-pressure attrition washing process, applying a low S/L ratio may reduce the opportunities for particles to contact and hence decrease the removal efficiency. Since the amount of treated wastewater increases at lower S/L ratios, a suitable S/L ratio must also be considered from an economic perspective [13]. When a S/L ratio of 1:0.5 was applied, the contaminated soil could not pass through the washing device and clogging occurred in the pipe. This is likely because the slurry was too dense [26]. Accordingly, this study selected 1:1 as the optimal S/L ratio, which caused no clogging in the pipe and produced relatively little secondary wastewater.

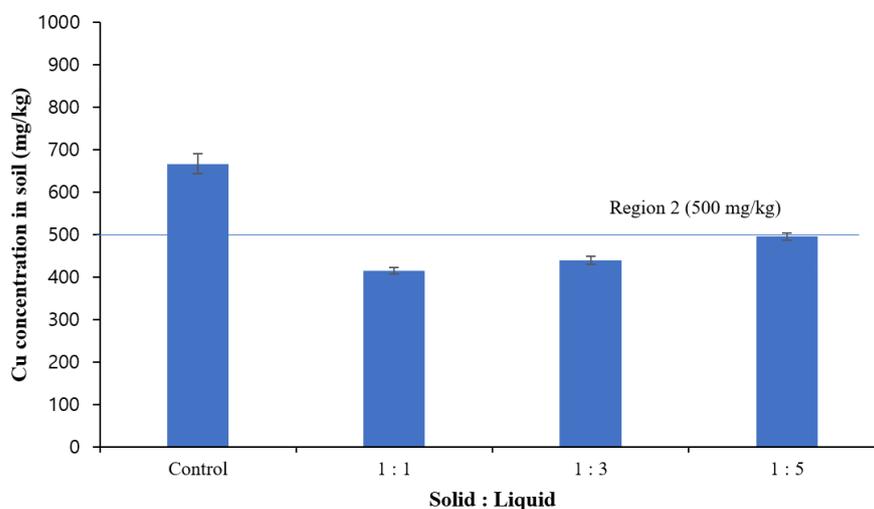


Figure 6. Cu concentrations remaining in the soil using a solid-liquid ratio of 1:1, 1:3 and 1:5 for the washing of soil.

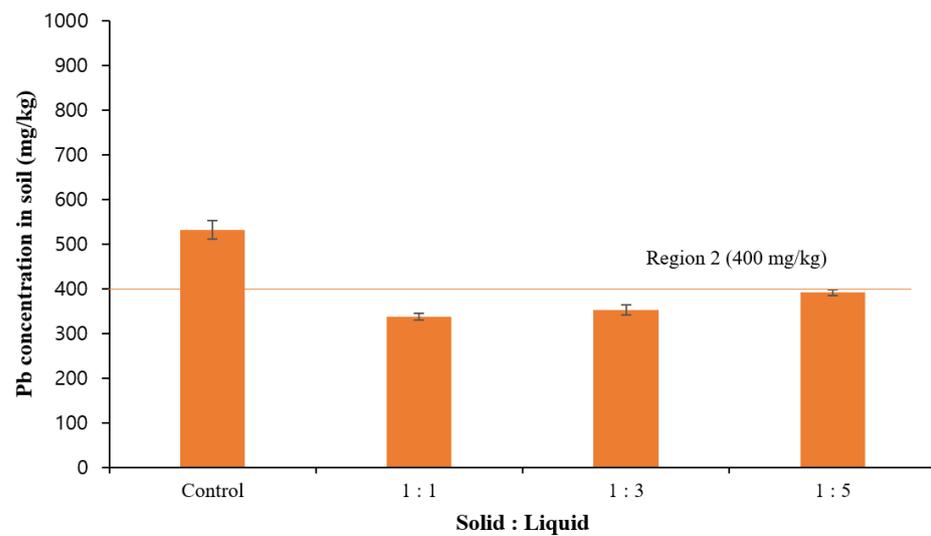


Figure 7. Pb concentrations remaining in the soil using a solid-liquid ratio of 1:1, 1:3 and 1:5 for the washing of soil.

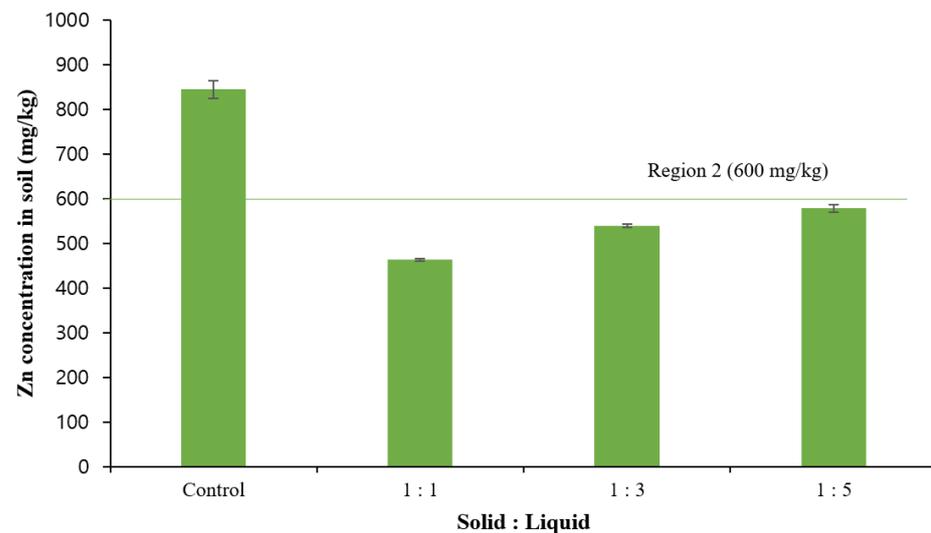


Figure 8. Zn concentrations remaining in the soil using a solid-liquid ratio of 1:1, 1:3 and 1:5 for the washing of soil.

3.4. Optimal Number of High-Pressure Washing Cycles

To determine the optimal number of washing cycles, washing was performed one, two, and three times under optimal pressure and S/L ratio conditions determined in the previous experiments (5 MPa, 1:1), and the resulting changes in concentration are shown in Figures 9–11. After one washing cycle, the Cu, Pb, and Zn concentrations in the remediated soil were 423 mg/kg, 340 mg/kg, and 573 mg/kg, respectively, which satisfied the Soil Contamination Warning Standards (Region 2). The removal efficiency increased with each successive washing cycles, to a maximum of 55.2% (Cu), 47.6% (Pb), and 52.3% (Zn) after the third washing. However, there were no substantial differences in removal efficiency in the remediated soil between second and third washing cycles, as the largest difference was less than 3.8% (Pb). Li et al. [27] reported that when soil contaminated with As, Cd, Pb, and Zn was washed three times with a pH 2 cleaning agent, the removal efficiency increased by 11.2 to 36.2% compared to one washing cycle and that the extracted amount decreased with each washing cycle, which could be attributed to the reduction in exchangeable metals and oxide-bound metals. Furthermore, Gusiatin and Klimiuk [4] demonstrated that after two to three repeated washing cycles with saponin in soil contaminated with Cu, Cd, and Zn,

the fraction related to the mobility of heavy metals decreased and the more stable form increased. However, since it is challenging to perform repeated washing cycles on site, it is preferable to select the minimum number of washing cycles within a range that meets the contamination standard. Accordingly, one washing cycle was selected as the optimal number for the contaminated soil used in this experiment.

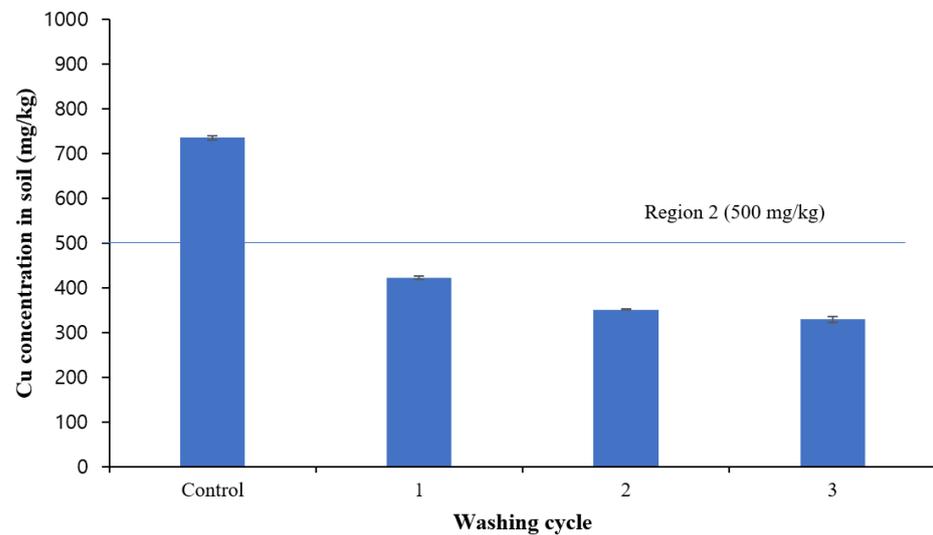


Figure 9. Cu concentrations remaining in the soil after 1, 2 and 3 high-pressure washing cycles.

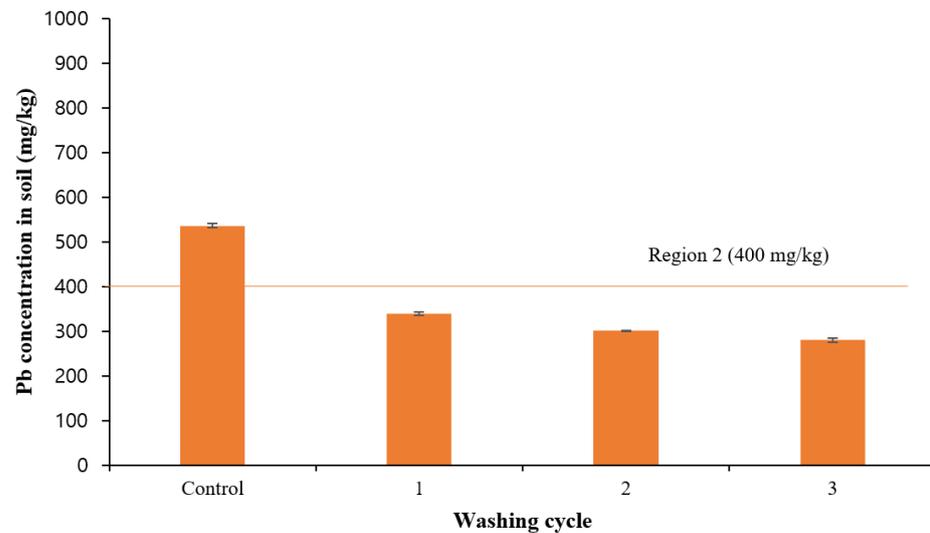


Figure 10. Pb concentrations remaining in the soil after 1, 2 and 3 high-pressure washing cycles.

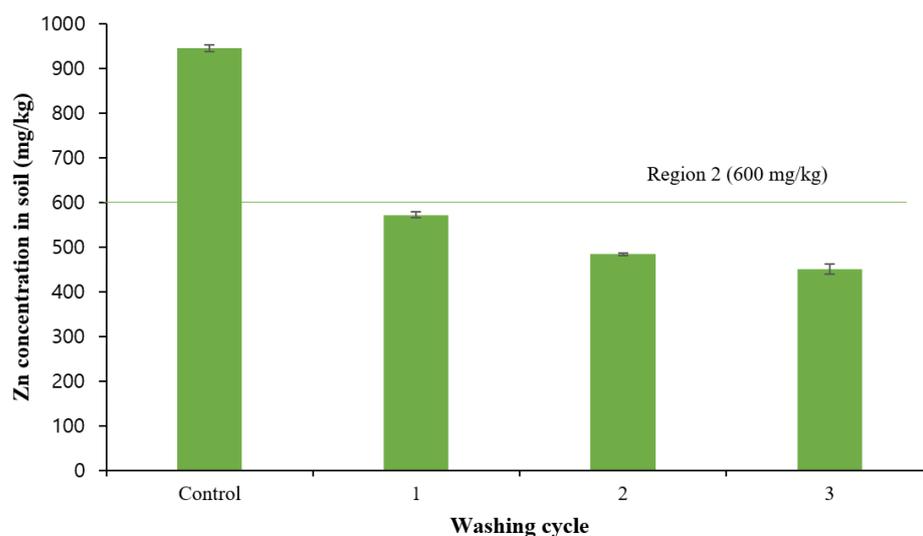


Figure 11. Zn concentrations remaining in the soil after 1, 2 and 3 high-pressure washing cycles.

3.5. Change in Particle Size Fraction during High-Pressure Washing and Separation

The treated soil was classified into contaminated, washed, treated, and separated soil, and the mass ratios based on particle size were compared (Table 2). For the contaminated soil and washed soil, the CS fraction decreased by 23.3% while the FS and SC fractions increased by 4.2% and 19.1%, respectively. This was attributed to the physical friction caused by the high-pressure water and the increase in fine soil due to wet separation [16,28]. The washed soil was separated into treated soil and separated soil by the difference in density. The treated soil (CS > FS > SC) and separated soil (SC > FS > CS) showed opposite particle size distribution trends, a phenomenon expected to affect the heavy metal concentration distribution.

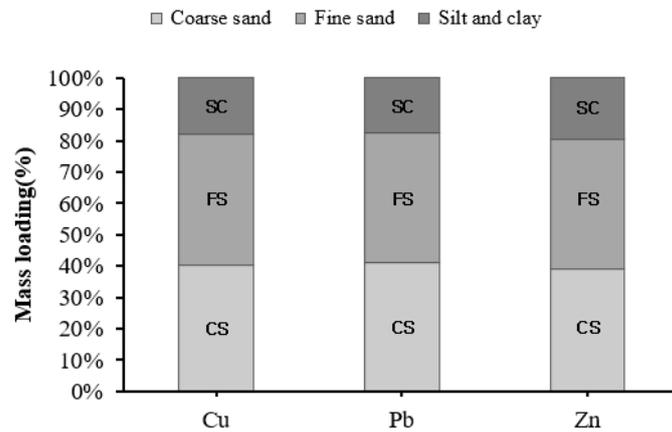
Table 2. Change in soil particle size fractions during the washing process.

Particle Size (mm)	Contaminated Soil (%)	Washed Soil (%)	Treated Soil (%)	Separated Soil (%)
Coarse sand, CS (2–0.42)	55.4	32.1	54.3	2.7
Fine sand, FS (0.42–0.074)	33.3	37.5	44.2	36.0
Silt and clay, SC (<0.074)	11.3	30.4	1.5	61.3
Total weight (%)	100	100	100	100

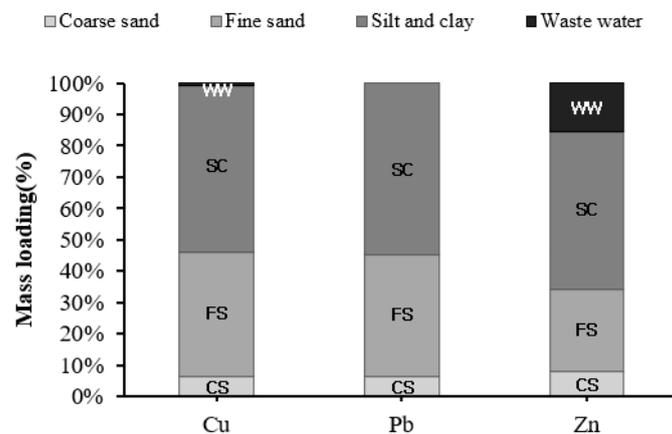
3.6. Change in Heavy Metal Mass Loading during High-Pressure Washing and Separation

Figure 12 shows a comparison and confirms changes in heavy metal mass loadings during washing and separation for the four types of soil, namely (a) contaminated, (b) washed, (c) treated, and (d) separated soil. Table 3 shows the initial Cu, Pb, and Zn concentrations in the various particle size fractions of the contaminated soil. As expected, the contaminant concentration is higher in the fine particle size fractions. Adsorption theories and experimental results confirm that, typically, heavy metals tend to accumulate onto fine rather than coarse particle size fractions [29]. In the short-term artificially contaminated soil used in this study, the heavy metal mass loading varied in the following order: FS > CS > SC (Figure 12a). For the washed soil, the heavy metal mass loading varied in the order of SC > FS > CS (Figure 12b). Heavy metal mass loading in the CS fraction was transferred to FS and SC by 31.1–34.6% after washing (Table 4). Therefore, heavy metals were concentrated from CS to FS and SC through high-pressure washing. After washing, the soil was divided into treated soil and separated soil according to the selection process.

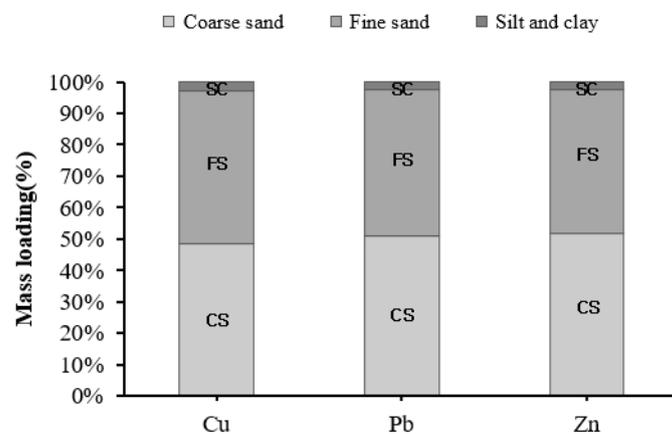
The treated soil's heavy metal mass loading was distributed in the order of CS > FS > SC (Figure 12c). In particular, the mass loading in SC was very low at 2.3–2.9% (Table 4). Conversely, the heavy metal mass loading of the separated soil was distributed in the order of SC > FS > CS (Figure 12d). In addition, the mass loading in SC and FS was 91.8–96.5% (Table 4). Therefore, the screening process can remove heavy metals from the contaminated soil by separating high concentration fine particles using the grit conveyor.



(a)

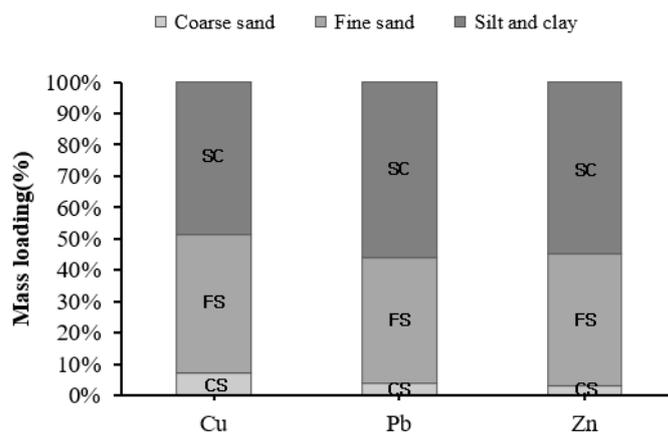


(b)



(c)

Figure 12. Cont.



(d)

Figure 12. Heavy metal mass loading for the three particle-size fractions: (a) contaminated soil; (b) washed soil; (c) treated soil; and (d) separated soil.

Table 3. Heavy metal concentration of contaminated soil for three particle size fractions.

Particle Size (mm)	Contaminated Soil		
	Cu (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
Coarse sand (2–0.42)	486.5	423.9	591.8
Fine sand (0.42–0.074)	846.2	715.4	1035.8
Silt and clay (<0.074)	1072.7	899.5	1447.0

Table 4. Heavy metal mass loadings change through high-pressure washing process for contaminated soil, washed soil, treated soil, and separated soil.

Particle Size (mm)	Contaminated Soil (%)			Washed Soil (%)			Treated Soil (%)			Separated Soil (%)		
	Cu	Pb	Zn	Cu	Pb	Zn	Cu	Pb	Zn	Cu	Pb	Zn
Coarse sand, CS (2–0.42)	40.1	40.9	39.2	6.4	6.3	8.1	48.7	51.1	51.9	8.2	4.2	3.5
Fine sand, FS (0.42–0.074)	41.9	41.4	41.2	39.6	39.0	26.1	48.4	46.6	45.5	43.1	39.2	41.2
Silt and clay, SC (<0.074)	18.0	17.7	19.6	53.4	54.7	50.1	2.9	2.3	2.6	48.7	56.6	55.3
Wastewater, WW	-	-	-	0.6	0.0	15.7	-	-	-	-	-	-

Additionally, some heavy metals in the contaminated soil were eluted with wastewater after washing (Figure 12b). According to a comparison between the mass loading calculated by multiplying the heavy metal concentration in the washing wastewater by the mass of the discharged wastewater and the mass loading in the soil, 0.6% of Cu, 0% of Pb, and 15.7% of Zn were eluted with wastewater. Namkoong and Kim [30] analyzed extract solutions in water of tailings contaminated with Cd, Cu, Pb, and Zn and found that although Zn was extracted the most among the four heavy metals, all of them showed low extraction efficiencies of less than 1%. In that respect, the 0.6% extraction efficiency of Cu after high-pressure washing does not greatly differ from that of the previous study, whereas the Zn extraction efficiency of 15.7% is very high. To investigate the presence of Cu, Pb, and Zn in the wastewater, the pH and Eh of the wastewater were measured. The pH of the discharged wastewater was confirmed to be 4.72 and Eh to be 0.362 mV. According to the Eh-pH diagram [31], Pb is present in the form of low-solubility PbSO₄ under these conditions, whereas Cu and Zn are present in the form of high-mobility Cu²⁺ and Zn²⁺.

Therefore, owing to the pH and Eh of the washing wastewater, Pb may not be detected due to its low solubility, while Cu and Zn may be detected at higher levels than Pb due to their high solubility. However, detection of Cu was very low compared to Zn. This may be a phenomenon caused by the complex contamination of Cu, Pb, and Zn. Additional studies will be needed using the sequential extraction method to identify the presence of heavy metals in wastewater.

3.7. Soil Surface Analysis Using SEM

Changes in the soil surface caused by soil washing are considered particularly important in Zn contaminated soil [32]. The effects on the soil surface before and after high-pressure washing were assessed using SEM. Figure 13 shows the surface morphology of the soil before, after one, and three washing cycles. The soil surface before washing was uneven and irregular, and the soil particles were randomly distributed (Figure 13a). After one high-pressure washing cycle, the soil surface became more uniform (Figure 13b). After three high-pressure washing cycles, the particles became noticeably more even compared to before washing and after one washing cycle (Figure 13c). As previously evidenced by the change in heavy metal concentrations, this is the result of disintegrating micro-contaminated soils or other contaminants bound to the soil aggregates after high-pressure washing.

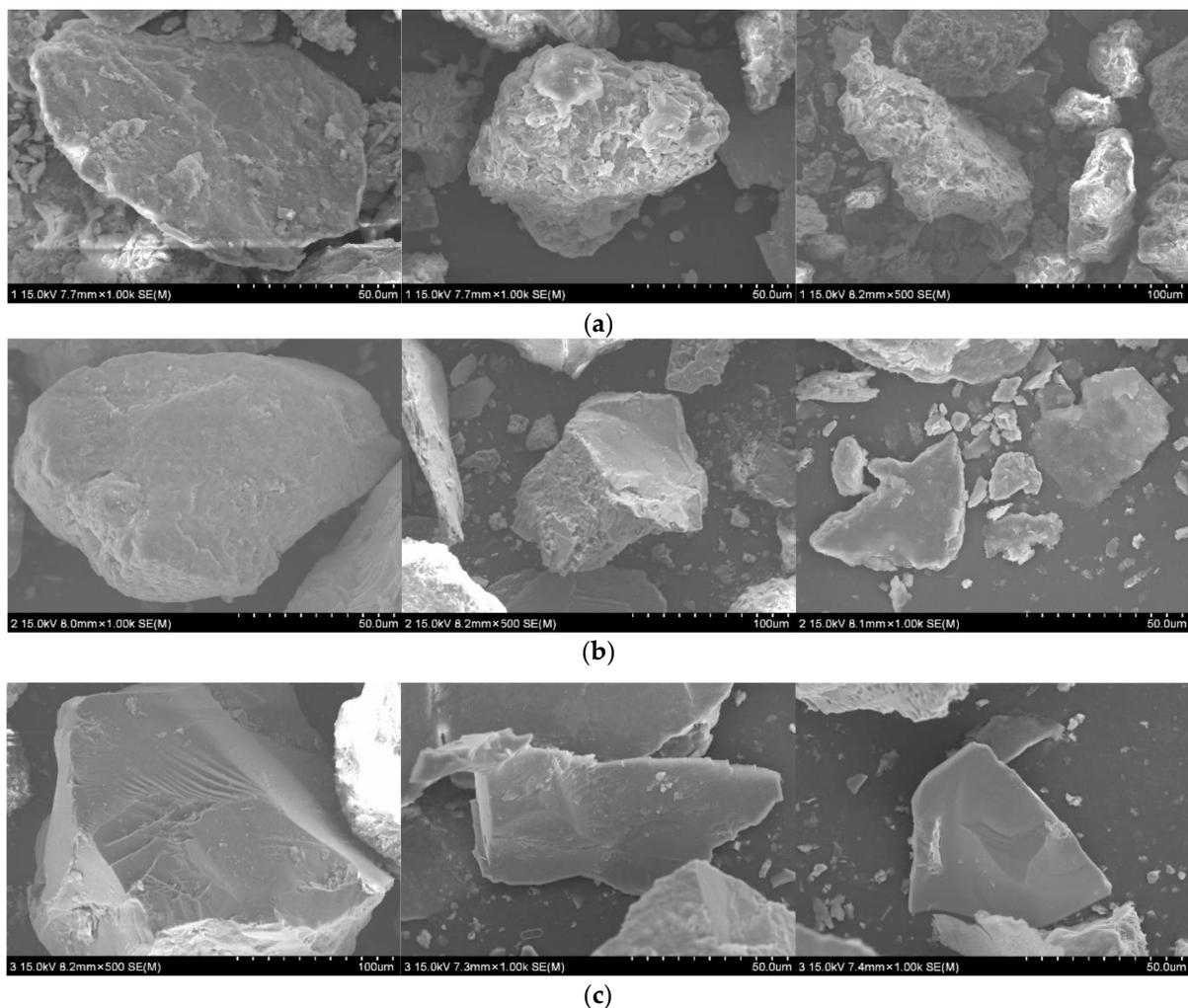


Figure 13. Scanning electron microscopy images of: (a) contaminated soil; (b) washed soil; and (c) soil that has been washed three times.

4. Conclusions

This study demonstrated the applicability of a high-pressure soil washing process for emergency recovery of heavy metals from contaminated soil. The high-pressure washing process is a physical soil washing method consisting of two parts: continuous washing with high-pressure water and separation that collects the coarse soil fraction via a screw conveyor. The optimization of the high-pressure soil washing system was evaluated at varying levels of pressure, S/L ratio, and number of washing cycles. The heavy metal removal efficiency increased as the washing pressure, the S/L ratio, and the number of washing cycles increased. The optimal conditions for the high-pressure washing system were attained at a pressure of 5 MPa, an input S/L ratio of 1 and one washing cycle. The removal efficiencies for each contaminant after one washing cycle were 37.7%, 36.6%, and 45.1% for Cu, Pb, and Zn, respectively and satisfied the Korean Warning Standard (Region 2). The SEM images showed that the surface of the treated soil particles became cleaner as the washing was repeated. As evidenced by the mass loading, the high-pressure washing process displaced 31.1–34.6% of heavy metal materials from the CS fraction to finer particle fractions or wastewater. Finally, the separation process removed the fine particles containing high concentrations of heavy metals from the contaminated soil. Based on these results, the high-pressure soil washing process can effectively remediate heavy metal (Cu, Pb and Zn) contaminated soil and represents a viable emergency response option.

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