Examining Soil Erodibility, Soil pH, and Heavy Metal Accumulation in a Nickel Ore Mine: A Case Study in Tubay, Agusan del Norte, Philippines

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ABSTRACT

Mining activity always presents threats to soil and water pollution. As an extractive industry, it disturbs the ground and the biodiversity associated with soil and plants. Its operations have led to severe geological and environmental problems, including the depletion of land and water resources, geological dangers, and ecological landscape devastation that may have accelerated the desertification of mining areas. This case study analyzed the soil's physical and chemical properties in a nickel laterite mine, including soil erodibility K factor, soil pH, and heavy metal accumulation, as a basis for establishing mine management protocol during and post-mining operations in Tubay, Agusan del Norte, Philippines. Results determined a slightly alkaline pH level. An estimate of soil erodibility ranging from 0.016 to 0.066 was determined using the USLE-K factor, with the highest erodibility at Mine 7, where % silt is high and % sand is lowest. X-ray fluorescence (XRF) spectroscopy was used to analyze soil samples. The findings show that Ni, Fe, Co, and Mn in the soil were above the WHO-permitted limits. The surface soil had mean values of 9,239 ppm for nickel, 302,618 ppm for iron, 639 ppm for cobalt, and 5,203 for manganese. Heavy metals in soil may be consumed by crops and pollute land and water.

1. INTRODUCTION

Nickel ore mining plays an immense role in the global nickel industry (Trescases, 1997) by creating valuable technologies and infrastructure, including operations in agriculture. They are Mg-rich or ultramafic rocks with primary Ni contents ranging from 0.2 to 0.4 percent through a lateritisation process (Golightly, 1981). The depth of a nickel laterite profile usually ranges from 10 meters to 50 meters below the surface (Nahon, 1986) and is excavated through open-cut mining methods, removing wasteful overburden.

Mining has long been vital to human economic prosperity; however, the economic and technological demands have increased mining disturbance over the years. Its operations have resulted in severe geological and environmental issues, such as the degradation of land and water supplies, geologic hazards, and ecological landscape destruction, potentially contributing to the desertification of mining areas (Jha, 2020; Lei et al., 2016; Wu, 2017; Zhang et al., 2011). Generally, nickel extraction significantly impacts water and sediment quality (Schmidt et al., 2012) if left uncontrolled and improperly managed.

The Philippines possesses vast copper, gold, nickel, and other minerals. Its economic expansion is fueled by the mining sector, both directly and indirectly. Approximately 24 nickel ore mines are active in the country. As of 2021, Region XIII - Caraga has fourteen (14) companies focused on exploring Nickel ore mines, with one location in Tubay, Agusan del Norte. The Tubay nickel ore mining site is about 10 km south of Lake Mainit, with rolling mountains, dense flora on the sidehills, and flatlands that encircle the coastline area. It receives 2,125.7 millimeters of precipitation annually with an average of 157 days with precipitation, according to climatic normal data

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from 1991 to 2021. The mining site is in a nearby community where the livelihood of the locals is mainly rice farming and fishing. Due to its proximity, the co-existence of mining and agriculture poses harm, especially in extreme rainfall events where erosion and sediment transfer can be a significant threat.

Soil erodibility, K, as a measure of soil sensitivity to erosion, shows the intrinsic susceptibility or resistance of the soil to erosive action and is the most critical component in predicting soil loss (Huang et al., 2022; Ostovari et al., 2019; Salehi-Varnousfaderani et al., 2022). The K factor in Universal Soil Loss Equation or USLE (Wischmeier and Smith, 1986) is most adopted in soil erosion models (Auerswald et al., 2014; Kulikov et al., 2020), represented by Equation 1:

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

Where; A is average annual soil loss, R is the rainfall factor, K is the soil erodibility factor, LS is the topography factor, C is the crop factor, and P is the control practice factor.

USLE is a conservation tool generally accepted and widely used in various kinds of research regarding soil management. It includes the estimation of erosion for land use (Okorafor et al., 2018), upland erosion (Almasalmeh et al., 2021; National Institute of Hydrology, 2017), specific sediment yield (Rajbanshi and Bhattacharya, 2020), erosion patterns (Pijl et al., 2020), as well as estimating soil erosion in mining (Ramli et al., 2020). This model and its subsequent Revised (RUSLE) and Modified (MUSLE) variants are commonly used worldwide, with a significant number of developed models (Aksoy et al., 2019; Hajigholizadeh et al., 2018). It has inspired several other models, including LISEM (Limburg Soil Erosion Model) (de Roo et al., 1998), WEPP (Water Erosion Prediction Project) (Morgan and Nearing, 2011), EUROSEM (European Soil Erosion Model) (Morgan et al., 1998), EGEM (Ephemeral Gully Erosion Model), and PESERA (Pan European Soil Erosion Risk Assessment) (Okorafor et al., 2018) and EPIC - Erosion Productivity Impact Calculator (Williams et al., 1990).

Sediment mobility through runoff directly impacts land and water quality. They are classified as significant contaminants in the aquatic environment (Frey et al., 2015; Milligan and Law, 2013). In a scenario where there is an anthropogenic activity like mining, heavy metals such as Ni, Fe, and Al are present in high concentrations (Apodaca et al., 2018; Gavhane et al., 2021) in mine waste (tailings dams and overburden waste rock sites) (El Azhari et al., 2017; Chileshe et al., 2020; Lei et al., 2016). In turn, heavy metals could endanger agricultural resources due to surface or groundwater pollution, offsite contamination via water erosion, and uptake by plants (Chileshe et al., 2020; Shirani et al., 2020). Additionally, fishes tend to experience sublethal stress from suspended sediments (Binet et al., 2018; Wang et al., 2020) rather than lethality. Additionally, natural weathering, such as wind erosion, rainfall flushing, and sulfide oxidation in the discarded overburden, may release heavy metals into soils, surface water, and groundwater, posing environmental hazards (Bartzas et al., 2021).

It is crucial to understand the possible impacts of the open-pit nickel mining site on its surrounding environment. Hence, the USLE-K factor is used in this study to examine the soil erodibility in Tubay, Agusan del Norte. Heavy metal accumulation in the soil is determined using X-ray fluorescence (XRF) spectroscopy. XRF spectroscopy has proven to be a dependable method for an in-situ soil analysis to evaluate metal pollution (Peralta et al., 2020). This study can produce insight that gives awareness to the locality, better mine management, and a decision tool for policymaking in the local government unit.

2. METHODOLOGY

2.1 Study site background

The research area (Figure 1) is a nickel ore mining facility located in the northern part of Agusan del Norte, Mindanao, Philippines, under the jurisdiction of the municipalities of Tubay, Jabonga, and Santiago, Agusan del Norte. The mine site lies within 9°10'30" and 9°19'30" north latitude and 125°29'30" to 125°33'30" east longitude. It is within a 4,995-hectare Mineral Production Sharing Agreement (MPSA) contract area. Boundaries of the mining site include the western range approximately 10 km south of Lake Mainit, rolling mountains with thick and varied vegetation on the sidehills, and flatlands that encompass the coastal area. According to the soil order classification by the Bureau of Soil and Water Management (BSWM) (DA-BSWM, 2017), the soil study site falls under Acrisols. The subsurface of Acrisols has more clay than the topsoil due to pedogenetic processes (particularly clay migration) that result in an argic subsoil horizon. Acrisols have low-activity clays and low base saturation in the 50-100 cm deep range. They are most prevalent in tropical, subtropical, and warm temperate regions where forests dominate native vegetation (IUSS and WRB, 2015). Acrisols are taxonomically related to USDA soil order Oxisols. Oxisols are tropical and subtropical soils with a high level of weathering and are rich in minerals such as quartz, kaolinite, and iron oxides (USDA-NRCS, 2023).

The mining facility has twelve areas for exploration; however, during the study, four of the mining sites were inaccessible, and safety was at risk; hence this study focuses on seven mining sites: 1, 2, 3, 4, 5, 7, and 9. The discharge area (10) was also included. As of 2021, an estimated 20% of the mined area was undergoing rehabilitation leaving at most 80% bare soil.

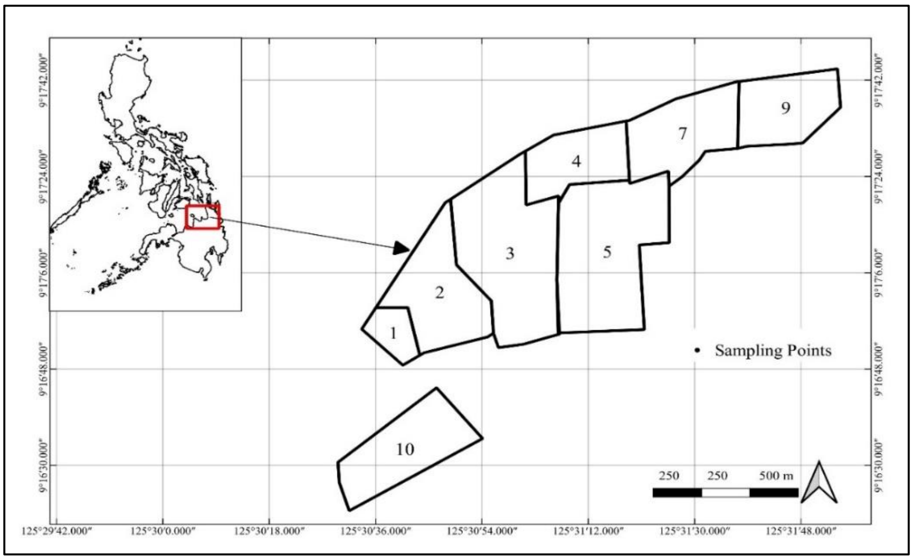

Figure 1. Study area for soil quality assessment

2.2 Soil sampling and analysis

A total of eight mine locations served as test zones for soil samples, including the discharge area, to evaluate the soil composition in the nickel laterite mine. This research utilized a composite soil sampling method. Each mine site had 18 subsamples taken, totaling 144 subsamples. Each subsample was mixed and blended to create three homogenous samples, while large rocks and other elements were removed. Forty-eight (48) composite samples, 24 at the mine surface and 24 at the settling ponds, were analyzed for this study.

Soil samples were collected from 0 to 15 centimeters from the top surface. Each sample was air-dried and sieved through a 2 mm mesh for analysis, including particle size distribution of sand, silt, clay, soil texture, organic matter content, and pH. Table 1 presents the summary of the soil analysis conducted in this study.

Particle Size Analysis (PSA) determines the soil's relative sand, silt, and clay amounts. These size fractions constitute the mineral component of the soil when combined. The particle distribution of sand (0.05-2.00 mm), silt (0.05-2.00 mm), clay (<2 mm), and clay were determined using the sieve analysis and hydrometer method (Gee and Or, 2004) and USDA triangle (USDA, 1987) for soil texture. Table 2 presents the common soil textural classes according to USDA.

Table 1. Summary of soil analysis conducted in this study

Parameter	Method	Reference
% Sand	Sieve analysis	Gee and Or (2004)
% Silt	Sieve analysis/ Hydrometer test	Gee and Or (2004)
% Clay	Sieve analysis/ Hydrometer test	Gee and Or (2004)
Organic matter	Loss of ignition	Nelson and Sommers (2018); ASTM D7348 (Webster, 2003)
Soil pH	Electrochemical	ASTM D4972-19
Heavy metals (Ni, Co, Fe, Mn)	XRF	
Soil erodibility factor, K	USLE	Wischmeier and Smith (1986)

Table 2. USDA textural classes of soil (coarse and moderately coarse)

Common names of soils (general texture)	Sand	Silt	Clay	Textural class
Sandy soils (coarse texture)	86-100	0-14	0-10	Sand
	70-86	0-30	0-15	Loamy sand
Loamy soils (moderately coarse texture)	50-70	0-50	0-20	Sandy loam

Soil texture affects nutrient retention, water storage, drainability, and other agricultural variables. Clay soils hold more nutrients and water than sandy soils.

Soil organic matter plays a crucial role in soil quality and erodibility. It influences how soil particles aggregate to form a stable soil structure (Kumar and Kushwaha, 2013). It is measured using the Loss of Ignition (LOI) method (Nelson and Sommers, 2018), Equation 2:

$$\%OM = \frac{W_{105} - W_{450}}{W_{105}} \times 100 \qquad (2)$$

Soil samples (2mm) were carefully weighed and put into a 450°C preheated porcelain crucible. Samples were dried in the furnace at 105°C for 16 hours and left cool in a desiccator, establishing the initial weight (W_{105}). The samples were heated again to 450°C in the furnace for 16 hours. After cooling, the final weight (W_{450}) is determined. According to (Murphy et al., 2012), soil organic matter levels are based on the soil textural class, ranging from extremely low (1%) to average (2% to 4%) to very high (>5%) by weight.

Soil erodibility factor K of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1986) determines the estimated soil erodibility in the area. Soil erodibility is a critical indicator for assessing a soil's erosion vulnerability, with a mathematical formula shown in Equation 3:

$$K = 2.1\,M^{1.14} \times 10^{-4}\,(12 - OM) + 3.25(S - 2) + 2.5(P - 3) \qquad (3)$$

Where; M, Equation 4, is the texture of the top 15 cm of soil, Equation 4, relating to soil particles, OM is the organic matter content determined in the laboratory, as described in Table 2 using the Loss of Ignition (LOI) method (Nelson and Sommers, 2018), and S and P are codes for soil structure and permeability, respectively. The percentage of clay is 0.002 mm, the percentage of silt is 0.002-0.050 mm, and the percentage of extremely fine sand is 0.05-0.10 mm (USDA, 1987).

$$M = (100 - \%\ \text{clay})\ (\%\ \text{very fine sand} + \%\ \text{silt}) \qquad (4)$$

As the soil texture becomes finer, soil erodibility increases. Increased erodibility readings imply that the soil is more prone to erosion (Kumar and Kushwaha, 2013). Soil erodibility factor ranges from 0.02, the least erodible, to 0.64, for most erodible soils (IWR, 2002). Clay-rich fine-textured soils have low K values ranging from 0.02 to 0.15, while sandy soils range from 0.05 to 0.20. Medium textured soils, including silt loam, have moderate K values, 0.25 to 0.40. Silty soils are the most erodible, crust readily, and have a high drainage rate (Pijl et al., 2020).

Soil samples at MS and SP passing through a 2 mm sieve were evaluated for pH level. Soil pH measures soil acidity or alkalinity and is crucial in agricultural productivity management (Gozukara et al., 2022). Nutrient mobilization, microbial activity, and plant uptake increase with ideal pH. In this study, soil pH determination used an electrochemical method described by (Webster, 2003) and ASTM D4972-19. Twenty (20) g of air-dried soil was added with 20 mL of reagent water, covered, and continuously stirred at 240 rpm for 5 min. The soil suspension was allowed to stand for about 1 hour to allow most of the suspended clay to settle out from the suspension. After which, the electrodes for pH reading was immersed into the suspension. Soil pH ranges from <5.5 as strongly acidic to strongly alkaline at >9.2. The ideal soil pH is between 6.5 and 7.5, approaching neutral (Khan et al., 2022).

X-ray fluorescence (XRF) spectroscopy, a non-destructive method in determining the elemental makeup of substances, was used to analyze heavy metals in the soil samples, including Ni, Co, Fe, and Mn. Powdered soil samples (approximately 50 µm) were placed in a 30 mm outer ring cup with holes lined with a 3.6 µm Mylar film and were analyzed using the Epson 1 EDXRF machine. The maximum permissible limits for Ni, Co, Fe, and Mn according to World Health Organization (WHO, 1996) are listed in Table 3.

Table 3. Maximum allowable limit of heavy metals concentrations in soil by WHO (1996)

Heavy metal	Maximum permissible level in soil in ppm
Ni	50
Fe	50,000
Co	50
Mn	2,000

2.3 Statistical analyses

Pearson's correlation analysis determined the relationships between the soil erodibility indicators and their influencing factors. The linear regression method evaluated the correlations between soil erodibility indicators and soil surface characteristics.

3. RESULTS AND DISCUSSION

3.1 Particle size distribution, soil texture, organic matter, and K factor

Table 4 displays the soil particle distribution (% sand, % silt, % clay) and organic matter content within the research region's 0-15 cm topsoil. The study region has an average sand content of 90.61 percent, 7.76 percent silt, 1.33 percent clay, and an average organic matter content of 4.33 percent, classified as sandy soil (USDA, 1987). Categorizing by each mine site, each was classified as sandy except for Mine site 7. Mine site 7 falls under the loamy sand classification, which recorded the most significant percentage of silt and the lowest percentage of sand.

Mine site 4 recorded the highest % of sand at 94.46% and the lowest at Mine site 7 (84.78%). Percent silt is also highest at Mine site 4 (8.43%) and lowest in Mine site 2 at 4.07%. Clay concentration in the mining site is generally low, ranging from the highest at 2.72% (discharge) and the least at 1.21% (Mine site 1). By Murphy rating, the site has a high to extremely high OM rating (Murphy et al., 2012), with the highest value at site 5 (7.42%) and the lowest at mine 1 (2.3%). The estimated K values are generally low due to the high sand concentration (Pijl et al., 2020). K factors are most significant at mine site 7, where the percentage of sand is lowest, and silt is the most abundant.

Table 4. Summary data on particle size distribution, soil texture, organic matter, and K factor

Site	Elevation (m)	% Sand	% Silt	% Clay	Soil Texture	% OM	USLE-K
Mine 1	209	92.99	5.80	1.21	Sandy	2.38	0.027
Mine 2	245	94.46	4.07	1.47	Sandy	3.45	0.017
Mine 3	265	93.23	5.15	1.62	Sandy	2.29	0.016
Mine 4	262	90.27	8.43	1.30	Sandy	6.52	0.025
Mine 5	277	91.86	6.90	1.24	Sandy	7.42	0.016
Mine 7	130	84.78	13.54	1.68	Loamy sand	3.38	0.066
Mine 9	238	89.49	8.72	1.79	Sandy	5.91	0.033
Discharge	17	87.83	9.45	2.72	Sandy	3.28	0.045
Mean		90.61	7.76	1.63	Sandy	4.33	0.031

Figure 2 presents the variation of the K factor and the elevation change. The estimated K factor generally decreases at higher altitudes and increases as elevation decrease. Also exhibiting the lowest projected soil erodibility are mines 3 and 5 at higher elevations.

By correlation, as shown in Table 5, the USLE-K factor value correlates positively with silt and clay percentages in the soil and negatively with sand and organic matter. Regression analysis revealed a significant positive relationship between USLE-K and % silt (r=0.78, p=1.93E-05). Consequently, USLE-K has a significant negative correlation between % sand (r=0.80, p=9.44E-06). The indices of soil erodibility and susceptibility to erosion are impacted by soil aggregates (Khanchoul and Boubehziz, 2019; Kumar and Kushwaha, 2013; Madubuike et al., 2020). Given that sandy soils have a low drainage rate, the findings of this study indicating that sand content has a significant negative correlation with the erodibility factor suggest that soils high in the sand can achieve lower erodibility since sand content decreases soil erodibility (Khanchoul and Boubehziz, 2019; Madubuike et al., 2020; Radziuk and Switoniak, 2021).

In contrast, there is a clear positive link between clay and silt. High silt-content soils are more prone to erode due to their ease of detachment and high runoff rate, while clay particles create clumping (Ghosal and Das Bhattacharya, 2020; Radziuk and Switoniak, 2021). As a binder for the aggregates needed for soil structure analysis, clay is essential for calculating the K factor. Clay particles, however, might not combine with water, increasing soil loss.

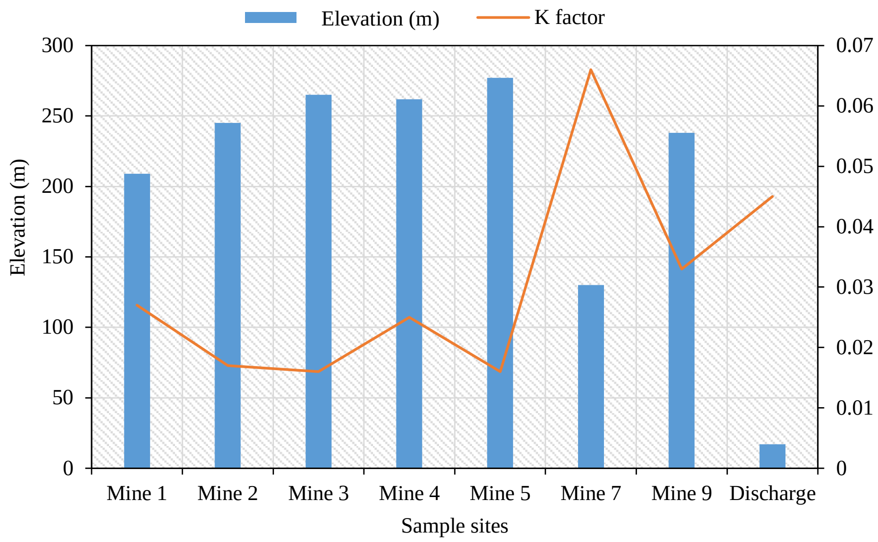

Figure 2. Site elevation (m) vs. K factor

Table 5. The correlation coefficient of soil properties and erodibility factor, K

	% Sand	% Silt	% Clay	Organic matter
1. % Sand	-			
2. % Silt	-0.98	-		
3. % Clay	-0.81	0.68	-	
4. OM	0.09	-0.07	-0.13	-
5. USLE-K	-0.80	0.78	0.65	-0.29

This study shows a significant positive correlation between the percent clay and soil erodibility (r=0.65, p=0.0011), suggesting that a higher percentage of clay in the soil may increase erodibility. Clay-rich soils, however, seem to show considerable resilience to erosion in other studies (Khanchoul and Boubehziz, 2019; Madubuike et al., 2020; Ostovari et al., 2019). The only likely direct source of a positive correlation between clay content and K factor value is a contemporaneous decline in sand content (Radziuk and Switoniak, 2021). The clay content in the soil samples under examination is likely insufficient to generate an aggregate resistant to erosion, but it is sufficient to decrease the soil's permeability and raise the likelihood of surface runoff (Radziuk and Switoniak, 2021).

The association between OM and K is not as strong as in this study's other soil characteristics. OM shows no significant correlation between OM and K (r=0.29, p=0.19). A related study shows that OM in the soil properties may reduce soil erodibility (Madubuike et al., 2020) at the mine site. Higher OM concentrations suggest that soil detachment susceptibility and erosion will decrease (IWR, 2002; Khanchoul and Boubehziz, 2019).

3.2 Soil pH

Overall, the mine site is generally classified as slightly alkaline, as in Figure 3. Soil pH in the settling pond is relatively higher than at the surface, ranging from 7.2 to 8.6 and 7.0 to 8.4, respectively. SP shows a strong alkaline pH value (8.6) in mine 1 and gradually decreases to a moderately alkaline value of 8.2 at the exit. Meanwhile pH level at the surface also recorded a moderately alkaline value of 8.4 at the exit area.

Nevertheless, the surface and settling pond's pH level generally shows values within the acceptable pH. The result suggests that soil at this level is calcareous (Thomas, 1996). Hence, soil acidity and the addition of lime are not a concern. Carbonate-rich soil is said to have the ability to stabilize organic materials due to chemical stabilization mechanisms (Virto et al., 2017). A strong alkaline observed at the settling pond of mine site 1 corroborates an initial high pH level and decreases when mine residues pass through a series of settlings ponds. A correlation coefficient of r=0.70, p=0.0013 suggests a significant positive relationship between pH at the surface and the settling pond.

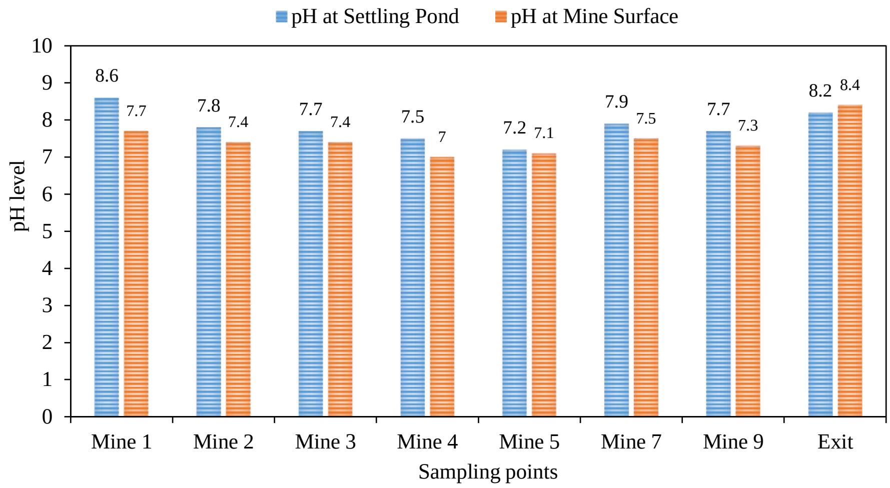

Figure 3. pH Level at the settling ponds (SP) and mine surface (MS)

3.3 Heavy metal concentration

3.3.1 Nickel (Ni)

Nickel concentrations were recorded from a minimum of 6,980 ppm to a maximum of 11,350 ppm at the mine surface, while nickel in settling ponds ranged from 5,000-11,000 ppm, illustrated in Figure 4. These values exceeded the maximum allowable limit (MAL) by WHO at 50 ppm for all mine sites. The recorded concentrations are approximately 130-200 times higher than the allowable limit.

3.3.2. Iron (Fe)

The permissible allowable limit of Fe content in the soil is 50,000 ppm, as recommended by WHO. In Figure 5, the iron concentration recorded higher values than the limit for all mine sites. Fe is found to have a concentration of 185,650-443,100 ppm at MS and 95,250-463,775 ppm at SP.

3.3.3. Cobalt (Co)

WHO recommends a Co concentration of 50 ppm maximum allowable limit in soil. By XRF analysis, the sampling sites exceeded the limit by 8 to 22 times more. The highest Co accumulation at MS was found in Mine sites 3 and 5 at 700 ppm, while 1,125 ppm was recorded in Mine site 5 (SP), as shown in Figure 6.

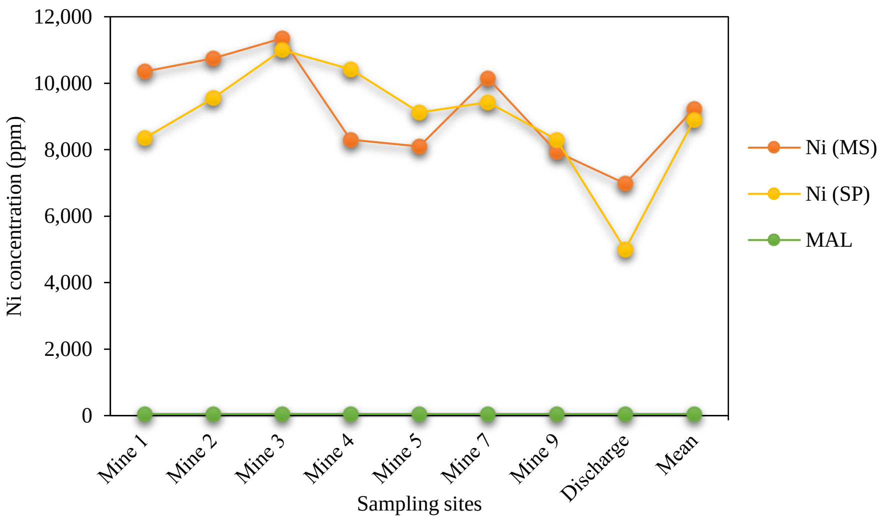

Figure 4. Nickel concentration in the mine surface (MS) and settling pond (SP)

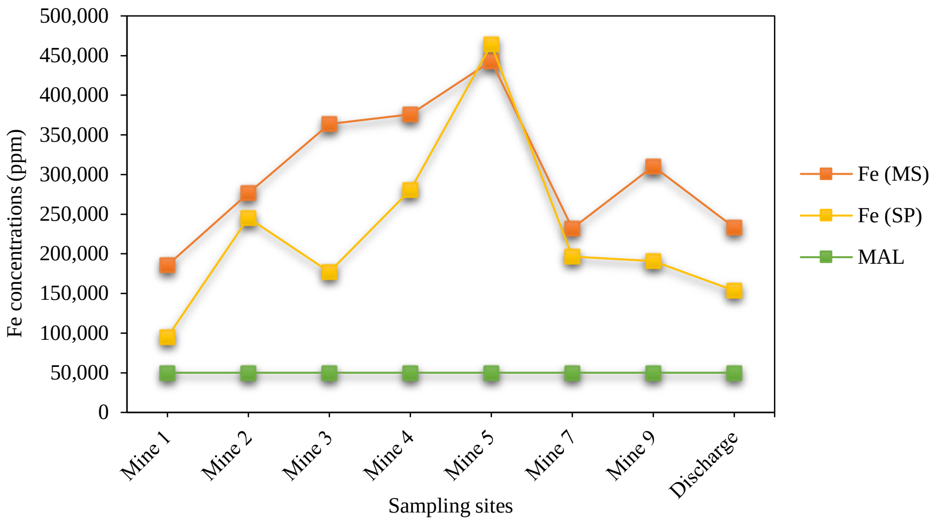

Figure 5. Fe concentrations in the mine surface (MS) and settling pond (SP)

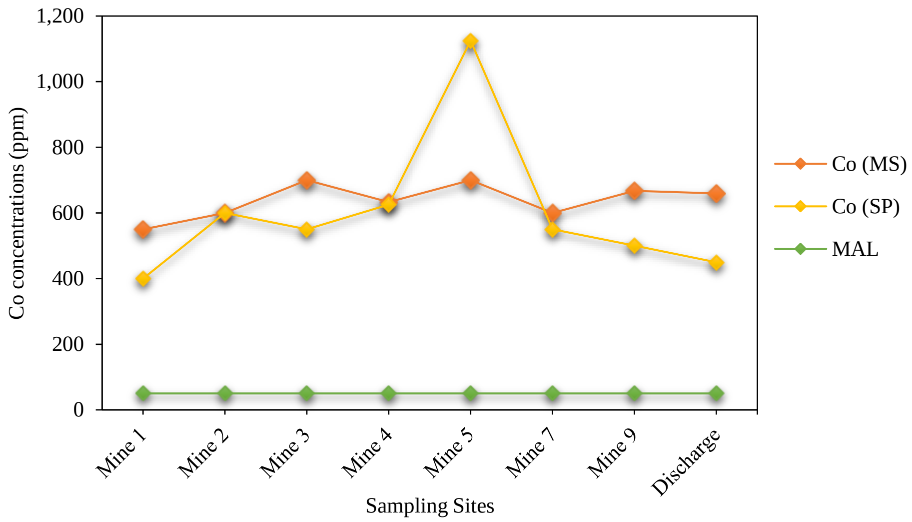

Figure 6. Co concentrations in the mine surface (MS) and settling pond (SP)

3.3.4. Manganese (Mn)

Manganese (Mn) recorded the lowest concentrations compared to WHO values (2,000 ppm), ranging from 3,850-7,500 ppm and 3,300-8,475 ppm at the mine surface and settling pond, respectively, Figure 7. However, the values still exceeded the allowable limit as recommended by WHO, except at Mine site 1 (SP), which has 2,000 ppm, just equivalent to the maximum allowable limit.

3.4. Implications and future work

It is well established that soil is more prone to erosion in areas with a high silt concentration. Due to their ease of detachment and fast flow rate, silt is more sensitive to soil erodibility (IWR, 2002; Radziuk and Switoniak, 2021), while organic matter and a high sand content reduce soil erosion impacts (Chen et al., 2021; Kumar and Kushwaha, 2013; Tian et al., 2022). The area with the highest silt concentration had the highest significant value for K; as a result, soil conservation management has to be given more consideration in this area. However, calibration and validation can improve the K-factor estimations' accuracy. An area-specific map of the soil erodibility may also help plan soil conservation strategies, modeling, and forecasting erosion. Correspondingly, accurate information on the site data is beneficial to prevent soil loss and minimize the consequences on its surroundings, particularly in high rainfall events.

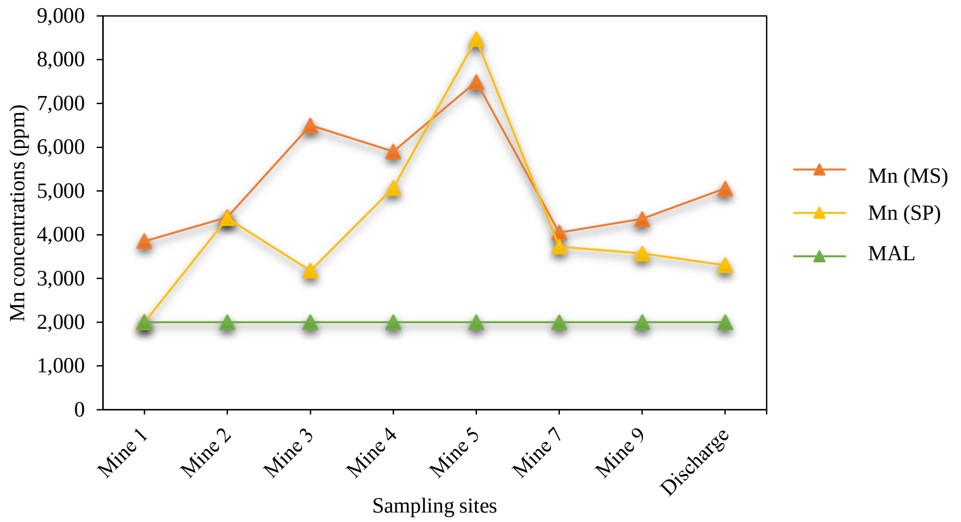

Figure 7. Mn concentrations in the mine surface (MS) and settling pond (SP)

Although the soil pH level in the area is ideal, the overly high presence of heavy metals is alarming. It causes plant growth inhibition, chlorosis, necrosis, and wilting (Bhalerao et al., 2015; Prematuri et al., 2020; Sreekanth et al., 2013). When considering the impact on the food chain, the ingestion of plants from soils with significant levels of heavy metals could be dangerous to human health. Ni also adversely affects marine plants and organisms (Gavhane et al., 2021). Hence, natural farming is not an option before any mine rehabilitation is applied. Post-mining remediation and revegetation may be carefully planned to remove the excess presence of heavy metal in the soil, specifically Ni, Fe, Co, and Mn, and reduce harmful environmental effects and possible re-utilization of the site. Further research should be carried out to study the accumulation of heavy metals in the surrounding environment, especially in crops and waters.

Due to the significant residues of Ni, the possibility of phytomining in the area can also be considered as part of a progressive rehabilitation strategy to re-vegetate huge areas stripped by lateritic nickel mining and generate income by “harvesting” nickel metal. Developing plant-based remediation technologies for Ni-contaminated soils has garnered much interest due to its cost-effectiveness, environmental friendliness, and lack of adverse side effects (He et al., 2012). Hyperaccumulators, plants accumulating high heavy metal concentrations, make excellent models for investigating metals’ uptake, movement, and storage and their evolution and environmental adaptation.

4. CONCLUSION

The nickel ore mining site in Tubay, Agusan del Norte, was subjected to soil erodibility estimate, pH value determination, and heavy metal accumulation (Ni, Fe, Co, Mn). This study has determined an erodibility estimate of 0.016 to 0.066 using the USLE-K erodibility factor formula. The k factor is highest at mining site 7, where sand is the lowest (84.78%), and silt is highest (13.54%). The nickel ore mine has a slightly alkaline pH level at an average soil pH of 7.4 and 7.8 at the surface and settling pond, respectively, within the acceptable range. The heavy metal accumulation of Ni, Fe, Co, and Mn exceeded the recommended permissible limit by WHO. The excessive heavy metal levels in the soil are potentially available for crop intake and may pose a threat to land and water environment pollution, including humans.

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