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Analysis of Soil Fertility and Heavy Metals Contamination on Post-Mining Laterite Nickel Southeast Sulawesi, Indonesia

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Abstract. The aim of this study was to assess soil fertility and heavy metal contamination in soil on reclaimed land in two sample areas. Area R1, trees are difficult to grow and R2, trees can grow. This investigation was conducted to reveal the level of soil fertility, concentration and enrichmentof various heavy metals in contaminated soil. Twenty-two samples, twelve sampling positions inR1 and ten sampling positions in R2. Inductive study combined ICP-MS (Inductively Coupled Plasma Mass Spectrometry) and ICP-OES (Inductively Coupled Plasma-Optically Emission Spectrometry) methodologies to determine the concentration levels of Cu, Pb, Zn, Ni, Co, Mn, As, Cd and Cr. A total of four R1 soil samples and four R2 soil samples were measured by XRD to determine the mineralogy and study the flame emission photometry method, extraction and Walkley-Black to determine the soil physicochemistry: texture, pH, K^+, Na^+, Ca, Mg, Available Phospor, K, organic carbon, base saturation and cation exchange capacity (CEC). Correlationcoefficient analysis and cluster analysis, coupled with principal component analysis, were used to analyze the data and to identify possible sources of these heavy metals. Overall, the levels of heavy metal enrichment are arranged in the following EF order: Cr R1 < Cr R2 ; Mn R1 > Mn R2; Zn R1 = Zn R2. Heavy metals Mn, Cr, Co, Ni generally exceed moderate pollution and even strong pollution ($2 < \text{Igeo} < 3$; $3 < \text{Igeo} < 4$; $5 < \text{Igeo}$), and Zn, Cu low to moderate pollution levels ($0 < \text{Igeo} < 1$; $1 < \text{Igeo} < 2$), but Pb, Cd, As low pollution levels ($0 < \text{Igeo}$). The results showed that the difficulty of tree growth in all places in R1 was indicated by the physicochemical properties of soil texture and CEC which were in line with mineralogy in influencing soil fertility and even distribution of heavy metals. Compared to R2, the presence of tree growth was related to a positive correlation between soil texture and organic carbon which played an important role in fertilizing the soil and mineralogy support to control the uneven distribution of heavy metals.

Introduction

Nickel laterite deposits are formed from the laterization process of ultramafic rocks (Golightly, 1979, 1981; Elias, 2002 Marsh et al., 2013). Since 2004, Southeast Sulawesi has been the location for open-pit mining activities to extract nickel ore from laterite soil, while non-ore laterite rocks andsoil as waste are used as overburden material for post-mining land topographic degradation. Overburden includes soil and rock that are removed to gain access to ore deposits (Rankin, 2011; Vela-Almeida et al, 2015). Overburden is nutrient poor and deeply excavated soils can be phytotoxic, thus these are not suitable for reclamation without amendments (Carrick and Kru¨ger, 2007) but are often used for landscape contouring (Rankin 2011). Improper waste handling resultsin high concentrations of heavy metals (Mitchell et al. 2016).

The concept of mining sustainability generally mandates the recovery of functional land use (Ross & Simcock, 1997; Bowman & Baker, 1998; Cao, 2007; Maczkowiack, et al., 2012). Focusingon post-laterite nickel mining land in Southeast Sulawesi, it turns out that dozens of topographies show minimal success in revegetation. Mining activities change land topography and ultimately influence hydrogeological conditions (Bell et al. 2000; Santos et al. 2002). Mining alters the natural landscape

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and discharges large volumes of waste that pose serious pollution hazards to the environment and to agriculture (Festin et al, 2019). It is estimated that because the use of overburden material is only to cover the topography, there will be changes in texture and decreased soil resistance which is susceptible to the accumulation of heavy metals by rainfall. Muhardi et al (2022) stated that the tailings had a positive correlation with the heavy metals Mn, Cr, Co, Fe. The migration and transformation of heavy metals is closely related to soil resilience (Xu et al, 2017). Toxicity and persistence in the environment (Facchinelli et al. 2001; Loska and Wiechula 2003; Mehrabi et al, 2015). The sorption/desorption reactions of metal(loid)s on/from soil sorbents are influenced by pH, nature of soil components, and presence and concentrations of cations and inorganic anions (Caporale and Violante, 2016). Mineral dissolution from overburden material and high adsorption capacity of laterite soil are responsible for the elevated concentrations (Das and Chakrapani, 2011).

In this paper, the heterogeneous chemical nature of heavy metals contained in laterite soil is the reason for using multivariate statistical techniques that support the literature, namely: Pearson Correlation (PC), Cluster Analysis (CA), Principle Component Analysis (PCA). Multivariate analysis has the power of grouping individual parameters and variables (Ruiz et al, 1998; Yang etal, 2009; Franco-U et al, 2009; Hu et al, 2011; Yao et al, 2013). A multivariate statistical method such as the principal component analysis (PCA) and cluster analysis (CA) is a powerful tool for evaluating pollution levels among samples (Huang et al, 1994; Hani and Pazira, 2011).

The texture, pH and geochemical properties of soil are an ideal medium for water to transport, infiltrate and deposition heavy metal elements. Accumulation of heavy metals in soil may result in deteriorating soil quality, reducing soil fertility (Zang et al, 2017; Fei et al, 2020). Soil geochemical characteristics have undergone significant changes by anthropogenic activities (Alekseenko et al, 2017). So this study uses soil as a source of information in environmental geochemistry, for example the basic chemical properties of trace elements, mobility, enrichment, mineralogy, soil fertility and heavy metal contamination.

The aim of this research is to assess soil fertility and heavy metal contamination in soil from samples taken from two reclamation sites (R1 and R2) based on determining their concentrations and potential toxicity when they appear in the soil. The results obtained can serve as a reference level for future studies of post-mining nickel laterite lands providing insight into heavy metal speciation and as a selection of remediation reference options for suitable soil improvement.

Site Description

The research was conducted on post-mining reclaimed land for nickel laterite in the North Konawe administrative area, which is known as a mining economic area in Southeast Sulawesi. The research study was carried out in two post-mining land reclamation areas with revegetation characteristics that had not succeeded in growing with sample code R1 and vegetation characteristics that had succeeded in growing with sample code R2, dominated by only one type of Falcataria moluccana plant (Figure 1). Area R1 extends northeast-southwest (122°26'19.86”– 122°26'25.76” E and 03°49'33.95”–03°39'60.71” S) and area R2 extends east-west (122°26'17.27”– 122°26'22.88” E and 03°49'43.44”–03°49'47.39” S).

The southern Konawe area has a clear difference between the dry season and the rainy season. The dry season lasts for 5 months from July to November, and the rainy season from December to June with the lowest rainfall in September, namely 61 mm. The northern part of Konawe is known as a non-monsoon zone, that is, there is no clear boundary between the rainy and dry seasons. In fact, the rainy season occurs almost every month with an average rainfall of 319.5 mm/month and annual rainfall > 2000 mm (BMKG, 2022).

Some of the nickel mining entities are in South Konawe, North Konawe which is a geological regional ultramafic rock belt on Sulawesi Island which is dominantly located in the southeastern part. Laterization of ultramafic rocks produces alkaline chemical composition minerals, mainly nickel laterite, iron, manganese, cobalt, chrome and gangue oxide minerals such as quartz, magnesium, aluminium, in varying proportions. Apart from that, the presence of minerals with an acidic chemical composition such as copper sulphide, lead and cadmium in very low proportions, is related to ultramafic and metallogenic province types (Zhang et al, 2019; Scoates et al, 2017;Barnes and Lightfoot, 2005).

Sampling and Analysis

The research location was selected based on similarities in reclamation since 2008, identification of soil profiles and differences in revegetation. Using the Global Positioning System (GPS), sampling locations were designed to obtain representative samples which were carried out on two topographic reclamation hills with different characteristics of no vegetation in the north and vegetation in the south (Figure 1).

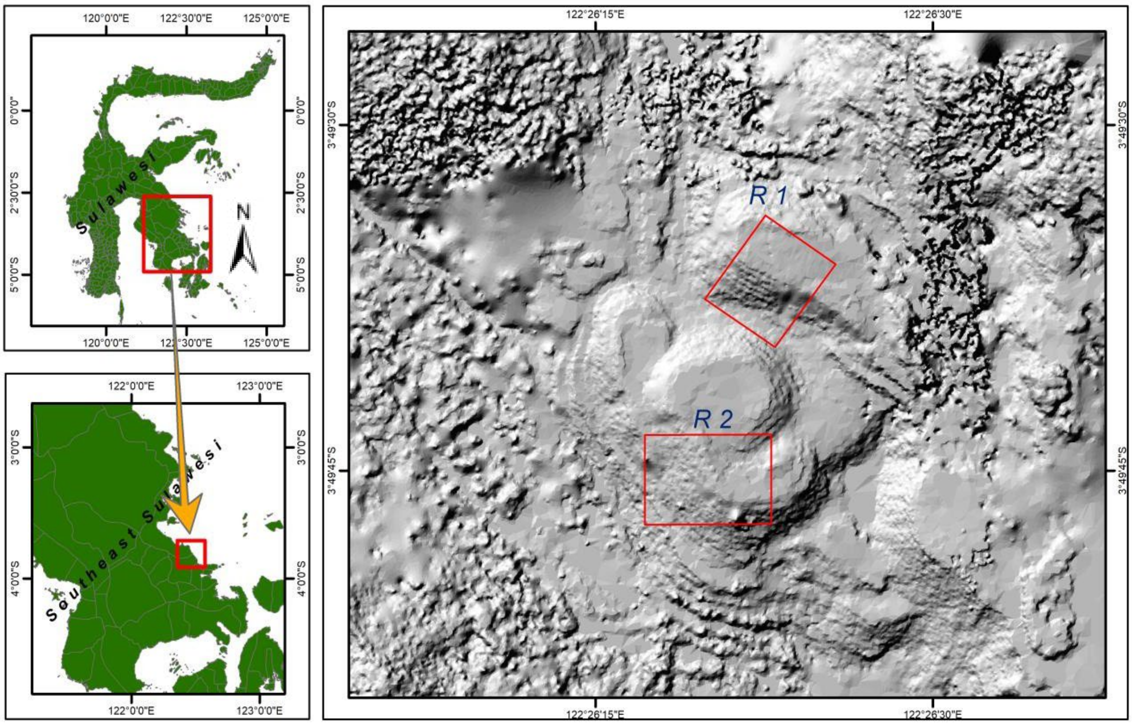

Fig. 1. Sample groups R1 and R2 at the research location.

A series of standard soil collection procedures refers to Zheng (2005) and Guo (2009), where one kg of fresh soil is collected at each sampling point for one analysis method. In this study, three investigation methods were used, so that at one sampling point there was three kg of soil in different bags. Surface soil samples were taken using a hand drill where the sampler handle was made of steel with an overall length of 1.0 m and a diameter of 2.5 cm, carried out at a depth of (0-20cm), (20-40cm). Soil samples per kilogram were placed in polyethylene bags and transported.

Analysis Method 1. A total of 22 samples were divided into two groups: R1 (Reclamation 1) 12 samples and R2 (Reclamation 2) 10 samples. For R1, it is divided into R1A representing depth (0- 20cm) and R1B (20-40cm), and R2A (0-20cm), R2B (20-40cm). R1A has 6 samples: 1A-6A and R1B has 6 samples: 1B-6B, for R2A has 5 samples: 7A-11A and R2B has 5 samples: 7B-11B. All samples for investigation of major elements, minor elements, trace elements using neutron activation analysis at X-Ray Laboratories PT Intertek Jakarta using plasma ICP-MS (Inductively coupled plasma mass spectrometry) and ICP-OES (Inductively Coupled Plasma-Optically Emission Spectrometry). Detection limit 1 mg kg-1 for As; 0.05 mg kg-1 for Cd; 5 mg kg-1 for Cr; 1 mg kg-1 for Cu, Mn, Ni, Pb, Zn. The results of investigations on sample quality control, accuracy of minor element and trace element analysis are in accordance with international standards.

Analysis Method 2. A total of 8 samples for soil fertility analysis, for R1A represented by 4 samples (1A to 4A) and for R2B represented by 4 samples (7A to 10A). Soil samples were air-dried and sieved (mesh size 2 mm). Investigations include: texture following USDA standards (1999), pH values were analyzed in H2O (1:2.5 soil:solution ratio); K+ and Na+ by flame emission photometry after extraction with Mehlich-1; Ca and Mg by titration after extraction with 1 mol L-1 KCl solution; Available Phosphorus (AP) and K etraction HCl 25%. Organic carbon (OC) was determined by the Walkley-Black method. Cations concentrations were used to calculate base saturation and cation exchange capacity cmol/kg. All samples for psychochemical soil investigations were determined according to the method described by Blackmore et al (1981), Rayment and Higginson (1992) and carried out at the Soil Chemistry and Fertility Laboratory, Department of Soil Science, Hasanuddin University.

Analysis Method 3. A total of 8 bulk soil samples for mineralogical analysis, representative for R1A (1A, 2A, 3A, 4A) and for R2A (7A, 8A, 9A, 10A). Preparation of 10-20 grams of soil samples was weighed using a scale with an accuracy of 4 decimals. Destruction, the soil was put into a 1000 ml beaker, then poured 200 ml of 10% H_2O_2 solution. Continued with a heating process at a temperature of 100°C, following the stages of Moore and Reynold (1997), Kahle et al (2002). All samples for the investigation of mineralogical composition used X-ray diffraction (XRD, shimadzu maxima X-7000 diffraction meter) and were carried out at the Department of Geological Engineering, Hasanuddin University.

XRD Analysis

XRD analysis Bulk mineralogy of soil samples from selected representative samples for R1A and for R2A (7A,8A,9A,10A) was examined by X-ray diffraction method (Shimadzu Maxima X- 7000 difracrometer with Cu Ka irradiation). The 2 lm clay mineral fraction was obtained using the sedimentation method (Rowell 2014). Samples were centrifuged twice for 15 minutes using a Sigma 4-15 centrifuge. The clay suspension was pipetted onto a glass slide and allowed to dry at room temperature. Air-dried, ethylene glycol-saturated and heated (550ºC) samples were used for determination of clay mineral species according to the method described by Moore and Reynolds (1989). Measurements were performed at 40 kV and 40 mA and scanning speed from 3 to 302H (or from 2 to 302H) at a step size of 0.022H min-1. Phase identification and peak area determination were carried out using Win XRD software.

Statistic Analysis

Pearson correlation statistics (CP) have analytical power in their coefficient values which explain the size of the relationship between two variables (Ma et al, 2015). For this study, CP was used to determine the relationship between different heavy metals, then required an analysis of the sensitivity of each heavy metal in relation to its source.Similarities and differences in the chemical properties of heavy metals are variable classifications in the hierarchical agglomeration type cluster analysis (CA) method. The results are in the form of a dendogram where automatic steps with a hierarchical CA procedure in standardizing groupings are a solution of the distance values between clusters (squared Euclidean distance) to assess compactness and correlation. The purpose of CA isto identify groups or clusters of similar sites on the basis of similarities within a class and dissimilarities between different classes (Sparks, 2000). Strengthening CP and CA results using additional analysis, namely principal component analysis (PCA), a variable reduction technique in which a number of measured parameters can be extracted into a small number of variables into principal components. PCA was interpreted in accordance with the hypothetical source of heavy metals (lithogenic, anthropogenic or mixed) (Yuan, 2013). Classification of variables in the Pearsoncorrelation analysis (CP), Cluster Analysis (CA) and principal component analysis (PCA) methods is carried out using using SPSS Version 26.IBM.

Calculation of Indices to Assess Anthropogenic Influence

Enrichment Factors (EFs)

Quantitative assessment of the relative levels of heavy metal contamination in soil by lithogenic and geogenic for two sequences of sample groups R1A and R1B to R1AB, and two sequences of sample groups R2A and R2B to R2AB. So a comparison is made with the background Concentration of the earth's crust using Fe as a reference element following the assumption that its content in the earth's crust is not disturbed by anthropogenic activities.

EF was calculated according to the regenerated equation of Zoller et al. (1974) (Lu et al., 2009) (Eq.(1)) :

$$EF = ([Cx/Cref]_{soil}/([Cx]/[Cref]_{crust} \quad (1)$$
$$EF_M = ([M]/[Fe])_{soil}/([M]/[Fe])_{crust}$$

Where (Cx/Cref) sample is the concentration of the heavy metal being examined in the sample and Fe in the sample. (Cx/Cref) background is the ratio between the heavy metal concentration and the reference Fe concentration of the upper continental crust (Wedepohl, 1995). Five contamination categories are recognized on the basis of the EF: these are <2 denoting deficiency to minimal enrichment; 2-5, moderate enrichment; 5-20, significant enrichment; 20-40, very high enrichment; >40, extremely high enrichment (Lu et al., 2009).

Geo-Accumulation Index (Igeo)

Applying a quantitative assessment of the geoaccumulation index (Igeo) of contamination in sediments (Muller, 1969) and soil pollution (Loska et al, 2003) for two sequences of sample groups R1A and R1B to become R1AB, and two sequences of sample groups R2A and R2B to become R2AB. So Igeo makes it possible to assess contamination by comparing the latest concentrations of metals in post-mining fields. Igeo is calculated using the equation:

Geo-accumulation was proposed by Muller (1969) and was defined as follows:

$$I{-}geo = \log2\ [Cn/1{:}5 \times Bn]$$

where Cn is the metal concentration measured in n samples, and Bn is the average geochemical background of n elements in the earth's crust. The geo-accumulation index has been categorized into seven levels of contamination ranging from highly contaminated to not contaminated (Muller 1969; Barbieri 2016).

In this study, the homogeneity of laterite soil has been chosen as a special criterion for ultramafic rocks as geochemical background concentrations of Cr, Co, Ni, Mn, and general criteria for igneous and sedimentary rocks for geochemical background concentrations of Pb, Zn, Cd, Cu, As. The constant 1.5 compensates for possible natural fluctuations in the content of certain substances in the environment, as well as detecting very small anthropogenic influences (Loska et al, 2004; Ji et al, 2008). Seven Igeo classes (Muller, 1969) represent the level of soil pollution, as follows: Class 0 = Igeo < 0 (practically uncontaminated);Class 1= 0 < Igeo < 1 (uncontaminated to moderately contaminated); Class 2 = 1 < Igeo < 2 (moderately contaminated); Class3 = 2 < Igeo < 3 (moderately to heavily contaminated); Class 4 = 3 < Igeo < 4 (heavily contaminated); Class 5 = 4 < Igeo < 5 (heavily to extremely contaminated); Class 6 = 5 < Igeo (extremely contaminated).

Results and Discussion

Physicochemical Soil Characteristics on Post-Mining Land

Soil properties measured on post-mining land R1A were identified as showing parameters that influence soil fertility. Table 1, the physical properties of soil texture R1A are dominated by clay silty, while R2A varies with the sand clay silty texture. So, the layer depth of 0-20 cm in R1A has lower porosity than the soil in R2A. Porosity is very important because it greatly influences the physical properties (soil structure and aeration), soil chemistry (nutrient movement) and biology (soil microorganism activity) which influence plant growth, so that the physical and chemical properties of R2A soil are relatively good compared to R1A.

OC content and Ntotal R1A ≤ R2A. So in RA1 the soil's ability to provide nitrogen and the solubility of basic cations is reduced, thereby affecting CEC (Cation Exchange Capacity). The study area has high rainfall causing acidic pH, so that in R1A, R2A there is penetration and leaching by rainwater of the soil texture which affects the reduction of nitrogen. The influence of rainfall was identified on the tendency of low AP which was influenced by Ca and metals, this was strengthened by the similarity of the CEC R1A, R2A values. That rainfall affects the mobilization of increased metals (generally Mn in laterite soils) and disrupts soil adsorption, so that in R1A soil fertility is very low to provide nutrients for plant growth.

Table 1. Physicochemical soil characteristics at R1A and R2A, R1A and R2A.

Sample	O C	N	AP				pH	Ca	Mg	Na	K	CEC
	(%)		(ppm)	Sand	Silt	Clay	H2O			cmol/kg		
R1A												
1A	0,92	0,08	9,13	37,04	17,10	45,85	5,49	2,96	2,38	0,14	0,34	27,69
2A	0,59	0,09	10,94	33,75	15,84	50,40	5,27	3,17	2,46	0,14	0,25	24,66
3A	0,62	0,05	8,16	5,39	51,41	43,18	5,75	3,40	2,23	0,23	0,18	20,43
4A	1,72	0,15	9,19	29,41	33,29	37,29	6,04	3,91	2,60	0,22	0,42	21,35
5A	0,66	0,12	9,73	6,83	63,29	29,87	5,92	2,13	1,85	0,21	0,22	19,15
6A	0,80	0,07	10,22	7,86	72,99	19,14	5,75	2,53	2,23	0,19	0,16	18,32
R2A												
7A	0,98	0,09	7,68	36,99	28,90	34,10	5,58	2,99	1,71	0,15	0,19	26,32
8A	0,95	0,12	9,74	15,22	65,46	19,31	5,74	2,32	1,84	0,22	0,32	21,35
9A	1,00	0,07	10,83	32,34	34,51	33,13	5,84	3,38	1,31	0,15	0,23	18,15
10A	0,95	0,10	10,28	34,36	36,12	29,51	5,46	2,53	1,16	0,23	0,28	19,31
11A	1,05	0,10	8,11	25,55	35,61	38,82	5,92	3,40	1,79	0,17	0,16	18,36

The soil texture properties in R1A are correlated with the XRD results where the mineral composition shows enrichment in quartz, chlorite, diopsid, montmorillonite, hematite, magnetite, goethite, spinel, talc, maghemite. The discovery of spinel, montmorillonite and talc which supplies Mg, Fe, Al to the clay texture which disrupts the hydrous phase balance of hematite, maghemite, geotite, and activates spinel to significantly increase the mobility of heavy metals. Spinel often results in the sequestration of contaminants such as Cu, Ni, Zn (Schindler et al, 2019). Thechemistry of the spinel mineral in ultramafic rocks is of the low Al and high Cr variety (Sahu et al, 2020). The minerals observed in quartz, diopsid, chlorite, spinel are an indication that the soil texture originates from the high intensity of weathering of serpentinized ultramafic rocks. Chlorite is rarely found in soil and is an indicator of intensive weathering (Schulze, 2005). Diopside represents the Ca product of serpentinized ultramafic pyroxene, and spinel forms in surface soils, contributing to Zn and Pb (Schindler et al, 2021). Large amounts of fertilizer added regularly to the soil contain small amounts of the heavy metals Cd, Pb which significantly increase in the soil (Jones and Jarvis, 1981). Application of certain phosphatic fertilizers inadvertently adds Cd and other potentially toxic elements to the soil, including Pb (Raven et al, 1998).

Multivariate Statistical Analysis

Correlation Analysis

The correlation matrix to identify the correlation between metal concentrations and soil properties in R1A at the significance level of $p < 0.05$ and $p < 0.01$. Based on the Pearson correlation coefficient, it appears that the nine heavy metals (Mn, Cr, Co, Ni, Pb, Zn, Cu, Cd, As) found a significant positive correlation except Ni, Cd, in 4 groups: (1) Mn concentration was strongly correlated with Co, Pb, As Cu (correlation coefficients respectively 0.94; 0.94 and 0.95); (2) Cr concentration is strongly correlated with Co, Zn (correlation coefficients 0.83 and 0.84, respectively); (3) Co concentration is strongly correlated with Pb, As (correlation coefficients 0.85 and 0.87, respectively); (4) Pb concentration is strongly correlated with Cu, As (correlation coefficients 0.87 and 0.89 respectively). Shows that the geogenic group of metals Mn, Cr, Co have the same source of rock weathering. And the sources of rock weathering are different from the metal groups Pb, Cu, As, Zn.

Correlation matrix analysis of all measured soil properties showed several typical correlations identified. Significant positive correlation was observed between sand, silt, clay and CEC ($p < 0.01$, 0.05). These findings show that the study area which is classified as having monthly rainfall has an effect on relatively smaller spaces in the soil and allows water penetration to increase oxidation, which is strengthened by the positive correlation between Ca and Na, Ca and Mg accompanied by Fe, Al found in chlorite , diopsid, montmorillonite. Apart from that, significant correlations were observed between Na and pH, between K and OC, in fact a correlation was also found between Ntotand Ni, where Ni was not included in the correlation matrix. This implies that a significant positive correlation causes a decrease in pH values thereby reducing the supply of nitrogen to the soil. It wasfound that CEC, Mg, Ca, Na, Ntot and soil texture directly or indirectly influence soil fertility and heavy metal mobility, as shown by the positive correlation between Ntot and Ni ($p<0.01$), between K and Cr ($p <0.05$). Other metals did not show significant correlations with all soil properties. The next finding was that there was no significant correlation between pH and heavy metals (except Ni, Cr), but at least pH played a role in heavy metal concentrations. Soil with low pH can facilitate the migration and availability of heavy metals (Zhang et al, 2001; Li et al, 2005). The Pearson R2A correlation matrix, was used to identify the correlation between metal concentrations and soil properties. It was found that the heavy metals Mn, Co, Cr, Zn, Cu were significantly positively correlated ($p<0.05$) in 2 groups: (1) Mn concentration was strongly correlated with Co (correlation coefficient 0.90); (2) Zn concentration is strongly correlated with Cr and Cu (correlation coefficients 0.92 and 0.93, respectively). Shows that this metal has a geogenic source.

Correlation matrix analysis shows that only a few soil properties have been identified as having significant correlation. Significant negative correlations were observed between Ntotal and Cr, then between Na and Cr, but positive effects between Ca and Cr, and Ca-Zn. These findings indicate that an increase in the concentration of the heavy metal Cr can cause a decrease in Ntot and Na values, while an increase in Ca actually increases the soil organic value (SOC) which is supported by the negative correlation of silt and sand particles, and silt and clay.

Cluster Analysis

Analysis of the R1A cluster results is illustrated in the dendogram (figure 2), showing two clusters: (1)Mn\\Co\\As\\Pb; (2)Cr\\Zn and without Ni, Cd, Cu clusters. The manganese, arsenic and lead clusters form independent groups according to group 1 of the Pearson Correlation (CP) R1A results,as do chrome and zinc, according to group 2 of the Pearson Correlation (CP) R1A results.

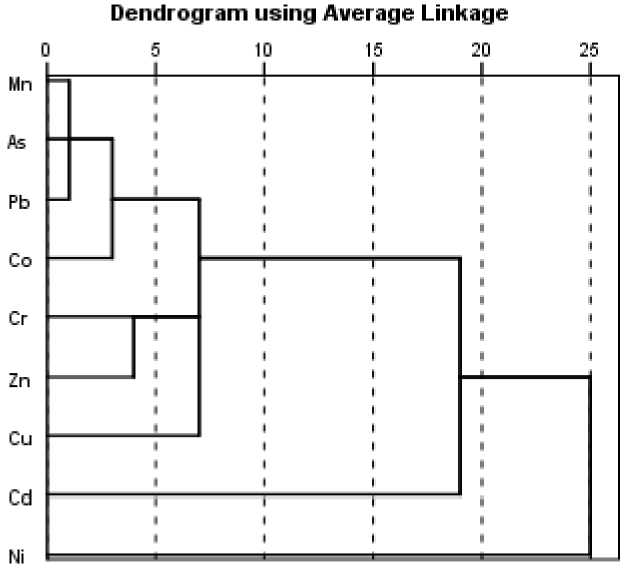

Fig. 2. Dendrogram derived from hierarchical cluster analysis of heavy metal content in soil in R1A.

Analysis of the R2A cluster results is illustrated in the dendogram (figure 3), showing two clusters: (1) Mn \\ Co (2); Zn\\Cu\\Cr and without Pb, As, Cd, Ni clusters. The results of this grouping are in accordance with the results of the Pearson Correlation (CP) R2A. That the independent group manganese, cobalt corresponds to group 1 and the zinc, copper, chrome cluster corresponds to group 2 according to the Pearson Correlation (CP) R2A analysis results. The lead, arsenic, cadmium and nickel clusters form their own group, which shows that the heavy metal group comes from geogenic sources.

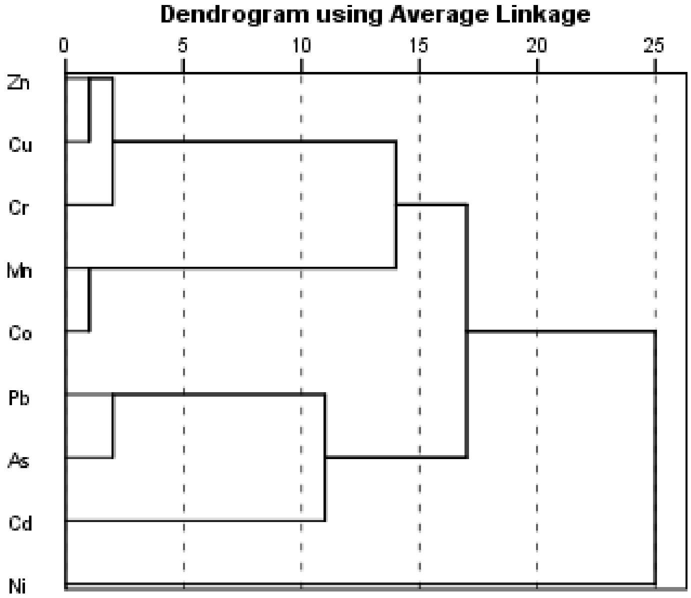

Fig. 3. Dendrogram derived from hierarchical cluster analysis of heavy metal content in soil in R2A.

PCA Analysis

Through rotation, the distribution of variables becomes clear and real in R1AB in table 4, the large factor loadings are increasingly increased in value and vice versa, compared to before the rotation was carried out. 3 rotations of matrix components are produced, according to the number of factors obtained, namely the distribution of variables into factors with the rotation process. From the results above, after rotation, there are seven elements that are highly correlated (cut offpoint = 0.55) except Ni and Cd. Factor 1 is Mn, Cr, Co, Pb, As (0.947; 0.843; 0.893; 0.925; 0.625). Factor 2which is highly correlated is Zn, Cu (0.705; 0.685).

Through rotation of the variable distribution, it becomes clear and evident in R2AB, that large factor loadings increase in value and vice versa, compared to before the rotation was carried out. 3 rotations of matrix components were produced, according to the number of factors obtained, namely the distribution of variables into factors with the rotation process. From the results above, after rotation, there are seven elements that are highly correlated (cut offpoint = 0.55) except Ni, Cd, with factor 1, namely, Zn and Cu (0.937 and 0.873) and Cr (0.838). For factor 2 which is highly correlated, namely Mn, Co,(0.924; 0.946). For factor 3 which is highly correlated, namely Pb, As (0.908; 0.773).

Enrichment Factors (EF)

The mean EF for heavy metal enrichment in R1AB very high enrichment (EF=20-40) was observed in Cr (min 18,009 to 49,117), significant enrichment (EF=5-20) in Mn (4,113 to 11,336) and Zn (7,728 to 10,604). Minimal enrichment (EF<2) was observed in Co (0.004 to 0.007), Ni (0.032 to 0.17), Pb (0), Cu (0.703 to 1.117), Cd (0), As (0).

Mean EF for heavy metal enrichment in R2AB extremely high enrichment (EF>40) was observedin Cr (min 24,546 to 64,208), significant enrichment (EF=5-20) in Mn (3,726 to 7,479) and Zn (7,084 to 11,909). Minimal enrichment (EF<2) was observed in Co (0.003 to 0.006), Ni (0.017 to 0.026), Pb (0), Cu (0.693 to 1.262), Cd (0), As (0). From the category of all heavy metals, only Pb, Cd, As whose EF shows no pollution from these three heavy metals in the study area and refers to the physical properties of the soil, then Pb, Cd is the possible source of pollution from the addition of fertilizer. Furthermore, the results of the Pearson Correlation analysis show that the heavy metalsAs, Cu are different sources of pollution from Pb, Cd. Geogenic pollution is confirmed by minimal enrichment for Ni and Co related to soil sources, namely: enrichment results from ultramafic weathering. The enrichment factor analysis for Mn, Cr, Zn is at the highly polluted stage, and the EF of the three metals in R1AB is lower than R2AB. In connection with these metals, differences in the use of overburden as post-mining land cover and other geogenic causes can be attributed.

Presents the spatial distribution of heavy metals in R1. The spatial patterns of Mn, Cr, Co, Ni show the same distribution trend with high concentrations in the north-northeast-south area and low concentrations in the northwest-west area. This distribution pattern appears to be smooth andregular, indicating that soil texture factors, low porosity and OC play an important role in controlling the distribution of these heavy metals. Substantively, these heavy metals are produced from the weathering of ultramafic rocks and soil formation. Of all these heavy metals, it seems that the irregular pattern of high concentrations of Cr and low concentrations of Zn means that thesource of the cover soil used to cover the land is a mixture of top soil taken from within the researchlocation.

Geoaccumulation Index (Igeo)

In table 2, the Igeo mean for heavy metal contamination in R1AB extremely contaminated (class 6) is observed at Cr (min 5.681 to max 7.130) and Ni (6.268 to 7.172). Heavily contaminated (class 4) was observed in Co (3.121 to 4.012) and moderately to heavily (class 3) was observed in Mn (1.900 to 3.362), which allows Mn with Co in class 4. Moderately (class 2) was observed in Zn (1.207 up to 1.750), and uncontaminated status (class 0) was observed for Pb, Cd, As, except Cu (- 0.063 to 0.605) uncontaminated to moderately.

Mean Igeo on heavy metal contamination in R2AB extremely contaminated (class 6) was observed at Cr (min 6.148 to max 7.535) and Ni (6.253 to 6.880). Heavily contaminated (class 4) was observed at Co (2,755 to 3,950) and moderately to heavily (class 3) was observed at Mn (1,777 to 2,783). Moderately (class 2) was observed in Zn (1.188 to 1.938), and uncontaminated status (class 0) was observed in Pb, Cd, As, except Cu (-0.063 to 0.802) uncontaminated to moderately. The similarity of R1AB and R2AB in Pb, Cd, As, Cu, Zn contamination is the metal mobility behavior which can be caused by rain so that fluctuations in contamination lie at (uncontaminated to moderate contamination, this is reinforced by Mn, Co being at medium to high transition. Likewise,the enrichment of metals by Cr, Ni, these two metals originate from the geochemical environmentof laterite soil, so the mobility of both is greatly influenced by water infiltration.

The results of IgeoR1, Igeo R2A, R2B compared with EF R1AB and EF R2AB are not easy because there are differences in the nature of the Igeo calculation which involves a logarithm function and a background value multiplication factor of 1.5. However, at least in this study referring to the Igeo and EF similarity approach, the main observations are aimed at heavy metals, namely Cr (Igeo = EF), and also Mn, Ni, Co, Zn.

Table 2. Geo- accumulation index at R1AB (0-40cm) and R2AB (0-40cm).

Sample	Element	min	max	Mean	SD	Skew	Kurt	Geo- accumuation Index	Degree Igeo
R1AB	**Mn**	1,900	3,362	2,367	0,410	1,378	2,217	2 < Igeo < 3	Class 3
R2AB		1,777	2,783	2,364	0,283	-0,624	1,182	2 < Igeo < 3	Class3
R1AB	**Cr**	5,681	7,130	6,500	0,445	-0,418	-0,0502	5 < Igeo	Class 6
R2AB		6,148	7,535	6,925	0,405	-0,366	0,245	5 < Igeo	Class 6
R1AB	**Co**	3,121	4,012	3,488	0,278	0,212	-0,546	3 < Igeo < 4	Class 4
R2AB		2,755	3,950	3,569	0,365	-1,302	1,670	3 < Igeo < 4	Class 4
R1AB	**Ni**	6,268	7,172	6,689	0,280	0,449	-0,525	5 < Igeo	Class 6
R2AB		6,253	6,880	6,640	0,203	-0,692	-0,214	5 < Igeo	Class 6
R1AB	**Pb**	-4,672	-1,087	-3,227	0,870	1,107	3,029	Igeo <0	Class 0
R2AB		-4,672	-1,865	-3,116	0,760	-0,599	1,300	Igeo <0	Class 0
R1AB	**Zn**	1,207	1,750	1,461	0,144	0,345	0,574	1 < Igeo < 2	Class 2
R2AB		1,188	1,938	1,544	0,241	-0,128	-0,639	1 < Igeo < 2	Class 2
R1AB	**Cu**	-0,063	0,605	0,158	0,207	0.,23	0,368	0 < Igeo < 1	Class 1
R2AB		-0,063	0,802	0,338	0,321	0,020	-1,496	0 < Igeo < 1	Class 1
R1AB	**Cd**	-1,907	1,000	-0,448	0,870	-0,375	-0,088	Igeo <0	Class 0
R2AB		-1,907	1,900	-0,224	1,224	0,95	-0,0845	Igeo <0	Class 0
R1AB	**As**	-1,263	1,322	-0,200	0,684	0,479	1,769	Igeo <0	Class 0
R2AB		-1,263	0,737	-0,188	0,814	-0,0451	-1,523	Igeo <0	Class 0

Discussion

The level of fertility at the two different locations is in accordance with the physicochemical and mineralogical properties of the soil (Table 1), which were measured from testing soil samples (representatives of R1A and R2A) at shallow depths (0-20cm) for R1 and R2. The results of the positive correlation analysis of R1 soil texture with Cation Exchange Capacity (CEC) were accompanied by a decrease in oxygen, organic carbon, nitrogen and cation base solubility. This correlation occurs in decreasing porosity, increasing groundwater penetration which results in decreasing pH and phosphorous. In line with the presence of minerals in the soil such as: talc, diopsid, spinel, montmorillonite, where these minerals contain the elements Ca, Na, Mg, Fe, Al. These elements can reduce the control of soil absorption properties and lead to disruption of the balance of the oxidation phase in hydrous minerals, such as hematite, maghemite and geotite. The physical and chemical atmosphere of the soil is represented by the mineral spinel, which can increase the mobility of heavy metals Mn, Cr, Co, Pb, Cu, As, Zn. Spinel often results in the sequestration of contaminants such as Cu, Cr, Ni, Zn (Schindler et al, 2019; Sahu et al, 2020).

These findings reveal that the difficulty of tree growth at all places in R1 is correlated with the low level of soil fertility and the uneven distribution of heavy metals at shallow depths.

Furthermore, in R2, the results of the positive correlation of soil tests on Ca and Zn lead to the role of these two cations in porosity which gradually increases organic carbon which comes from rotting plant leaves and plant roots. It seems that there are indeed places that have soil fertility at shallow depths, and their distribution could expand to the extent that there is no further reclamation treatment or changes in plant types. Highlighting the presence of spinel, talc, quartz, gibbsite minerals which increase the soil's ability to resist heavy metal toxicity, which is supported by the results of cluster analysis, factor analysis, and negative correlation analysis of nitrogen and sodium. Strengthening soil absorption to inhibit the mobility of heavy metals Mn, Cr, Co, Cu, and apparently Pb, As, Cd, Ni, is difficult to reduce soil fertility. Thus, soil fertility R2 really shows the control of the activity of uneven distribution of heavy metals and the existence of ecological balance in shallow depth soil. One of the main factors that explains the geogenic emergence of heavy metal concentrations is explaining the soil source (soil parent). The research area is filled with laterite soil, which is a type of residual soil resulting from the weathering of ultramafic rocks. Due to the serpentinization process, ultramafic has different chemical and mineral compositions so that laterization produces nickel types: silica, ferrous and fractured (Golightly, 1981; Kadarusmanet al, 2004; Maulana et al, 2015; Zhang et al, 2020; Tonggiroh et al. , 2017).

In particular, the results of PCA analysis of heavy metals Mn, Cr, Co (Table 4) in soil R1 are influenced by the geochemical characteristics of nickel-ferrous laterite and serpentinized ultramafic mineralogy, such as: chlorite, diopsite, montmorillonite. In contrast to the PCA results of heavy metals Zn, Cu, Cr (Table 5) in R2 and the presence of minerals such as: spinel, talc, quartz, gibbsite. The geochemical characteristics of the soil come from silica nickel and fractured nickel. Inaddition to the geochemical and mineralogical characteristics of the soil from geogenic pollution sources, the high anthropopigenic concentrations of heavy metals in the study area are also highlighted by the results of the EF (Table 6) and Igeo (Table 7) analysis. Explanation of EF: Cr R1 < Cr R2; Mn R1 > Mn R2; EF Ni, Co, Cu ; Igeo Mn, Cr, Co, Ni and CP analysis results (Table 2), that the enrichment of Mn is higher than Cr in R1. The enrichment pattern implies a reduction in thesoil's geochemical capacity for heavy metal mobility caused by errors in reclamation of the use of soil obtained from within the R1 location when used to cover post-mining topography. Different in R2, EF value and CP analysis results (Table 3) that Mn enrichment is lower than Cr. The enrichment pattern explains the soil's ability to inhibit the mobility of heavy metals due to the implementation of reclamation using soil taken from outside the R2 location. From the category of all heavy metals, only Pb, Cd, As whose EF shows no pollution at the study location.

Conclusion

These findings reveal that the implementation of reclamation has not met the technical rules for using overburden material taken from within the location or from outside the post-mining land location, which of course can affect the physicochemistry of the soil and provide space for the distribution of heavy metal contamination. Assessment of soil fertility and mineralogy as well as heavy metal contamination As, Cd, Cr, Co, Cu, Mn, Ni, Pb, Zn was carried out on soil at two locations (R1 and R2) based on soil physicochemical, mineralogical, EF and I-geo properties. The difficulty of tree growth in all places in R1 is shown by the negative correlation analysis of soil texture and CEC which is in harmony with mineralogy in influencing soil fertility and the even distribution of heavy metals. Compared to R2, the presence of tree growth is related to the positive correlation of soil texture and organic carbon which play an important role in soil fertilization and mineralogical support to control the uneven distribution of heavy metals. Overall, the degree of heavy metal enrichment was arranged in the following EF order: Cr R1 < Cr R2 ; Mn R1 > Mn R2; Zn R1 = Zn R2. The heavy metals Mn, Cr, Co, Ni are generally more than moderately polluted or even strongly polluted ($2 < \text{Igeo} < 3$; $3 < \text{Igeo} < 4$; $5 < \text{Igeo}$), and Zn, Cu have low to moderate pollution levels ($0 < \text{Igeo} < 1$; $1 < \text{Igeo} < 2$), but Pb, Cd, As pollution levels are low ($0 < \text{Igeo}$).

All heavy metal pollution levels were high in R1 and R2, mainly due to geogenic and anthropogenic inputs. Continuous reclamation activities without paying attention to the rules for using top soil as topographic cover, which causes environmental degradation, especially post- mining land, becomes unproductive and poses a greater risk to public health. The results presented will provide valuable reference information on remediation for appropriate soil improvement, for policy makers in determining exactly how to sustainably manage post-laterite nickel mining land in the future.

References

[1] Schulze DG., 2005. Encyclopedia of Soils in the Environment. ScienceDirect

[2] USDA., 1998. Natural Resources Conservation Service. Soil Quality Indicators: pH. http://www.isuvaslui.ro.

[3] Zang F., Wang S., Nan Z., Ma J., Zhang Q., Chen Y., Li Y.,2017. Accumulation, Spatio-Temporal Distribution, and Risk Assessment of Heavy Metals in the SoilCorn System Around a Polymetallic Mining Area from the Loess Plateau, Northwest China. Geoderma 305, 188–196.

[4] Fei, X.,Lou, Z., Xiao R., Ren, Z., Lv, X.,2020. Contamination Assessment and Source Apportionment ofHeavy Metals in Agricultural Soil through the Synthesis of PMF and GeogDetector Models. Sci. Total Environ. 747,141293.

[5] Sutherland RA., Tolosa CA., Tack FMG., Verloo MG.,2000. Characterization of selected element concentration and enrichment ratios in background and anthropogenicallyimpacted roadside areas, Archives of Environmental Contamination and Toxicology, Vol.38, 428–438

[6] Guo, M.,2009. Soil sampling and methods of analysis. J. Environ. Qual.

[7] Zheng, W.,2004. The Technical Specification For Soil Environmental Monitoring (HJ/T 166–2004);Chinese Standard: Beijing, China,pp. 4–17.

[8] Akhter, MS., Madany, IM.,1993. Heavy metals in street and house dust in bahrain. *Water Air Soil Pollut. : 66*,111–119

[9] Hani, A.,Pazira, E.,2011. Heavy metals assessment and identification of their sources in agricultural soils of Southern Tehran, Iran. *Environ. Monit. Assess.* 176, 677–691. https://doi.org/10.1007/s10661-010- 1612-3

[10] Huang, W., Campredon, R., Abrao, JJ., Bernat, M., Latouche, C.,1994. Variation of heavy metals inrecent sediments from Piratininga Lagoon (Brazil): Interpretation of geochemical data with the aid ofmultivariate analysis. *Environ. Geol.* 23, 241–247.

[11] Hu., KL., Zhang, FR., Lu, YZ.,Wang, R.,Xu, Y.2011. Spatial distribution of concentrations of soilheavy metals in Daxing county, Beijing. *Acta Sci. Circum.* 24, 463–469

[12] Ruiz F., González-Regalado ML., Borrego J., Morales JA., Pendón JGP., Muñoz JM.,1998. Stratigraphic sequence, elemental concentrations and heavy metal pollution in Holocene sediments fromthe Tinto-Odiel Estuary, southwestern Spain. *Environ. Geol.* 34, 270–278.

[13] Yang P., Mao R., Shao H., Gao Y., 2009. The spatial variability of heavy metal distribution in thesuburban farmland of Taihang Piedmont Plain, China. *C. R. Biol.* 332, 558–566.

[14] Franco-Urıa A., Lopez-Mateo C., Roca E., Fernandez-Marcos, ML.,2009. Source identification of heavy metals in pastureland by multivariate analysis in NW Spain. *J. Hazard. Mater.* 165, 1008–1015.

[15] Yao R J., Yang J., Gao P., Shao H., Chen X., Yu S., 2013. Multivariate simulation and assessment of three dimensional spatial patterns of coastal soil salinity using ancillary variables. *Fresenius Environ. Bull.* 22,39–52.

[16] Silva., MTB., Hermo B S., García-Rodeja, E., Freire, NV.,2005. Reutilization of granite powder as anamendment and fertilizer for acid soils. Chemosphere.61(7):993–1002.

[17] Mehta, N., Cocerva, T., Cipullo, S., Padoan, E., Dino, G A., Ajmone-Marsan, F., Cox, S F., Coulon, F., De Luca, D A., 2019. Linking oral bioaccessibility and solid phase distribution of potentially toxic elements inextractive waste and soil from an abandoned mine site: Case study in Campello Monti, NW Italy. *Scienceof the Total Environment*, *651*, 2799-2810.

[18] Magaly G Valencia-Avellan, Rebecca Slack, A E, B Anthony Stockdale C., Robert John George Mortimer .,2017. Effect of episodic rainfall on aqueous metal mobility from historical mine sites *Environ. Chem. 14*, 469–475

[19] Kahle, M., M. Kleber, and R. Jahn. 2002. *Review of XRD Based Quantitative Analysis of Clay Mineralsin Soils: The Suitable of Mineral Intensity Factor*. Geoderma109:191-205

[20] Kadir S., Adogan M S, Elitok O, Helvaci C,„2015.Composition and Genesis of the Nickel-Chrome- Bearing Nontronite and Montmorillonite in Lateritized Ultramafic Rocks in the Muratdği Region (Uşak,Western Anatolia), Turkey Clays and Clay Minerals volume 63, pages 163–184

[21] Moore, D M., Reynold, R C., 1997. X-Ray Diffraction and the Identification and Analysis of ClayMineral. Oxford University Press, Oxford.

[22] Blackmore, L C., Searle P L., Daly B K., 1981. Methods for chemicals analysis of soils. N. Z. Soil BureauSci. Rep. 10A. Soil Bureau, Lower Hutt. New Zealand.

[23] Jianwei Bu., Ziyong Sun ., Aiguo Zhou ., Youning Xu ., Rui Ma ., Wenhao Wei., Meng Liu.,2016.Heavy Metals in Surface Soils in the Upper Reaches of the Heihe River, Northeastern Tibetan Plateau, China. International Journal of Environmental Research and Public Health. MDPI

[24] Rayment, GE., Higginson FR., 1992. Australian laboratory handbook of soil and water chemicals methods. Australian soil and land survey handbook. Inkata Press, Melbourne, Sydney

[25] Scragg A.,2006. Environmental Biotechnology, Oxford University Press, Oxford, UK, 2nd edition

[26] Schindler M, Mantha H, Hochella Jr MF,2019.The formation of spinel-group minerals in contaminated soils: the sequestration of metal(loid)s by unexpected incidental nanoparticles.V. *20:1* GeochemicalTransactions

[27] Lasat M M., 2000. Phytoextraction of metals from contaminated soil: a review of plant/soil/metal interaction and assessment of pertinent agronomic issues. *Journal of Hazardous Substances Research*,vol. 2, pp. 1–25

[28] Jones L H P., Jarvis S C., 1981. The fate of heavy metals in *The Chemistry of Soil Processes*, Green D J., Hayes M H B., Eds., p. 593, John Wiley & Sons, New York, NY, USA

[29] Raven P H., Berg R., Johnson G B.,1998. Environment. Saunders College Publishing, New York, NY, USA, 2nd edition

[30] Bowles J F W., 2021. Encyclopedia of Geology (Second Edition), Scinecedirect

[31] Miguel Ángel Olego .,Miguel Javier Quiroga ., Cristina Mendaña-Cuervo ., Jorge Cara-Jiménez ., Roberto López 3 and Enrique Garzón-Jimeno,2021.Long-Term Effects of Calcium-Based Liming Materials on Soil Fertility Sustainability and Rye Production as Soil Quality Indicators on a Typic Palexerult.Processes,9:1181, MDPI

[32] Michael Schindler., Haley Mantha ., Michael F. Hochella Jr.,2021.The formation of spinel-group minerals in contaminated soils: the sequestration of metal(loid)s by unexpected incidental nanoparticles Geochemical Transactions,20:1

[33] Das S K., Chakrapani G J., 2011. Assessment of trace metal toxicity in soils of Raniganj Coalfield, India Environ Monit Assess 177: 63–71

[34] Antonio G. Caporale1., Antonio Violante., 2016. Chemical Processes Affecting the Mobility of Heavy Metals and Metalloids in Soil Environments Curr Pollution Rep (2016) 2:15–27

[35] Santos A., Alonso E., Callejon M., Jimenez J C., 2002.Distribution of Zn, Cd, Pb and Cu metals in groundwater of the Guadiamar river basin. Water Air and Soil Pollution,134(1–4), 273–283

[36] Bell F G., Stacey T R., Genske D D.,2000. Mining subsidence and its effect on the environment: some differing examples. Environmental Geology, 40(1–2), 135–152

[37] Lizárraga-Mendiola L., González-Sandoval M R., Durán Domínguez M C., Márquez-Herrera C., 2009. Geochemical behavior of heavy metals in a Zn–Pb–Cu mining area in the State of Mexico (central Mexico). Environmental Monitoring and Assessment, 155, 355–372.doi:10.1007/s10661-008-0440-1

[38] Filius A., Streck T., Richter J., 1998. Cadmium sorption and desorption in limed topsoils as influenced by pH: Isotherms and simulated leaching. J. Environ. Qual. 27, 12–18.

[39] McBride, M. B., Suave, S., Hendershot, W., 1997. Solubility control of Cu, Zn, Cd, and Pb in contaminated soils. European J. Soil Sci. 48, 337–346

[40] Behzad Mehrabi., Shiva Mehrabani., Behrouz Rafiei., Behrouz Yaghoubi., 2015.Assessment of metal contamination in groundwater and soils in the Ahangaran mining district, west of Iran. Environ Monit Assess 187: 727

[41] Adriano DC.,1986. Trace elements in the terrestrial environment (p. 533). New York: Springer

[42] Facchinelli A., Sacchi E., Mallen L.,2001. Multivariate statistical and GIS-based approach to identify heavy metal sources in soils. Environmental Pollution, 114, 313–324

[43] Loska K., Wiechula D., 2003. Application of principal component analysis for the estimation of source of heavy metal contamination in surface sediments from the Rybnik Reservoir. Chemosphere, 51, 723– 733

[44] Emma Sandell Festin., Mulualem Tigabu ., Mutale N., Chileshe., Stephen Syampungani., Per Christer Ode´n.,2019. Progresses in restoration of post-mining landscape in Africa. J. For. Res. 30(2):381–396

[45] Rankin W J.,2011. Minerals, metals and sustainability: meeting future material needs. CSIRO Pub, Collingwood

[46] Vela-Almeida D., Brooks G., Kosoy N.,2015. Setting the limits to extraction: a biophysical approach to mining activities. Ecol Econ 119:189–196

[47] Carrick P J., Kru¨ger R., 2007. Restoring degraded landscapes in lowland Namaqualand: lessons from themining experience and from regional ecological dynamics. J Arid Environ 70:767–781

[48] Golightly JP., 1979. Nickeliferous laterites: A general description, in Evans, D. J. I., Shoemaker, R. S. and Veltman, H., eds., International Laterite Symposium: New York, Society of Mining Engineers, pp. 3–23.

[49] Golightly J P., 1981. Nickeliferous Laterite Deposits., *Economic Geology 75th Anniversary Volume* pp. 710 – 735.

[50] Elias M., 2002. Nickel laterite deposits - a geological overview, resources and exploitation: Hobart,University of Tasmania, Centre for Ore Deposit Research Special Publication 4, p. 205–220.

[51] Marsh E., Anderson E., Gray F., 2013. Nickel-cobalt laterites—A deposit model, in U.S. GeologicalSurvey Scientific Investigations Report.

[52] Mustafa M., Maulana A., Irfan UR., Tonggiroh A., 2022.Determination of heavy metal elementsconcentration in soils and tailing sediments from lateritic nickel post-mining areas in Motui District, Southeast Sulawesi J. Degrade. Min. Land Manage. , pp. 3273-3279

[53] Muller G., 1969. Index of geoaccumulation in sediments of the Rhine River. GeoJournal, 2, 108–118.

[54] Sahu A., Vishwakarma N., Singh Y., Verma C B., 2020. Mineral chemistry of high-Al chromian spinel from ultramafic rocks of the Babina–Prithvipur transect, Bundelkhand Craton, central India: Implicationfor petrogenesis and tectonic setting. Article number: 182 (2020) Journal of Earth System Science volume 129

[55] Maulana A., Christy A G., Ellis D J., 2015. Petrology, geochemistry and tectonic significance of serpentinized ultramafic rocks from the South Arm of Sulawesi, Indonesia Chemie der Erde,75:1, 73-87

[56] Tonggiroh A., Jaya A., Irfan UR., 2017. Type of nickel laterization, Lasolo fracture and mollase deposits of Southeast Sulawesi, Indonesia. Eco. Env. & Cons. 23 (1), pp. (97-103)

[57] Zhang Y., Qie J., Wang XF., Cui K., Fu T., Wang J., Qi Y., 2020. Mineralogical Characteristics of the Nickel Laterite, Southeast Ophiolite Belt, Sulawesi Island, Indonesia Mining, Metallurgy & Exploration 37:79–91

[58] Zhang Z W., Wang Y L., Wang C Y., Qian B., Li W Y., Zhang J W., You M X., 2019. Mafic-ultramafic magma activity and copper-nickel sulfide metallogeny during Paleozoic in the Eastern Kunlun OrogenicBelt, Qinghai Province, China. China Geology v 2 : 4,p467-477

[59] Scoates J S., Scoates R F J., Wall C J., Friedan R M., Couëslan C G., 2017. Direct Dating of Ultramafic Sills and Mafic Intrusions Associated with Ni-Sulfide Mineralization in the Thompson Nickel Belt, Manitoba, Canada. Economic Geology 112 (3): 675–692.

[60] Barnes S J., Lightfoot P C., 2005. Formation of Magmatic Nickel Sulfide Ore Deposits and Processes Affecting Their Copper and Platinum Group Element Contents. Society of Economic Geologists, Inc. *100th Anniversary Volume,* pp. 000–000