Assessment of Heavy Metal Contamination in Paddy Field Soils: A Case Study in Ranau Valley, Sabah, Malaysia

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Abstract. The weathering of ultrabasic rocks surrounding the Ranau Valley in Sabah, Malaysia, contributes to the formation of soils with elevated concentrations of heavy metals. These metals, including Manganese (Mn), Nickel (Ni), Chromium (Cr), and others, have the potential to disperse into nearby paddy fields, leading to significant soil contamination. This study aims to: (a) determine the concentrations of heavy metals in the paddy field soils of Ranau Valley and (b) map their spatial distribution using Geographic Information System (GIS) technology. The results revealed that Mn was the most abundant metal, with concentrations reaching 13,855.67 mg/kg, followed by Iron (Fe), Ni, Zinc (Zn), and Cr. Several metals, including Mn, Ni, and Cr, exceeded established soil toxicity thresholds, particularly in areas influenced by ultrabasic rocks and agricultural practices. Elevated levels of Copper (Cu), Lead (Pb), Zn, and Cadmium (Cd) were also observed in regions affected by the use of chemical fertilizers. These findings highlight the potential risks to agricultural productivity and food safety in the region, as metals such as cadmium and lead can accumulate in crops, posing health risks to local populations. To address these concerns, remediation strategies such as organic amendments and pH adjustments are recommended. Regular monitoring and sustainable soil management practices will be essential to safeguard soil health, ensure food security, and reduce environmental risks in the Ranau Valley.

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1 Introduction

Heavy metal contamination in agricultural soils has become a global concern due to its impact on food safety and environmental health [1]. Metals like Manganese (Mn), Nickel (Ni), Chromium (Cr), Cadmium (Cd), and Lead (Pb) can accumulate in soils through natural weathering, mining, industrial activities, and agrochemical use, especially in paddy fields where irrigation may increase their bioavailability [2, 3]. In the Ranau Valley, Sabah, Malaysia, ultrabasic rocks and agricultural practices contribute to elevated concentrations of metals such as Mn, Ni, Cr, and Cobalt (Co), which can harm soil fertility and crop health [4].

Soil health is critical for agricultural ecosystems and food production. In paddy fields, persistent heavy metals reduce crop yield and quality, with toxic metals like Cd and Pb posing long-term health risks, including kidney damage and cancer [5]. This study aims to assess the concentration and spatial distribution of heavy metals in Ranau Valley's paddy fields using Geographic Information System (GIS) technology, providing insights to guide remediation efforts and promote sustainable land management. The findings will help mitigate the impact of heavy metals on soil health, productivity, and food safety.

2 Method and Materials

This study was conducted in the Ranau Valley, Sabah, Malaysia, within the geographical coordinates 5°57'20" to 5°58'52"N latitude and 116°40'42" to 116°42'20"E longitude. The region is known for its ultrabasic soil, formed from the weathering of ultrabasic rocks in the area. These soils are rich in heavy metals, which have potential impacts on the paddy fields located downstream of these formations. The study area is shown in Figure 1.

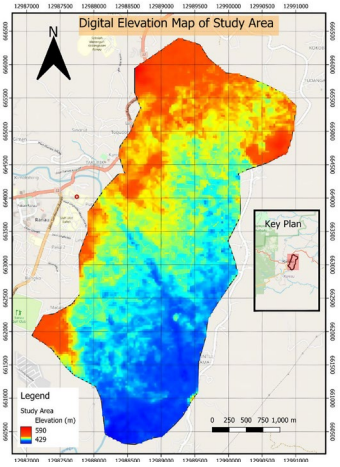

Fig. 1. Map of the study area.

2.1 Soil Sampling and Preparation

Soil samples were collected from 22 different stations across the study area. Each sample was air-dried at room temperature, crushed, and sieved through a 2 mm mesh to ensure

uniform particle size for the physicochemical analyses. For heavy metal content analysis, samples were further sieved using a 63 μm nylon sieve to isolate finer particles, which are more reactive and likely to reflect the true heavy metal content in the soil.

2.1.1 Physicochemical Analysis

Several physicochemical properties of the soil were measured, including pH and organic matter content, as these parameters significantly influence heavy metal availability in soils. Organic matter content was determined by drying approximately 5 grams of soil at 105°C in an oven overnight, then further heating the sample at 400°C in a muffle furnace to calculate the total organic matter. The soil's pH was measured by mixing 10 grams of soil with 25 ml of distilled water, allowing the mixture to equilibrate, and then measuring with a calibrated pH meter.

2.1.2 Determination of Heavy Metal Content

To determine the heavy metal concentrations, air-dried soil samples (<63 μm) were extracted using a 0.5M ammonium acetate-acetic acid solution. The extracts were analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), which accurately quantifies metal concentrations, including Mn, Cd, Pb, Cu, and others. This method provides high sensitivity and precision for detecting even trace levels of heavy metals.

2.2 Geographic Information System (GIS) Mapping

The collected data were processed using ArcGIS 10.1 software, employing the Inverse Distance Weighted (IDW) method to generate spatial distribution maps of the heavy metals across the study area. By creating three-dimensional graphics and mapping heavy metal concentrations, the study provides a clear visualization of contamination hotspots. This approach allows for the identification of specific areas where remediation efforts may be required.

2.3 Statistical Analysis

To evaluate the relationships between soil characteristics and heavy metal concentrations, correlation analysis was employed. This analysis helped to identify how soil pH, organic matter content, and other physicochemical properties influence the retention and mobility of heavy metals in the soil. Specifically, Pearson's correlation coefficient was used to assess the strength and direction of relationships between variables, such as the concentration of heavy metals (e.g., Mn, Cd, Cu, Pb) and soil properties. All statistical analyses were performed using SPSS software, ensuring robust data handling and interpretation. The significance of correlations was tested at three different levels: 5%, 1%, and 0.1%, providing a clear understanding of the relationships between variables. Quality control measures, including data validation and calibration of analytical instruments, ensured the reliability and accuracy of the results.

3 Results and Discussions

3.1 Physico-chemical Properties Of Paddy Soil

The paddy soils in Ranau Valley show varying levels of organic matter (ranging from 2.38% to 13.62%, averaging 7.66 ± 4.24%) and pH, both of which significantly affect heavy metal

retention and plant growth. Organic matter is crucial for binding heavy metals, reducing their mobility and bioavailability, thus mitigating their toxicity to plants and the environment [6]. However, due to the plowing of rice fields, organic matter decomposition is accelerated, leading to lower average values. Additionally, organic matter content decreases with soil depth, further impacting the soil's capacity to retain metals [7].

Soil pH in the valley ranges from 4.54 to 5.68, indicating generally acidic conditions influenced by organic matter decomposition, weathering of ultrabasic rocks, and natural erosion processes [8]. Low pH increases the solubility and mobility of heavy metals, raising the potential for plant uptake. The combination of low pH and variable organic matter content plays a key role in influencing heavy metal behavior in the soil, impacting soil health and crop productivity in the region [9].

Table 1. pH value and soil organic matter for each station.

Station	pH	SOM%
1	5.15	5.26
2	4.99	7.95
3	4.64	2.38
4	5.12	10.89
5	5.15	5.35
6	5.07	6.70
7	5.26	7.13
8	5.08	6.05
9	4.96	8.42
10	5.26	7.50
11	5.68	6.07
12	5.64	8.09
13	4.67	11.21
14	4.85	7.12
15	4.78	6.20
16	5.05	5.52
17	5.14	5.54
18	4.62	8.80
19	4.54	6.10
20	4.57	5.63
21	4.98	13.62
22	4.73	4.45

The characteristics of soil are influenced by several factors, including organic matter content and pH. The weathering of ultrabasic rock hills, combined with development activities in the area, exposes the soil to erosion, causing heavy metals to be transported to lower regions. Ultrabasic soils are known for their high heavy metal content, which can significantly impact soil fertility [11]. Excessive metal concentrations can lead to stunted plant growth, reduced productivity, and increased susceptibility to damage.

3.2 Heavy metal concentrations in soil

The concentration of heavy metals in the paddy soils varied considerably across the study area. The metals measured included Mn, Fe, Ni, Zn, Cr, Co, Cu, Pb, Cd, and arsenic (As), as shown in Table 2. Mn had the highest concentration, with a maximum value of 13,855.67 mg/kg recorded at station 8, located in the northeast quadrant of the valley. In contrast, Cd had the lowest concentration, with values as low as 0.55 mg/kg at station 7.

Table 2. Heavy metals concentrations for each sampling station.

	Heavy Metal									
Station	Cu	Zn	Cd	Pb	Cr	Mn	Fe	Co	Ni	As
1	217.30	620.98	4.64	52.80	151.73	2723.10	2917.64	53.08	144.18	8.68
2	24.46	179.93	1.00	5.58	212.35	8188.68	8555.40	55.18	250.07	3.97
3	37.11	196.45	1.13	28.70	125.52	7309.73	7791.10	59.04	104.07	4.77
4	22.01	244.78	1.04	2.47	444.88	2096.60	3189.39	378.22	1494.58	1.87
5	10.42	120.82	0.70	3.36	162.20	3246.94	10950.57	43.75	166.40	2.16
6	13.87	137.61	0.93	4.93	208.25	4817.53	15052.50	58.97	212.90	2.54
7	17.65	137.77	0.55	14.09	186.95	4463.70	5025.49	96.95	296.23	1.59
8	36.97	155.29	0.94	7.27	288.33	13855.67	5212.11	278.29	1317.74	1.42
9	11.02	133.16	1.06	2.50	187.44	2908.48	9031.70	89.01	322.65	1.81
10	41.90	475.54	1.30	12.67	233.76	1202.81	5517.19	108.89	441.45	1.67
11	65.58	167.10	1.05	6.37	171.41	1462.89	1914.40	166.65	762.84	1.45
12	41.98	191.40	1.18	8.71	219.94	1610.59	3212.22	134.14	372.65	1.51
13	23.20	470.50	1.85	16.09	504.05	6567.14	5590.81	459.30	1719.52	1.46
14	34.53	183.81	1.57	7.90	156.90	4434.67	2210.29	41.32	97.70	1.04
15	77.82	352.03	2.62	13.08	170.39	5816.38	8817.91	18.40	248.26	1.30
16	17.26	165.29	1.99	21.14	174.45	2503.56	2182.02	46.66	90.83	1.41
17	13.76	145.17	1.36	17.69	171.16	2498.10	2064.38	54.49	99.24	1.43
18	28.26	235.45	1.81	7.23	187.21	5472.39	16265.33	95.82	175.89	4.48
19	20.81	295.80	1.93	8.91	231.77	2777.92	5452.99	80.44	350.50	1.34
20	1209.28	760.65	12.90	71.69	181.96	3319.64	5551.51	64.12	257.93	1.94
21	17.61	278.40	1.02	16.65	139.97	2650.85	9610.97	61.90	240.03	1.96
22	34.42	179.10	1.25	16.15	173.58	7960.66	6951.22	50.30	263.76	1.17

The sequence of metal concentrations from highest to lowest was: Mn > Fe > Ni > Zn > Cr > Co > Cu > Pb > Cd > As, as shown in Table 3. Several heavy metals, including Mn, Fe, and Ni, were found at critical levels, raising concerns about soil toxicity and potential impacts on plant growth. Elevated concentrations of these metals, particularly at stations 8 and 13, were linked to the natural weathering of ultrabasic rocks and anthropogenic activities such as land clearing and the use of chemical fertilizers [12].

Table 3. Concentration of Heavy Metals in Soil Samples from Ranau Valley Paddy Fields (mean ± SD).

Heavy Metal	Concentration (mg/kg)
Mn	6503.04 ± 3999.06
Fe	4449.46 ± 2970.17
Ni	428.61 ± 467.87
Zn	264.87 ± 171.38
Cr	212.92 ± 92.27
Co	113.41 ± 113.71
Cu	91.69 ± 253.36
Pb	15.73 ± 16.68

Cd	1.99 ± 2.58
As	2.32 ± 1.76

3.3 Correlation between heavy metal and soil properties

The correlation tests between heavy metals and the soil properties are shown in Table 4. Based on the findings, it is revealed that several significant correlations between soil properties and heavy metal concentrations. Organic matter content showed a positive correlation with Cr, Ni, and Co, indicating that higher levels of organic matter help retain these metals in the soil. This suggests that organic matter plays a crucial role in reducing the bioavailability of toxic metals, potentially mitigating their harmful effects on plants.

Soil pH, on the other hand, showed negative correlations with most heavy metals, meaning that as soil acidity increases, the availability of metals such as Cu and Pb also increases. This relationship underscores the importance of maintaining balanced soil pH to prevent excessive metal uptake by crops.

Table 4. The correlation of heavy metals, pH and organic matter content in soil samples from Ranau Valley, Sabah, Malaysia.

	Cu	*Zn*	*Cd*	*Pb*	*Cr*	*Mn*	*Fe*	*Co*	*Ni*	*As*	*pH*	*SOM %*
Cu	1											
Zn	0.72	1										
Cd	0.97	0.80	1									
Pb	0.82	0.79	0.87	1								
Cr	-0.10	-0.15	-0.09	-0.22	1							
Mn	-0.09	-0.18	-0.12	-0.09	-0.14	1						
Fe	-0.09	-0.15	-0.11	-0.23	-0.15	-0.24	1					
Co	-0.11	-0.09	-0.13	-0.20	-0.93	-0.19	-0.22	1				
Ni	-0.09	-0.10	-0.12	-0.22	-0.91	-0.27	-0.22	-0.97	1			
As	-0.07	-0.32	-0.15	-0.42	-0.22	-0.03	-0.18	-0.19	-0.25	1		
pH	-0.27	-0.30	-0.35	-0.28	-0.05	-0.36	-0.36	-0.07	-0.07	-0.07	1	
SOM %	-0.17	-0.05	-0.17	-0.30	-0.50	-0.19	-0.14	-0.48	-0.43	-0.18	-0.06	1

n=36 r=0.4227* r=0.5368** r=0.6524***

*Significant correlation at the level of significance 5%. **Significant correlation at the level of significance 1% ** Significant correlation at the level of significance 0.1%

3.4 Spatial Distribution of Heavy Metals

The spatial distribution of heavy metals across the valley, as mapped using Geographic Information System (GIS) tools, highlighted contamination hotspots. Station 8, located in a hilly area, had the highest concentration of manganese, which decreases slightly in downhill

regions, as observed at Station 15. In serpentine soils, Mn is often associated with oxides, which affect its mobility and bioavailability. This distribution raises ecological concerns, particularly regarding soil and groundwater contamination, as Mn and Ni are easily mobilized in the presence of water [13].

In addition, Station 20 showed the highest concentrations of Cu, Pb, Zn, and Cd, which are likely linked to agrochemical pollution from fertilizer use. The presence of these metals in high quantities can negatively affect soil health and crop growth, while also posing potential health risks through the food chain. Station 13, which had the highest concentrations of Cr, Co, and Ni, is primarily influenced by natural factors such as the weathering of ultrabasic rocks.

Mapping of Heavy Metals in Rice Cultivation Areas, Ranau Valley are shown in Fig. 2 to 11:

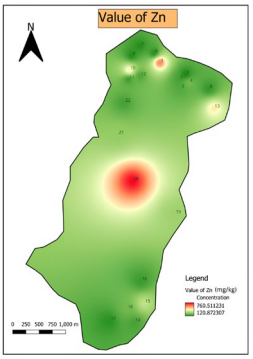

Fig. 2. Map of Zn distribution.

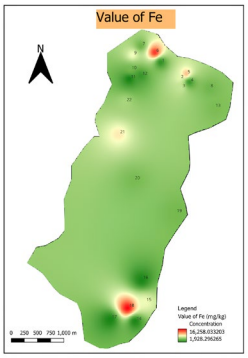

Fig. 3. Map of Fe distribution.

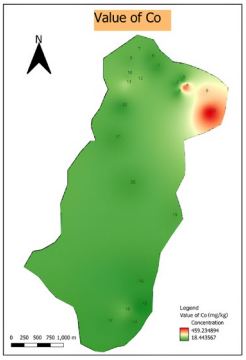

Fig. 4. Map of Co distribution.

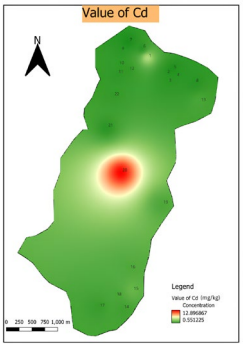

Fig. 5. Map of Cd distribution.

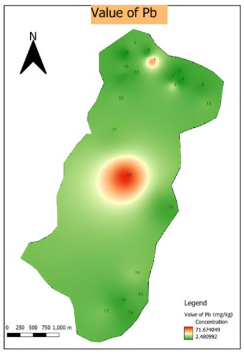

Fig. 6. Map of Pb distribution.

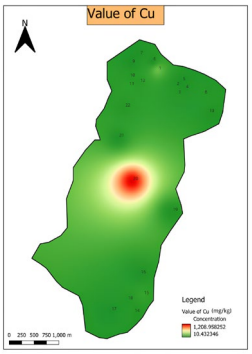

Fig. 7. Map of Cu distribution.

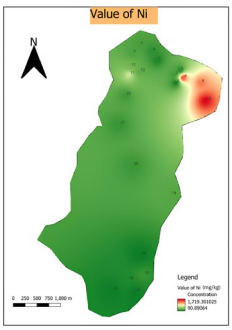

Fig. 8. Map of Ni distribution.

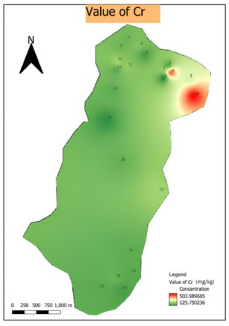

Fig. 9. Map of Cr distribution.

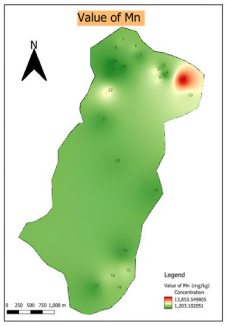

Fig. 10. Map of Mn distribution.

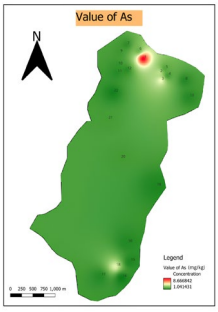

Fig. 11. Map of As distribution.

The Mn distribution map, Fig. 10, indicates that Station 8, located in the northeast quadrant of the map, exhibits the highest concentration of manganese at 13,855.67 mg/kg. This station is situated in a hilly area, and the concentration of Mn decreases in the downhill regions but remains above the levels required by plants, as seen at Station 15, which has 5,816.38 mg/kg. In serpentine soil, Mn is primarily associated with oxides and oxyhydroxides, forms that can affect its mobility and bioavailability in the environment [14]. Mn can be rapidly mobilized under certain conditions, particularly in the presence of water. The release of manganese, along with Ni, raises ecological and health concerns, especially regarding soil and groundwater contamination [15].

Heavy metals like Cu, Pb, and Zn are toxic to both soil and plants, with Cu becoming harmful at high concentrations by disrupting biological processes, particularly in acidic soils like at Station 20, where its availability increases due to low organic matter (5.63%) [16]. Pb levels were also high at Station 20, where acidic conditions facilitated its mobility, reducing crop productivity and posing health risks when absorbed by plants and entering the food chain [17]. Similarly, Zn, while essential in small amounts, was found in excessive levels due to fertilizer use, with its absorption increasing in acidic soils [18]. Cd, a highly toxic metal, showed elevated levels at Station 20, where low pH made it more bioavailable, raising concerns for food safety as Cd can accumulate in rice plants [19-20].

This study highlights significant environmental challenges in the Ranau Valley, where high concentrations of metals like Mn, Ni, Cu, Pb, and Cd, combined with low pH levels, pose risks to soil fertility and plant health, particularly through reduced yields and

stunted growth [21]. The contamination of rice fields with Cd and Pb poses serious risks to food safety in this rice-growing region. To manage this, remediation strategies like adding organic matter to raise soil pH and promoting sustainable farming practices, such as using organic fertilizers and crop rotation, are recommended. Continued monitoring and research are critical for safeguarding agricultural productivity and environmental sustainability in the area.

4 Conclusion

This study examined the concentrations and spatial distribution of heavy metals in the paddy field soils of Ranau Valley, Sabah, Malaysia, focusing on elements like Mn, Fe, Ni, Cr, and Cd. The results showed significant variations, with several metals exceeding toxicity thresholds, particularly Mn, Ni, and Cr, in areas influenced by ultrabasic rocks and agricultural activities. These elevated concentrations pose risks to soil health, crop yields, and the potential contamination of the food chain. Cadmium and lead, though found in lower concentrations, also raise long-term health concerns due to their potential to accumulate in rice, a staple crop in the region.

GIS mapping identified contamination hotspots, especially in areas with intensive fertilizer use, underlining the urgent need for targeted remediation efforts. The study recommends implementing organic soil amendments, adjusting soil pH, and adopting sustainable farming practices to reduce heavy metal bioavailability and improve soil health. Regular monitoring of soil and crop quality is crucial to prevent further contamination. This research provides important insights for future management strategies and policy decisions aimed at protecting soil quality and ensuring food security in the Ranau Valley.

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