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RESEARCH ARTICLE

Heavy metal distribution in profile samples of different land use systems in post gold mining areas of Kolar Gold Fields (KGF), Karnataka

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Abstract

Intensive gold mining activities in Kolar Gold Fields (KGF), Karnataka, have resulted in substantial buildup of toxic heavy metals in surrounding ecosystems. This study investigates the spatial and vertical distribution of eight heavy metals (iron, copper, manganese, zinc, nickel, cadmium, lead and arsenic) across profile samples of four land use systems ALUS (agricultural land use system), HLUS (horticultural land use system), BLUS (barren land use system) and FLUS (forest land use system) in the post mining areas. Metal concentration trends across soil depths were analyzed using multivariate techniques. Arsenic (As) and manganese (Mn) emerged as the most abundant contaminants, especially in BLUS (28.56 mg kg^{-1} and 37.72 mg kg^{-1}) respectively. Surface horizons consistently showed higher metal accumulation. The heavy metals in four land use systems followed the order of Mn> Fe> As> Ni> Cu> Zn> Pb> Cd. Such elevated levels of heavy metals can impair plant growth by disrupting nutrient uptake and inducing phytotoxic effects, thereby lowering crop productivity in contaminated soils. The decline in soil fertility associated with heavy metal build up highlights the urgent need for sustainable land management in post mining regions. Phytoremediation strategies, including the use of hyperaccumulator plants, offer a viable approach to restore soil health and mitigate ecological risk. Multivariate analysis like cluster analysis revealed strong association among metals, particularly Fe, Cu, Zn and As. Cluster analysis grouped ALUS and HLUS due to similar moderate contamination levels and same land management practices, while BLUS and FLUS formed distinct cluster with elevated metal loads. The heat map and box plot confirmed high spatial and vertical variability of heavy metal distribution. These findings underscore the environmental risks posed by abandoned mine tailings in the region and the damage it causes to plants and surrounding ecosystem.

Keywords: heavy metal contamination; land use systems; metal poisoning; soil pollution; toxic metals

Introduction

The mining industry, serving as a linchpin for global economic advancement, stands at the nexus of providing indispensable raw materials across diverse sectors (1). However, the ramifications of mining activities on the environment, particularly in the context of soil contamination, have emerged as a critical and pressing environmental concern (2). The existence of heavy metals in soil introduces significant environmental hazards, ranging from soil and water pollution to the disruption of ecosystems and the release of potentially deleterious substances into the environment (3). Heavy metals are a group of metallic elements that have relatively high atomic weight and density (usually >5 g cm^{-3}) and are often toxic to living organisms even at low concentrations. Examples include iron (Fe), copper (Cu), zinc (Zn), manganese (Mn), arsenic (As), nickel (Ni), cadmium (Cd) and lead (Pb), etc. The mining processes associated with copper, zinc, lead, manganese and iron, extensively utilized in industrial applications, have been identified as primary contributors to soil contamination (4). The mining processes associated with copper, zinc, lead, manganese and iron, are widely employed in industrial applications, potentially leading to air and soil pollution and finally damage plants and leads to bioaccumulation. Additionally, the mobilization of heavy metals into water sources exacerbates water pollution concerns, posing threats to aquatic life and potentially impacting human health (5). Heavy metal pollution causes severe health effects in humans, including neurological damage, kidney and liver dysfunction, bone disorders, reproductive problems and increased cancer risks, mainly due to bioaccumulation and oxidative stress (47). In the environment, heavy metals are persistent and non-biodegradable, contaminating soils, water and crops and disrupting ecosystems through bioaccumulation and biomagnification in food chains (48). Major environmental disasters, such as the Río Sonora mine spill in Mexico and the Kakhovka dam collapse in Ukraine, demonstrate their long-term ecological and health consequences.

Mining of metalliferous ore deposits is widely recognized as a main factor for environmental pollution. Activities such as excavation, transportation, smelting, refining and the disposal of mine tailings and wastewater acts as main cause in this impact (6, 7). These tailings often release various pollutants and toxic metals, which can eventually contaminate surrounding soil and water bodies. As a result, heavy metals contamination from mining remains a pressing environmental issue worldwide and damage plant growth (8, 9).

In India, gold is currently extracted from three main mines-Hutti, Uti and Hirabuddini-located in Karnataka. Additionally, it is recovered as a by-product from base-metal sulphide deposits in places like Khetri (Rajasthan), Mosabani and Singhbhum (Jharkhand), primarily through public sector operations. In the private sector, gold is also produced at Kundrekocha. According to Geological Survey of India (GSI), gold evolves as a siderophile element from the iron-nickel core at crustal spreading centers. During partial melting of the mantle, gold along with metals derived from sulphides rises with basaltic fluids into the crust along mid-oceanic ridges and at subduction zones. It is then associated with complex processes (convection, subduction, partial melting, hydrothermal processing, weathering, erosion and deposition) before returning to the mantle for recycling again at subduction centers. The deep-seated ore bearing solutions containing gold are of both magmatic and metamorphic origin. Gold occurs in a variety of litho assemblages and multiple geological environments such as greenstone belts, mantle derived intrusions, diaperic juvenile plutons and granulites.

Mining activities in the Kolar Gold Fields (KGF) began a long time ago. The Champion Reef Mine at Kolar Gold Fields (KGF) was once 3.2 km deep.i.e. the deepest point below the sea level ever reached by humans. The KGF were systematically exploited by John Taylor and Sons during 1880. Subsequently, the mines were taken over by Government of Karnataka in 1950. In 1972, the mines were taken over by the GOI when Bharat Gold Mines Limited (BGML) was formed. KGF produced in excess of 800 tonnes of gold per 51 million tonnes of ore before its closure in 2001. During 1881-1980, the gold production in KGF was about 47 g t^{-1} of ore (10). However, during 1991-1999, KGF returned only 03.0 g t^{-1}. All these factors had a growing impact on KGF functioning, thus leading to the closure of KGM due to losses incurred. At present, BGML has nearly 33 million tonnes of tailing sand with the gold content of 0.72g t^{-1} (11, 12). These tailings dumped in 15 locations which covered 2 km^2 of mining area (13). In KGF gold is extracted by cyanide extraction process which release large quantity of mine tailings and produce acid drainage (14). Particulate matter concentration beyond the permissible limit at KGF has indicated influence of tailings on air environment (15). Mine tailings contain minerals like amphiboles, chlorite, calcite, feldspar, mica, pyrite, quartz, etc. and have micronutrients which on weathering release large quantities of heavy metals (14, 16). The dispersion of these mill tailings onto the adjacent agricultural fields has resulted in deleterious effects on crop growth. The proficient administration of these locales necessitates intricate site characterization and the identification of appropriate remediation methodologies. Therefore, it is crucial to thoroughly understand how heavy metals are distributed both spatially and vertically in the surroundings of the Kolar Gold Fields.

Materials and Methods

Study area and site location

To study the spatial and vertical distribution of heavy metals, an assessment of soil profiles was carried out. The study area is located in KGF taluk of Kolar district which is in Eastern dry zone of Karnataka, India depicted in (Fig. 1). The area lies in latitude of 12^{0} 96' 17'' N, longitude of 78^{0} 27' 07'' E with an altitude of 884 m above the mean sea level. The details of the mining in KGF were shown in Table 1. A preliminary survey was conducted in the Kolar Gold Fields (KGF) region of Karnataka to identify various land use systems situated near mine tailings. Based on differences in vegetation cover, four distinct land use systems LUS were identified: forest (FLUS), horticultural (HLUS), agricultural (ALUS) and barren land use systems (BLUS). For each of these land use categories, two representative soil profiles were selected, resulting in a total of eight profiles. The agricultural land use profiles were labelled ALUS1 and ALUS2, while HLUS1 and HLUS2 represented the horticultural system. Similarly, BLUS1 and BLUS2 were assigned to the barren land system and FLUS1 and FLUS2 corresponded to the forest land use system. The geographic coordinates for all profile locations are listed in Table 2.

Preparation and sampling of profiles

To assess the complete vertical profile of heavy metals, soil samples were collected at multiple depths from each site down to the parent material (C horizon). A sample of soil weighing about 1 kg was taken at each depth, put in a polythene bags. After collecting the soil samples in clean polythene bags, the samples are first air-dried at room temperature to remove moisture and then visible impurities such as stones, roots and debris are carefully removed. The dried soil is gently crushed using a mortar and pestle to break down aggregates without altering the chemical composition and then it is passed through a 2 mm sieve to obtain the fine fraction suitable for heavy metal analysis. The sieved soil is thoroughly mixed to ensure homogeneity and stored in labelled airtight containers for further laboratory analysis.

For the determination of available heavy metals, a

Table 2. Location coordinates of DLUS

Land use system	Latitude	Longitude
ALUS1	12^{0} 59' 47'' N	78^{0} 17' 59'' E
ALUS2	12^{0} 59' 28'' N	78^{0} 57' 51'' E
HLUS1	12^{0} 58' 44'' N	78^{0} 16' 58'' E
HLUS2	12^{0} 59' 14'' N	78^{0} 16' 25'' E
BLUS1	12^{0} 58' 29'' N	78^{0} 16' 24'' E
BLUS2	12^{0} 58' 49'' N	78^{0} 15' 55'' E
FLUS1	13^{0} 00' 36'' N	78^{0} 15' 45'' E
FLUS2	12^{0} 59' 55'' N	78^{0} 15' 51'' E

Table 1. The mining history of Kolar Gold Fields

Details of the mining areas			
Mine starting year	1880	Technique of gold extraction	Cyanidation
Mine closing year	2001	Volume of ore milled	51.124 million tons
No. of mining shaft locations	12	Gold produced	800.3 tons
No. of tailing dumps sites	15	Volume of tailings generated	33 million tons

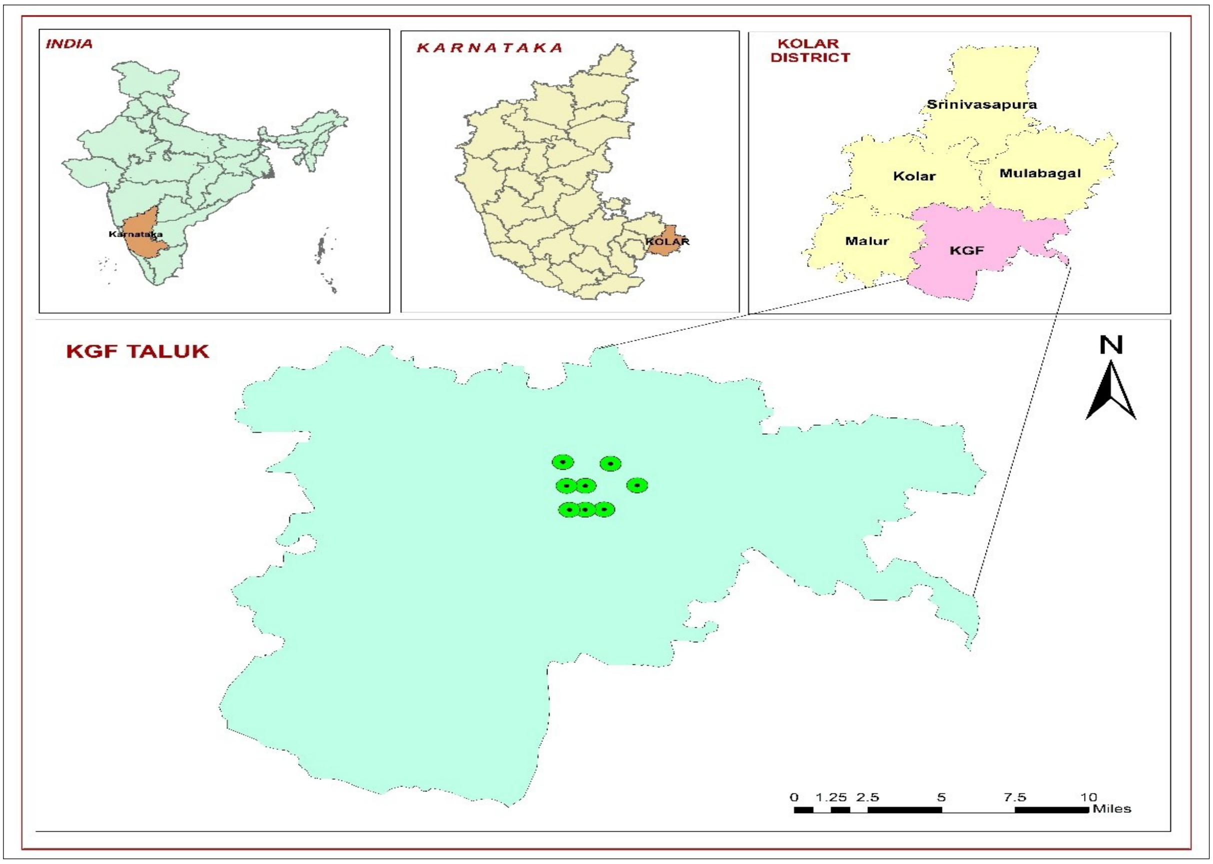


Fig. 1. Profile sampling location in Kolar Gold Field

weighed portion of the sieved soil (generally 10 g) is transferred into a conical flask and extracted with a suitable extractant such as DTPA (Diethylenetriaminepentaacetic acid) solution. The suspension is shaken on a mechanical shaker for the required time (usually 2 hr for DTPA extraction) and then filtered through Whatman No. 42 filter paper to obtain a clear extract. The filtrate is analyzed for available heavy metals using Atomic Absorption Spectrophotometry (AAS). Using the proper hollow cathode lamps, the filtrate was fed into an atomic absorption spectrophotometer where the concentration of each element is measured against standard calibration curves prepared using known metal solutions, to determine their concentration in the extracts (17).

Statistical analysis

R software (version 4.5.0) was used to conduct the statistical study. The "pheatmap" package was applied to create heat maps. Pearson's correlation analysis was used to determine the relationships between various heavy metals at a significance level of $P < 0.05$. To find trends in the distribution of heavy metals in various land use systems, hierarchical clustering was used. Ward's clustering approach was used to do a cluster analysis based on Euclidean distance. The "ggplot2" package was used to create box plots.

Results

The concentration of heavy metals in profile samples of different land use systems (DLUS) is provided in Table 3

Fe concentration in profile samples of DLUS

Across all LUS, Fe concentrations consistently showed a downward trend with greater soil depths, suggesting significant surface enrichment. In ALUS, Fe concentrations ranged from 7.17 mg kg^{-1} (ALUS1) to 5.04 mg kg^{-1} (ALUS2). Horticultural systems recorded values of 7.44 mg kg^{-1} (HLUS1) and 6.50 mg kg^{-1} (HLUS2). BLUS showed a higher surface Fe concentration, with 8.24 mg kg^{-1} in BLUS1 and 6.26 mg kg^{-1} in BLUS2. Forest systems showed comparatively lower values, with 7.76 mg kg^{-1} in FLUS1 and 5.18 mg kg^{-1} in FLUS2. The highest Fe concentration was observed in the Ap horizon of BLUS1, while the lowest was in the Ap horizon of FLUS2.

Cu concentration in profile samples of DLUS

Cu concentrations exhibited a marked decline with depth in all profiles. In agricultural systems, Cu decreased from 3.24 mg kg^{-1} to 0.70 mg kg^{-1} in ALUS1 (a 78.4 % reduction) and from 2.10 mg kg^{-1} to 0.58 mg kg^{-1} in ALUS2 (72.4 % reduction). In horticultural systems, a decrease from 2.10 mg kg^{-1} to 1.08 mg kg^{-1} (HLUS1, 48.6 %) and 2.04 mg kg^{-1} to 1.16 mg kg^{-1} (HLUS2, 43.1 %) was observed. Barren systems recorded 1.28 mg kg^{-1} to 0.90 mg kg^{-1} in BLUS1 (29.7 %) and 2.96 mg kg^{-1} to 1.44 mg kg^{-1} in BLUS2 (51.4 %). Forest systems followed similar trends with Cu declined from 1.76 mg kg^{-1} to 0.78 mg kg^{-1} (FLUS,1 55.7 %) and from 2.90 mg kg^{-1} to 1.14 mg kg^{-1} (FLUS2, 60.7 %). Surface horizons of agricultural profiles had relatively higher Cu than forest as well as barren systems.

Mn concentration in profile samples of DLUS

Mn concentrations were highest in the surface horizon of forest systems, particularly FLUS1 Ap (60.42 mg kg^{-1}). Agricultural and horticultural systems exhibited moderate Mn levels, with consistent depletion with depth. In barren systems, the Ap horizon of BLUS2 recorded a notable Mn level of 37.72 mg kg^{-1}. Across all land use systems, Mn concentration declined with depth, with the steepest reduction (88 %) observed in the forest system (FLUS1), decreasing from 60.42 mg kg^{-1} in the Ap horizon to 7.24 mg kg^{-1} in the Cb horizon.

Table 3. Heavy metal content (mg kg^{-1}) of DLUS

Horizons	Depth (cm)	Iron	Copper	Manganese	Zinc	Nickel	Cadmium	Lead	Arsenic
Agricultural land use system- 1 (ALUS1)									
Ap	0-23	7.176	3.24	10.13	3.02	8.46	0.122	2.08	18.56
Bt_1	23-40	4.640	0.72	6.78	0.28	5.28	0.052	0.70	16.21
Bt_2	40-71	2.860	1.54	3.10	0.32	0.10	0.050	1.38	15.62
Bt_3	71-95	1.840	0.70	1.80	0.14	0.38	0.054	0.78	12.13
Agricultural land use system- 2 (ALUS2)									
Ap	0-20	5.04	2.10	10.34	1.18	0.72	0.076	1.30	12.31
Bt_1	20-46	4.66	1.12	12.96	0.26	0.44	0.056	1.02	12.35
Bt_2	46-62	3.24	0.82	8.02	0.20	0.40	0.058	0.82	11.23
Cb	62-91	3.04	0.58	4.80	0.20	0.40	0.056	0.60	10.25
Horticultural land use system-1 (HLUS1)									
Ap	0-23	7.44	2.10	14.02	1.14	0.44	0.062	1.62	15.21
Bt_1	23-61	4.34	1.24	16.56	0.30	0.36	0.060	0.52	10.25
Bt_2	61-89	3.5	0.82	8.74	0.14	0.60	0.068	0.64	10.54
Bt_3	89-106	3.42	0.70	8.48	0.16	0.60	0.076	0.64	9.56
Bt_4	106-140	4.22	1.08	10.92	0.30	0.44	0.068	0.88	8.54
Horticultural land use system- 2 (HLUS2)									
Ap	0-37	6.50	2.04	11.46	1.34	0.38	0.07	1.32	12.36
Bw_1	37-57	3.36	1.18	5.62	0.18	0.54	0.062	1.00	10.25
Bw_2	57-85	3.84	1.16	5.00	0.18	0.54	0.068	0.20	9.65
Bw_3	85-130	3.82	0.78	3.82	0.38	0.48	0.07	0.36	8.56
Bw_4	130-185	3.92	1.16	5.40	0.04	0.50	0.08	0.54	6.32
Barren land use system- 1 (BLUS1)									
Ap	0-23	8.24	1.28	19.34	0.28	1.00	0.068	0.92	28.56
Bt_1	23-55	5.08	1.12	11.58	0.22	0.90	0.07	0.84	24.80
Bt_2	55-97	2.16	0.90	14.32	0.12	0.80	0.084	1.18	16.30
Barren land use system- 2 (BLUS2)									
Ap	0-20	6.26	2.96	37.72	0.48	1.32	0.074	0.14	25.62
Bt_1	20-36	4.06	0.05	20.76	0.01	0.72	0.08	0.22	19.54
Bt_2	36-72	4.56	1.36	21.70	0.30	0.68	0.078	0.20	18.47
Cb	72-118	5.88	1.44	30.24	0.48	0.74	0.072	0.38	15.62
Forest land use system- 1 (FLUS1)									
Ap	0-20	7.76	1.76	60.42	0.26	1.68	0.072	0.30	10.41
Bt_1	20-39	4.28	1.66	52.30	0.12	0.70	0.070	0.44	9.65
Bt_2	39-59	3.50	1.40	27.50	0.18	0.46	0.080	0.34	5.23
Bt_3	59-113	3.90	1.18	21.48	0.10	0.62	0.086	0.24	5.65
Cb	113-150	2.42	0.78	7.24	0.20	0.66	0.084	0.56	4.21
Forest land use system- 2 (FLUS2)									
Ap	0-20	5.18	2.90	40.44	1.12	0.92	0.066	0.80	9.56
Bt_1	20-47	2.16	1.32	10.46	0.18	0.52	0.060	0.42	8.85
Bt_2	47-80	1.96	0.96	6.00	0.10	0.44	0.070	0.36	7.65
Bc	80-140	2.18	1.14	6.38	0.26	0.62	0.070	0.44	7.66

Ap- surface ploughed layer, Bt1- beginning clay enriched subsoil, Bt2- middle of the Bt horizon, stronger clay accumulation, Bt3- deepest clay-enriched subsoil, Cb- buried parent horizon, Bw- subsoil with weak development of colour, Bc- subsoil with concretions.

Zn concentration in profile samples of DLUS

Zn levels were low across the profiles, with the exception of FLUS2 (1.12 mg kg^{-1}, Ap) and BLUS2 (0.48 mg kg^{-1}, Ap). Zn content exhibited a sharp decline with depth in all systems. Horticultural system HLUS2 displayed the highest vertical reduction in Zn (97 %). Agricultural systems, particularly ALUS1 (3.02 mg kg^{-1}, Ap), showed higher surface Zn levels compared to FLUS and BLUS.

Ni concentration in profile samples of DLUS

There were notable differences in nickel contents between land use systems. The highest Ni concentration was recorded in ALUS1 Ap (8.46 mg kg^{-1}), while other systems showed markedly lower values. Subsurface horizons across most systems contained <1 mg kg^{-1} of Ni. In ALUS1, Ni decreased sharply from 8.46 mg kg^{-1} (Ap) to 0.38 mg kg^{-1} (Bt3), marking a 95.5 % reduction.

Cd concentration in profile samples of DLUS

Cd was present at very low concentrations throughout the DLUS, with ALUS1 showing the highest level (Ap 0.122 mg kg^{-1}), decreased to 0.054 mg kg^{-1} in Bt3 (a 55.7 % reduction). A downward trend in Cd concentration with increase in depth was observed in each profile, except in HLUS1 (9.7 % increase), HLUS2 (14.3 % increase), BLUS1 (23.5 % increase), FLUS1 (16.7 % increase) and FLUS2 (6.1 % increase) was observed.

Pb concentration in profile samples of DLUS

Pb concentrations were highest in ALUS1 Ap (2.08 mg kg^{-1}), with a consistent pattern of decreasing levels with depth across all land use systems. In ALUS1, Pb decreased by 62.5 %, from 2.08 mg kg^{-1} (Ap) to 0.78 mg kg^{-1} (Bt3). The lowest surface Pb was recorded in BLUS2.

As concentration in profile samples of DLUS

As concentrations declined with depth across all land use systems, more gradually compared to other heavy metals. The highest surface As levels were found in barren system 28.56 mg kg^{-1}(BLUS1 Ap) and 25.62 mg kg^{-1} (BLUS2 Ap), with elevated concentrations persisting into the subsoil. In ALUS1, As decreased from 18.56 mg kg^{-1} (Ap) to 12.13 mg kg^{-1} (Bt3), a reduction of 34.6 %.

The heat map (Fig. 2) represents the distribution of heavy metals in x- axis of ALUS, HLUS, BLUS and FLUS. The colour intensity in the heat map indicates the variation in heavy metal accumulation, with light colour intensity in the heat map indicates the lower accumulation values and darker colour indicating higher accumulation values.

Across all land use systems, As and Mn consistently exhibited the highest standardized concentrations, as evidenced by strong red and orange colours on the heatmaps, indicating elevated levels, Ni and Fe were present at moderate concentrations in ALUS and HLUS, respectively as reflected by yellow shade. In ALUS, Pb, Cu, Zn and Cd were observed at lower concentrations, as indicated by lighter colour gradients. Similarly, In HLUS, Cu, Zn, Cd, Ni and Pb were all recorded at low levels. In BLUS, Pb appeared at a medium concentration, whereas Cu, Zn, Cd and Ni remained at low levels. In FLUS, Fe and Cu were found at moderate concentrations, while Zn, Cd and Pb exhibited low intensities, suggesting minimal accumulation in this system.

Table 4 (supplementary information) illustrates the relationships among different heavy metals across all land use systems. Fe showed a moderate but statistically significant association with Ni (0.368*) and exhibited strong positive correlations with Cu (0.599**), Mn (0.508**), Zn (0.534**) and As (0.544**). (** indicates highly correlated with each other). Cu had high correlation values with Zn (0.755**), Mn (0.425**), Ni (0.398*), Cd (0.353*) and Pb (0.405*). Zn also displayed strong positive associations with Pb (0.707**), Cd (0.527**) and Ni (0.674**). However, no significant correlations were observed between Mn and either Pb or Cd. As, except for its correlation with iron, showed minimal or no significant association with most of the other heavy metals.

The box plot (Fig. 3) explained the allocation of heavy metals ALUS, HLUS, BLUS and FLUS. Fe, Mn and Cu exhibited higher median concentrations (Q2) in the FLUS, with values of 5.0, 35 and 1.8 $mg\ kg^{-1}$ respectively. These elements also demonstrated wider interquartile ranges (IQR) of 3.9, 30 and 0.6 $mg\ kg^{1}$, indicating greater variability. In contrast, the HLUS recorded the lowest median values for Fe (2.7 $mg\ kg^{-1}$), Mn (12 $mg\ kg^{-1}$) and Cu (0.4 $mg\ kg^{-1}$), suggesting a more uniform distribution. Zn concentration was uniform across all land use systems, with

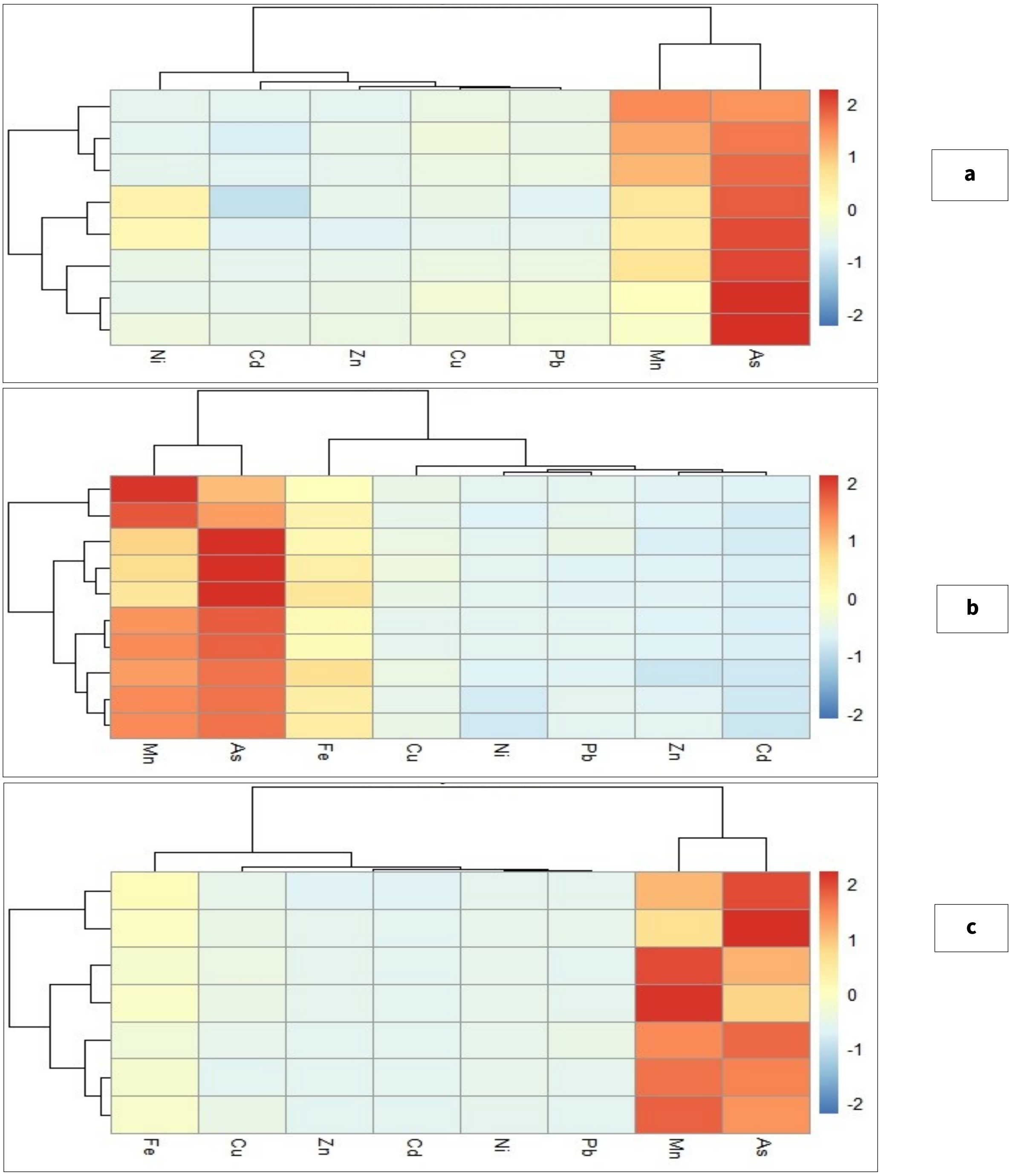


Fig. 2. The heat map of ALUS (a), HLUS (b), BLUS (c) and FLUs (d) of different heavy metals

consistently low median values (1.0 mg kg^{-1}) and narrow IQR (0.3 mg kg^{-1}), indicating limited variability and uniform distribution

Pb and Ni exhibited their highest median values in ALUS, at 1.0 mg $kg^{-1}$and 1.5 mg kg^{-1}respectively, accompanied by the widest IQR (0.7 mg $kg^{-1}$for Pb and 0.5 mg kg^{-1}). Lower Pb medians were observed across all LUS, suggesting uniform low concentrations with minimal variability. Cd showed narrow IQR across all land use systems, indicating low variability. Slightly elevated medians were noted in BLUS and FLUS (both 0.09 mg kg^{-1}) compared to ALUS and HLUS (both 0.07 mg kg^{-1}).

As concentrations were higher and most variable in BLUS, with an IQR of 7 mg kg^{-1} and the upper quartile exceeding 20 mg kg^{-1}. In contrast, ALUS showed moderate concentrations with a compact distribution, while FLUS and HLUS recorded lower medians and narrow IQR, indicating reduced As accumulation.

Cluster analysis was performed to examine the spatial grouping on the data using Ward linkage method and squared Euclidean distance, a common method to classify variable into cluster. The dendrogram of hierarchical cluster analysis of heavy metals in post gold mining areas of DLUS was shown in the (Fig. 4), where the distance axis represents the degree of association between groups of variables, i.e., the lower the value on the axis, the more significant the association.

The dendrogram illustrated two primary clusters. One major cluster included samples from ALUS (ALUS1 and ALUS2) and Horticultural Land Use Systems (HLUS1 and HLUS2). These samples shared moderate to low levels of heavy metals such as cadmium, lead and arsenic, reflecting similar management practices and soil profiles.

The second major cluster grouped Barren Land Use Systems (BLUS1 and BLUS2) and Forest Land Use Systems (FLUS1 and FLUS2). BLUS samples showed the highest levels of Mn, Pb and As, particularly in surface horizons. Forest systems, while showing high manganese in some layers (e.g., FLUS1), generally had reduced cadmium and arsenic levels. Variables such as Mn and As displayed strong contributions to the clustering pattern. Samples from deeper soil horizons (e.g., Bt3, Bt4, Cb) generally clustered separately from surface horizons (Ap).

Discussion

Table 3 represents the heavy metal concentration in profile samples collected from DLUS. Differences in heavy metal concentrations across these systems can be linked to multiple factors, such as human activities, intrinsic soil characters and ecological processes. In all land use systems, surface soils show elevated levels of heavy metals, which can be attributed to external sources like application of fertilizers, atmospheric deposition and the proximity to mining operation, including tailings and ore processing sites (18-22). The higher accumulation of heavy metals in the topsoil compared to sub soil layers across all LUS is also likely influenced by anthropogenic activities such as agricultural and mining, as well as the naturally greater organic matter content in surface layers, which tends to decline with depth (23). Fe is generally more concentrated in the topsoil of all LUS due to its limited mobility and its tendency to form stable oxides and hydroxides. As a result, Fe levels decrease progressively below the Ap horizon in each land use system (24).

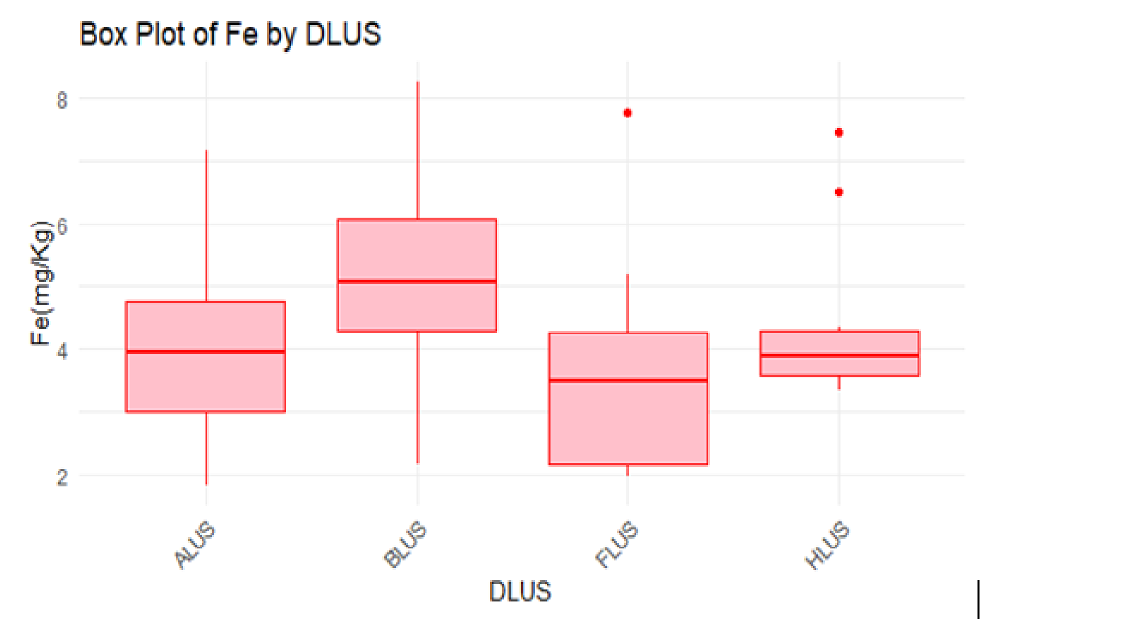
Cu, primarily derived from sulphide minerals in mine tailings, is also found in higher concentrations in surface horizons. Its relative insolubility causes it to bind with organic matter and clay near the surface leading to higher accumulation on the surface (25). However, a slight increase in Cu concentration with depth in some LUS was observed. This might be due to increase in silt and organic matter content with depth (26).

Mn and Zn follow similar patterns, often enriched in the surface soil due to tailings deposition and strong surface sorption. Under oxidizing conditions, Mn becomes relatively immobile and decreases with depth, though localized increases in deeper horizons may occur due to acid mine drainage (25, 27). The deeper accumulation of Zn can also be attributed to its partitioning onto clay particles and subsequent movement through illuviation processes (28).

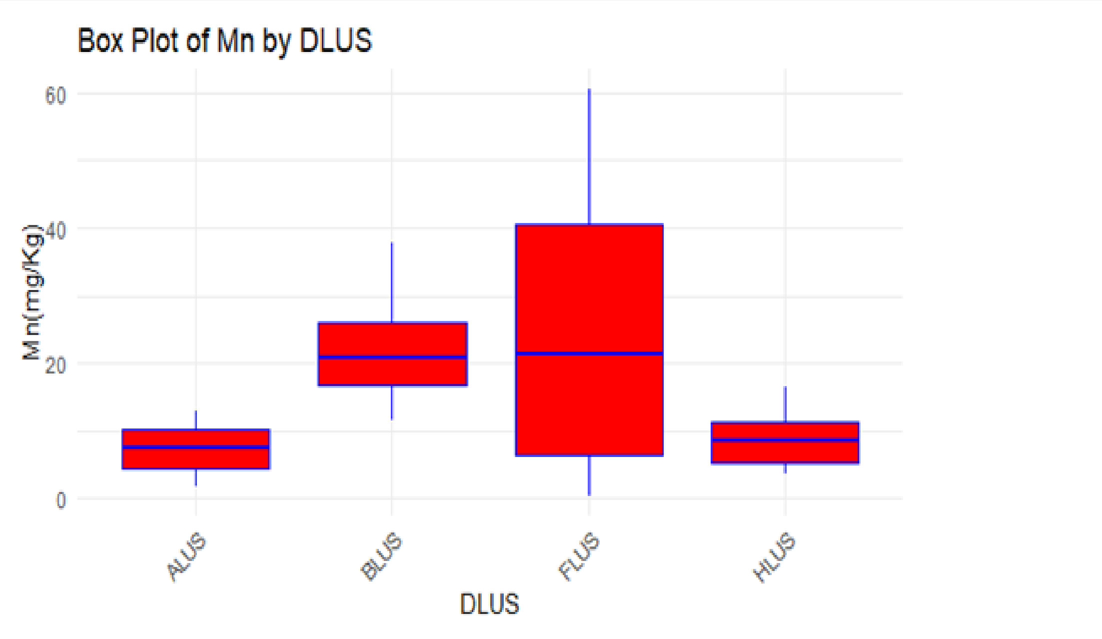
Cd, Pb, Ni and As are also generally concentrated in surface horizons (29, 30). Pb shows strong binding to organic matter, which is typically more abundant in surface soils (31). Pb often originates from galena (PbS) present in ore bodies, contributing to its enrichment in topsoil and forms stable organometallic complexes due to its low mobility (32). However, Pb concentrations may also increase at lower depths due to the facilitated transport of colloidal particles (33). This has been supported by findings in sandy soils, where colloid-facilitated transport contributes to Pb mobility (34-36).

Excess accumulation of heavy metals in surface soils can become phytotoxic, leading to oxidative stress, impaired photosynthesis, disruption of pigment and enzyme functions and overall suppression of plant growth and vigour (49). Cadmium (Cd), being highly soluble and mobile in soil, readily enters plant tissues, where it induces chlorosis and stunted growth by hampering nutrient uptake and damaging cellular components. Toxic metals such as Pb, Ni and As, which are concentrated in topsoil near mining and tailing zones, can inhibit root development, disrupt water-and-nutrient transport and provoke oxidative damage through reactive oxygen species (ROS), further impeding biomass accumulation particularly in ALUS and HLUS. Lead (Pb) strongly binds to organic matter, increasing its bioavailability to plants and leading to symptoms like chlorosis, necrosis and impaired growth, while nickel (Ni) can cause chlorotic interveinal patterns, wilting and reduced germination rates.

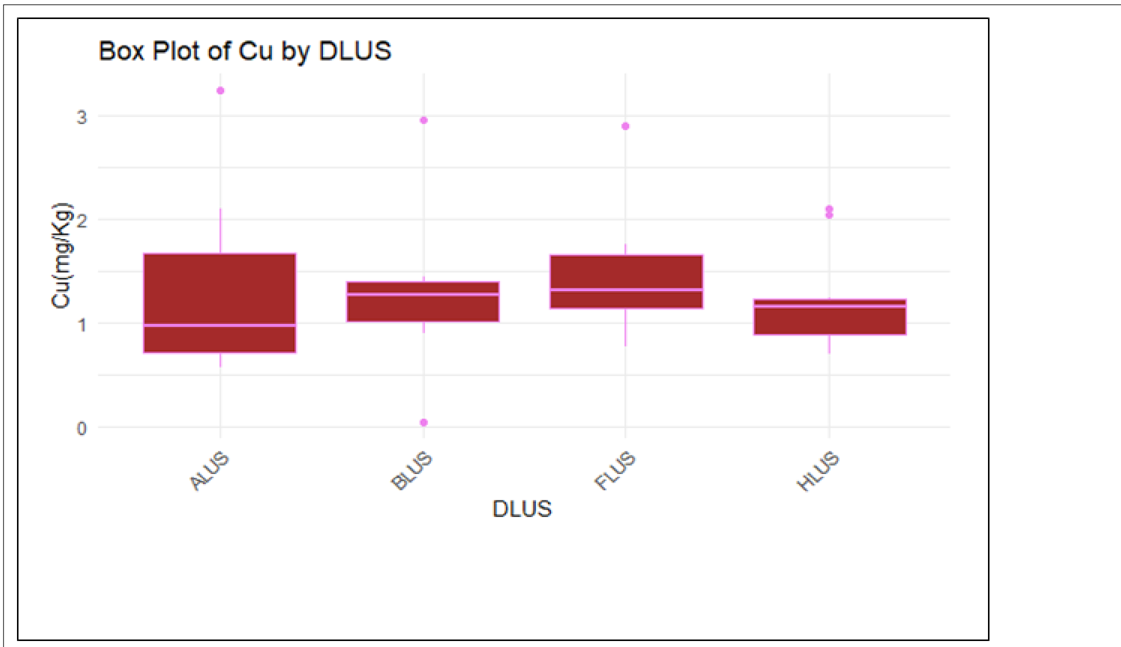
The distribution of heavy metals in the Kolar Gold Field region throughout the several land use systems (ALUS, HLUS, BLUS and FLUS) was depicted in a heat map (Fig. 2). In every land use system, Mn and As had the greatest amounts of any metal. The KGF region has a history of gold mining, which may be the reasons for its increase. Anthropogenic activities related to mining operations as well as geogenic causes raise As and Mn concentrations in all land use systems (23). Ni and As were present at moderate concentrations in ALUS and HLUS respectively. In BLUS lead (Pb) appeared at medium concentration, while in FLUS Fe and Cu were present in medium concentrations, remaining metals were present in low concentrations. The variation in heavy metal accumulation among various land use systems reflects the influence of these factors, with areas closer to mining sites exhibited higher concentrations (37). Another possible explanation is that soils with higher clay and OM possess increased CEC. This characteristic enables them to immobilize heavy metals through processes such as adsorption and complexation, thereby


Box Plot of Fe by DLUS
Fe(mg/Kg)
8
6
4
2
ALUS
BLUS
FLUS
HLUS
DLUS

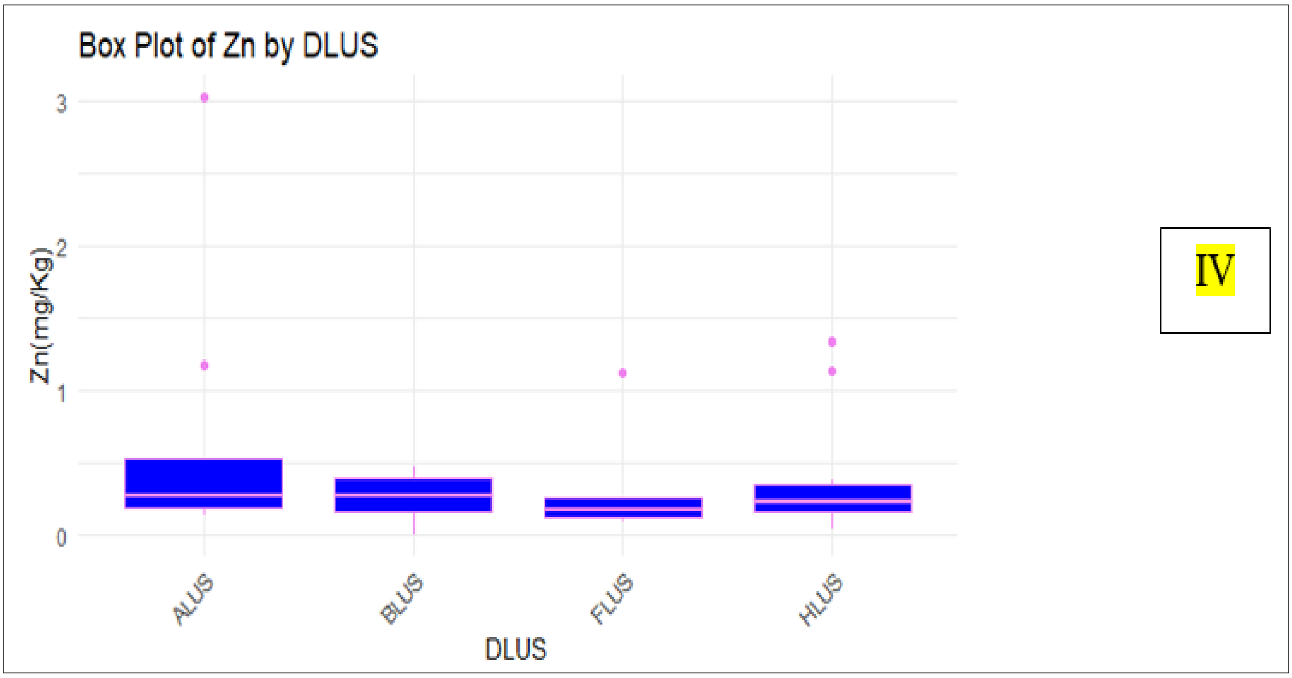
I

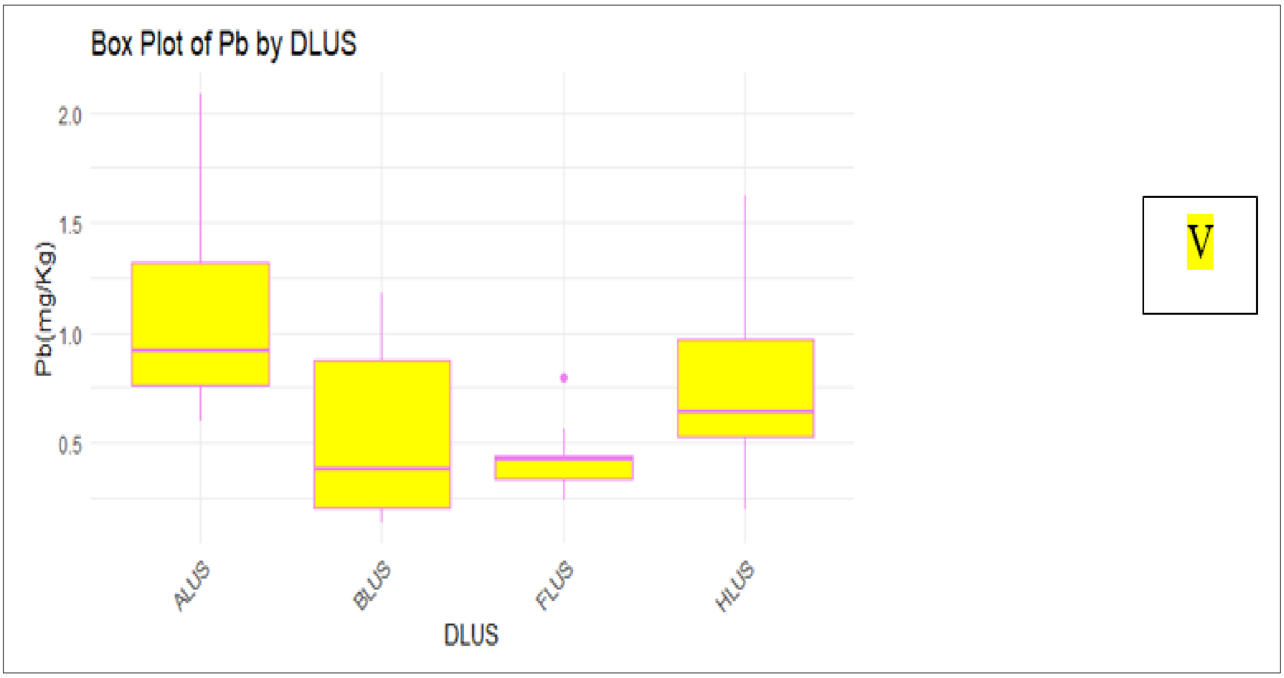

Box Plot of Mn by DLUS
Mn(mg/Kg)
60
40
20
0
ALUS
BLUS
FLUS
HLUS
DLUS

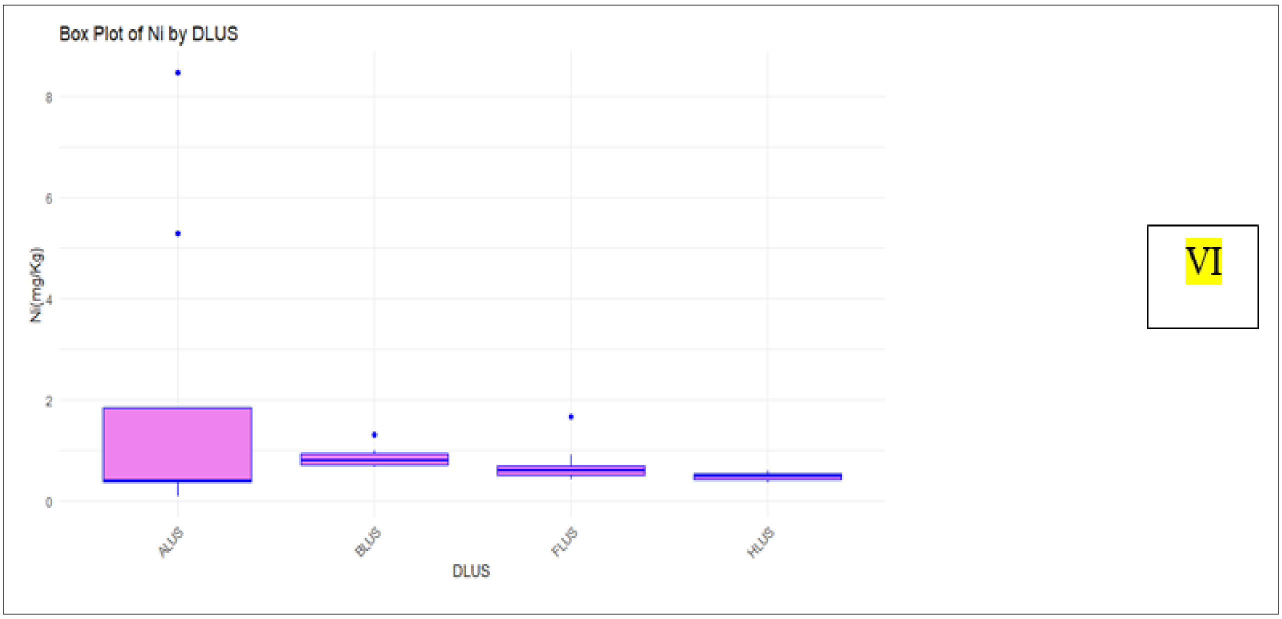
II

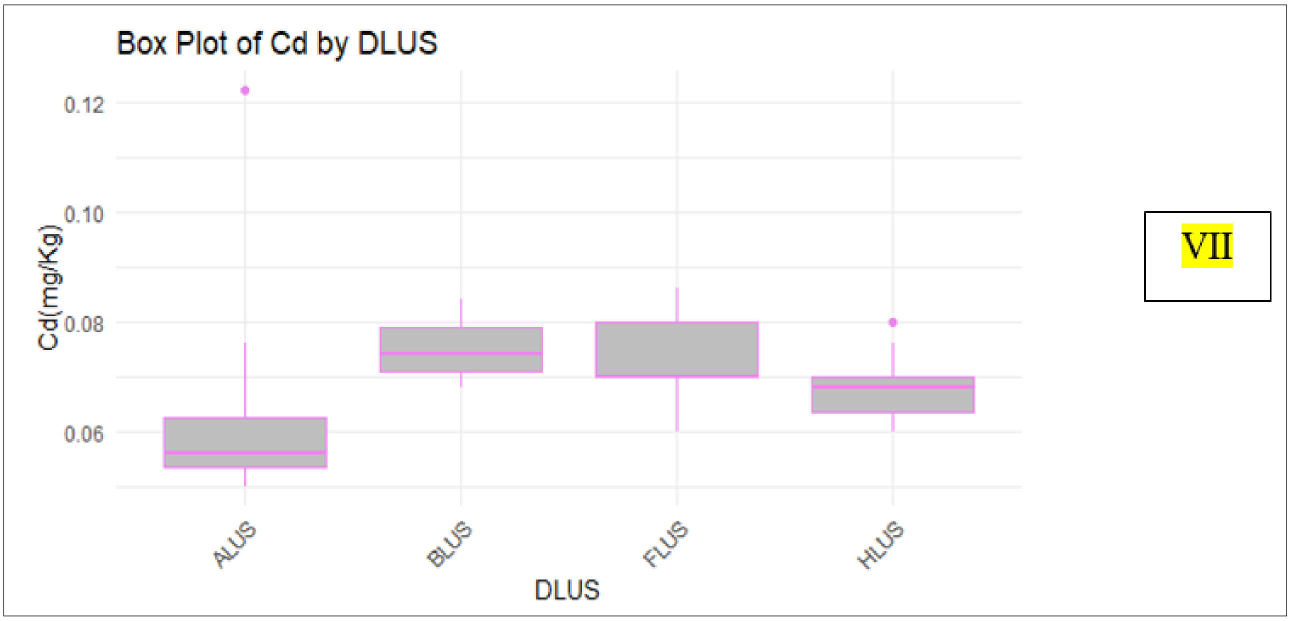

Box Plot of Cu by DLUS
Cu(mg/Kg)
3
2
1
0
ALUS
BLUS
FLUS
HLUS
DLUS

III


Box Plot of Zn by DLUS
Zn(mg/Kg)
0
1
2
3
ALUS
BLUS
FLUS
HLUS
DLUS
IV


Box Plot of Pb by DLUS
Pb(mg/Kg)
0.5
1.0
1.5
2.0
ALUS
BLUS
FLUS
HLUS
DLUS
V


Box Plot of Ni by DLUS
Ni(mg/Kg)
0
2
4
6
8
ALUS
BLUS
FLUS
HLUS
DLUS
VI



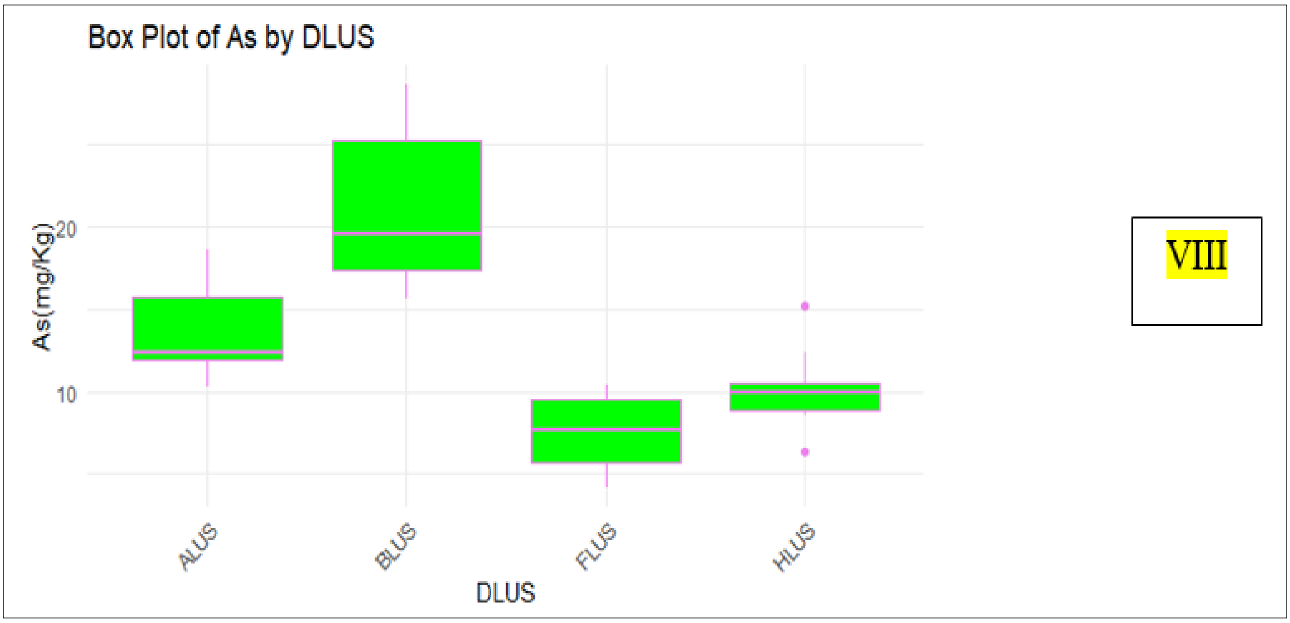


Fig. 3. Box plot of Fe (I), Mn (II), Cu (III), Zn (IV), Pb (V), Ni (VI), Cd (VII) and As (VIII) in ALUS, HLUS, BLUS and FLUS.

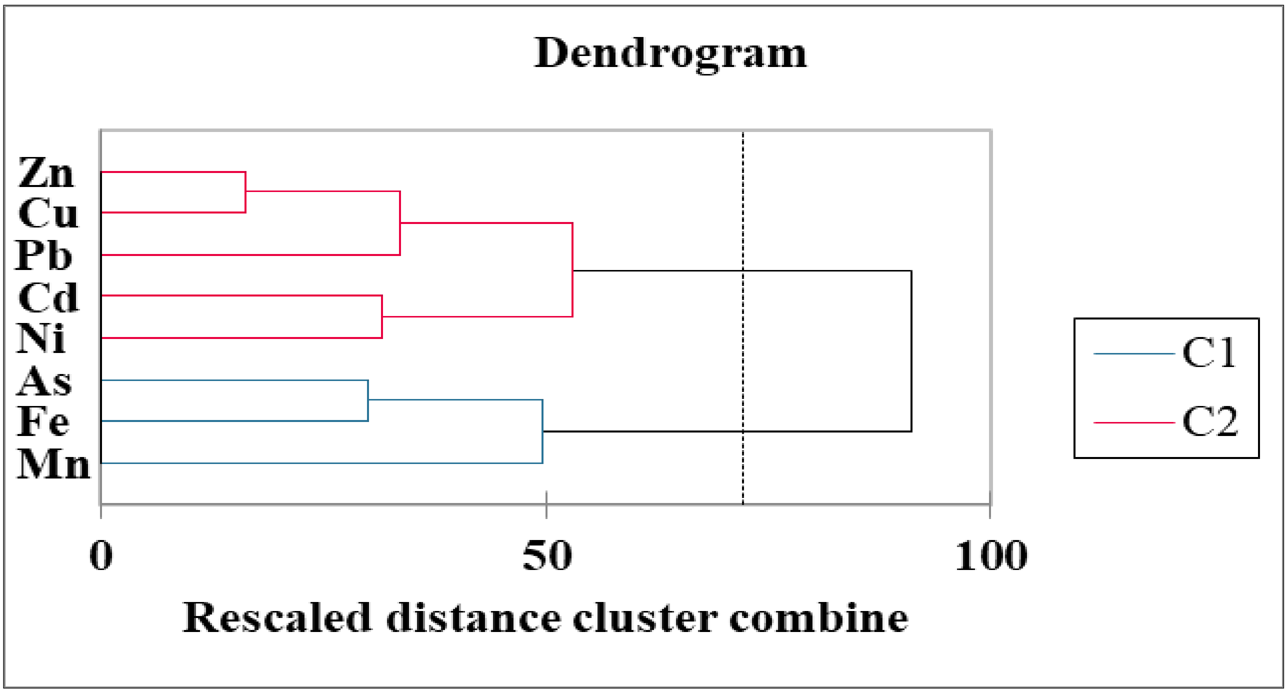


Fig. 4. The dendrogram of the hierarchical cluster analysis of heavy metals

decreasing the mobility of these metals. As a result, heavy metals accumulation varies across DLUS (38).

Correlation between different heavy metals was shown in Table 4. Fe showed strong correlation with Cu (0.534**), Mn (0.508**), Zn (0.534**) and As (0.544**), this might be due to iron oxides in the soil act as key adsorbent, have high surface area and reactivity, enabling them to bind various heavy metals, thereby influencing their distribution and mobility in soils (39). Cu exhibited strong correlation with Zn (0.755**) indicate that these metals share similar sources (40).

Box plot of different heavy metal distribution in ALUS, HLUS, BLUS and FLUS was presented in (Fig. 3). The higher median concentrations of Fe, Mn and Cu in the FLUS might be attributed to the natural weathering of mineral rich parent material and accumulation of metals in undisturbed organic rich forest soils (41). Forest litter and slow decomposition process contribute to metal retention and vertical stratification, explaining wider interquartile ranges observed in FLUS (42). HLUS recorded the lowest median values for heavy metals, likely due to regular organic input, irrigation and crop uptake reducing metal bioavailability (43). Elevated Pb and Ni in the ALUS of KGF can be attributed to usage of fertilizers, pesticides and sewage sludge and phosphorus fertilizers commonly used in agriculture often contains trace amount of these heavy metals in the raw materials used for the fertilizer production (44). Arsenic was found highest in BLUS was likely due to remnants of gold processing, where arsenopyrite is a common ore mineral in KGF, leading to its accumulation (45).

The hierarchical cluster analysis dendrogram, which shows the grouping pattern of heavy metal concentrations across various LUS and soil profile depths, is shown in (Fig. 4). Due to similar soil management techniques, such as controlled irrigation, organic amendments and routine tillage, which tend to dilute or disperse heavy metals like Cd, Pb and As across surface layers, ALUS and HLUS clustered together. Because of their comparatively unaltered or naturally accumulating profiles, BLUS and FLUS are clustered together. Due to air deposition and lack of plant uptake, BLUS exhibited greater surface accumulation of metals such as Mn, Pb and As, whereas FLUS accumulated Mn as a result of mineral cycling and litter breakdown (46).

Conclusion

This study highlights the significant variability of heavy metals across DLUS with in post mining area. By employing advanced statistical methods such as heat maps and hierarchical cluster dendrogram analysis, the research effectively identified the metal load in DLUS across the profiles. The findings revealed that surface horizons recorded higher contamination levels due to historical mining and tailing deposition. As and Mn were the most dominant metals in BLUS and FLUS, indicating severe ecological impact. ALUS displayed elevated levels of Ni, Pb and Cu, posing potential risk to crop production. Among all LUS heavy metal content followed the order of FLUS> BLUS> ALUS> HLUS. Correlation analysis revealed strong interdependence among several metals, suggesting common sources of contamination. Box plot analysis provided clear insights into the spatial and vertical variability of metal concentrations within each LUS. The formation of distinct clusters provided valuable insights about metal loads in DLUS. The uniformity of Zn and Cd concentrations across land use systems suggests limited mobility or source uniformity. Overall, the spatial distribution and association patterns of metals highlight the legacy of mining induced pollution in the region. Elevated heavy metal load can adversely affect plant growth by reducing nutrient uptake, inducing oxidative stress and impairing physiological functions. The decline in soil fertility due to metal toxicity may compromise crop productivity in agriculture lands. Therefore, adopting phytoremediation techniques like phytoextraction, Phyto stabilization and other eco-restorative strategies becomes crucial for mitigating risks and restoring soil-plant health in these post gold mining lands in a sustainable manner.

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Authors' contributions

RM and SKJ carried out the conceptualization. RM, SKJ, AS, VR carried out sample collection. RM, SKJ, AS, VR, BT conducted data analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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