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Prediction of trace element dynamics at the Lite-Bala site in the Democratic Republic of Congo (DRC)

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ABSTRACT

The transfer of trace elements from the soil to plants is determined by the physico-chemical characteristics of the soil, the nature and content of the trace elements and the duration of exposure. The aim of this study is to determine the physico-chemical characteristics of the soils at Lite-Bala that influence this transfer. Random sampling and analysis of physico-chemical parameters were carried out. Statistics were used to visualise the results and identify the key variables. The study showed that soils and sediments were more acidic (4.55 ± 0.35 - 5.86 ± 0.16) and oxidising (319.19 ± 8.18 – 387.58 ± 20.78 mV) than surface and pore waters (pH 6.43 ± 0.32 - 6.72 ± 0.49 and Eh ≤ 280 mV). Organic carbon levels were low (< 1.5%). Soil and sediment clay contents ranged from around 35 - 42% and 7 - 17% respectively. Statistically, the total inertia rate of 91.4 indicates with certainty that pH, oxidising power, clay and sand content regulate the transfer of trace elements from the soil to plants. There is a proven risk to human health and the environment at the Lite-Bala site. Monitoring and quantification of trace elements at the site is necessary to protect human health and the environment.

Keywords: Trace elements, Characteristics, Mobility, Transfer, Risk, Lite-Bala.

INTRODUCTION

There has been a boom in metal mining worldwide, particularly in the artisanal and Small-scale Gold Mining (ASGM) sector. Unfortunately, the increase in mining productivity has led to an increase in trace elements (TE) in the different environmental compartments of mining sites which can give

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rise to serious health and environmental problems (Coulibaly and Sako, 2024; Fonshiynwa et al., 2024; Mahmoud et al., 2024; Bikubanya et al., 2022; Ouattara et al., 2022). The various gold deposits generally have in the following trace elements (TE) in common : Au, Ag, Fe, Cu, Pb, Zn, Hg, Mo, Sb, As, Te (Bruni and Hatert, 2017). To gain a better understanding of the levels and distribution of trace elements on a site, it is essential to assess the physicochemical characteristics of the various compartments. However, the level of degradation and risk depends on the physicochemical characteristics of the site (Hamkary et al., 2024; Souareba et al., 2024; Rwiza et al., 2023; Ibrahim et al., 2019; Assad, 2017).

In the Democratic Republic of Congo (DRC), there have been few studies in the gold ASGM sector. They have been carried out more in the eastern part of the country, particularly in the socio-economic, anthropological and development, theological fields, and less in the environmental field (Bikubanya et al., 2022). Therefore, this study focused on the dynamics of TE at the Lite-Bala gold site. The main objective was to predict the mobility and transfer of trace elements in the soil, sediment and water conditions of the Lite-Bala gold site.

MATERIALS AND METHODS

Presentation of the study area

The Lite-Bala gold site is located north-west of the central Congo basin in the province of Nord-Ubangi, precisely between the parallels 3°48'0" – 3°44'3" in the Northern hemisphere and the meridians 23°6'30" – 23°9'0" to the East (Figure 1).

Eight gold deposits (2 non-active and 6 active) and 6 camps were identified on the site, which is located in a hot equatorial zone with wide temperature variations (11 to 20°C). The site located in the dense forest, has two seasons, a rainy season from March to October, and a dry season from November to February, and dense forest. Average annual rainfall does not exceed 1,600 mm. The landscape at the gold site consists of plateaus and hills with gentle slopes (< 3%) and low altitudes (< 700 m). The geology of the site consists of schistose and sandstone rocks with little or no metamorphism. The soils belong to the group of ferralsols, mineral soils derived from highly altered materials and rich in kaolinites and iron sesquioxides. The hydrography of the gold site is dense, like that of the central Congo basin (Omasombo et al., 2019; IUSS Working Group WRB, 2022).

The site's population, estimated at 6,000, fluctuates with productivity and the province's economic situation. Subsistence crops (cassava and corn) are grown around the site, and small-scale trade takes place within the site. The health situation is precarious with several diseases (hypertension, dermatitis, gastrointestinal diseases, kidney diseases, anorexia, sexually transmitted diseases, malaria, urinary infections, etc.) (Bikubanya et al., 2022; Mendes and Poiata, 2016).

Sampling strategy

Combined random sampling was adopted as the sampling strategy. The number of samples to be taken is determined by the surface area of the area ($\sqrt{A}$ +1, where A is the surface area in hectares) or by the length of the river studied (Hamkary et al., 2024; Casado et al., 2021; Ye et al., 2020; Bataillard et al., 2012). Thus, 28 soil samples were taken on the surface (0 – 25 cm) (SS) in zones 1 and 2, and in depth (40 – 65 cm) (DS) in zone 2. Ten samples of River Water (RW), ten samples of Interstitial Water (IW) taken from the sediments after a 24-hour rest and two samples of Spring Waters (SW) were collected on site (Figure 1). The samples were packaged in plastic bags and Polyethylene (PE) bottles, after drying the soil and sediments under shade or acidification. (1 ml concentrated acid for 1 liter of water). The sampling campaign for the rainy season was carried out from 4 to 24 May 2023.

Physico-chemical analyzes

The physico-chemical variables influencing the mobility and transfer of TEs to plants are mainly hydrogen potential (pH), redox power (ORP or Eh), organic carbon (Corg), granulometry and dissolved oxygen (O_2) (Hamkary et al., 2024; Gasser et al., 2023; Quimeby and Normand, 2022; Tremel-Schaub and Feix, 2020, 2005; Bataillard et al., 2012). In the field, the Oyster Meter multiparameter probe, model 341350A, fitted with a saturated electrode Ag/AgCl, *KCl* (E_0= 0.199 mV) was used to determine hydrogen potential (pH) (NF T 90 008) and redox power (ORP or Eh) (ISO 11271: 2002) on a soil or sediment solution (1:5 v/v), while dissolved oxygen (O_2) in the water was measured with a HANNA HI 9146 oximeter. In the laboratory, organic carbon (Corg) was determined using the Walkley-Black method and particle size (NF P 94-057) was dones using the sedimentation method. Cation exchange capacity (CEC) was determined by the ammonium acetate method (Miravo et al., 2023; IUSS Working Group WRB, 2022; Keddari et al., 2019).

Identification of risk factors

The risk factors were identified using an approach based on the assessment of the risk of polluted soils to human health coupled with the ecotoxicological approach for the protection of ecosystems. The different approaches stipulate that the risk absolutely requires the concomitant presence of three factors: a source of pollution, a vector for transferring pollutants to a point of exposure and the presence of potential targets (humans, animals, vegetation, ecosystems) (Ahoussi, 2021; Lu et al., 2019; Bataillard et al., 2012).

Statistical processing

Descriptive statistics were used to compare the variability and distribution of variables between different compartments of a site and to identify extreme or outliers (boxplots). PCA was used to identify variables with a strong contribution to the dynamics of TMEs and those that are highly correlated (Keddari et al., 2019; Lu et al., 2019).

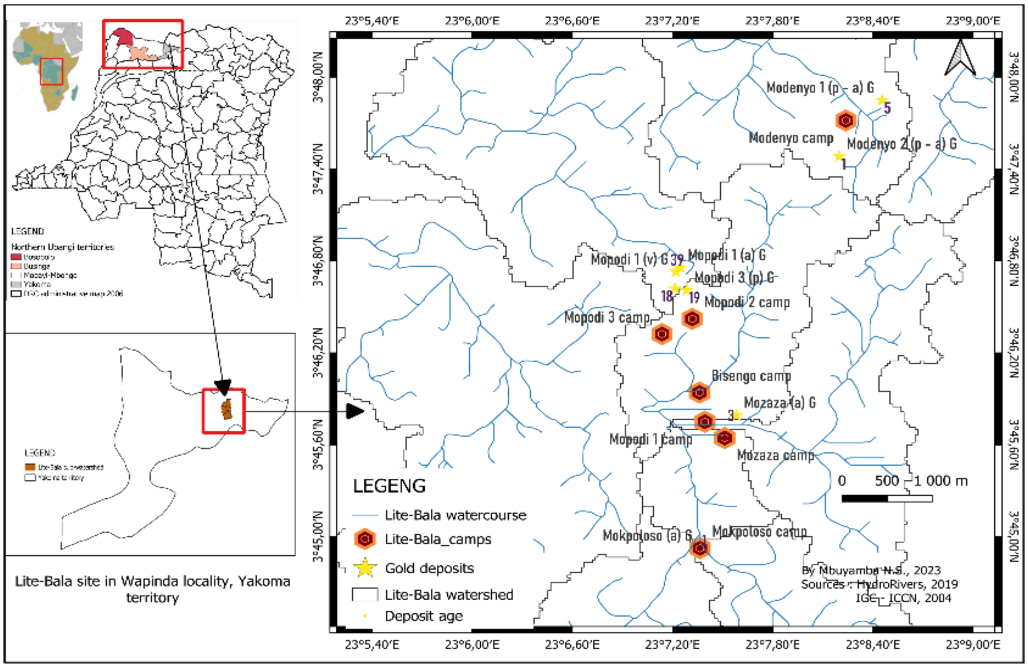

Figure 1: Location map of the Lite-Bala gold site and sampling.

RESULTS

Analyzes of physicochemical variables of soils and sediments of the Lite-Bala gold site.

Figure 2 shows the pH of the various compartments at the gold site. This figure shows that the pH of the site is generally acidic (pH < 7) with mean pH values ranging from 4.55 ± 0.35 to 4. 62 ± 0.46 for surface soils (SS) and deep soils (DS) in zone 2, and from 5.46 ± 0.17 for surface soils (SS) in zone 1, then from 6.72 ± 0.49 to 6.51 ± 0.28 for river water (RW) and finally from 6.43 ± 0.32 to 6.54 ± 0.12 for interstitial water (IW) in zones 1 and 2 respectively. The study revealed considerable heterogeneity or fluctuation in pH for river water and pore water in zone 1, and for river water and pore water in zone 2. It shows an extreme point for SS.

Figure 3 shows the redox capacity (ORP or Eh) of the solutions in the different compartments of the gold site. This figure shows the redox capacity values for the various compartments: 390 ± 20 mV for the deep soil (DS), 340 ± 10 mV - 390 ± 30 mV respectively for the surface soil (SS) in zones 1 and 2, 380 ± 20 mV for the spring water (WS), 270 ± 30 mV for the surface water (RW) and finally 270 ± 10 and 360 ± 40 for the interstitial water (IW) respectively in zones 1 and 2. A high degree of heterogeneity in redox power was observed in the RW and IW compartments in zone 1, RS and SS in zone 2, as well as the presence of two extreme points for DS in zone 2.

Figure 4 illustrates the organic carbon content of soils and sediments at Lite-Bala. This figure shows that organic carbon levels vary between 0.20% and 0.80%. In surface soils, organic carbon levels are 0.79 ± 0.36% and 0.40 ± 0.13% respectively in zones 1 and 2. They are 0.26 ± 0.16% in deep soils, and 0.57 ± 0.12% and 0.58 ± 0.10% in sediments in zones 1 and 2. These levels are higher for SS in zone 1 than in zone 2. There is considerable heterogeneity in the organic carbon variable in the SS compartment in zone 1 and the DS compartment in zone 2.

Figure 5 shows the sand, clay and silt composition of the soils and sediments at Lite-Bala, together with their cation exchange capacity (CEC). This figure shows that the clay content of the soils (SS and DS) is higher (36.00 ± 13.79 – 41.07 ± 2.40%) than in the sediments (7.01 ± 3.48 – 16.63 ± 2.60%), while the sand content is higher in the sediments (57.24 ± 2.20 - 82.41 ± 9.25%) than in the soils (39.78 ± 4.9079 – 40.07 ±0.90% in SS and 39.14 ± 6.27% in DS). Silt levels fluctuate around 18.87 ± 1.69 – 23.60 ± 5.47% and 24.86 ± 10.00% respectively in surface and deep soils and 26.13 ± 2.06 – 10.58 ± 7.23% in sediments in zone 1 and 2. However, there were very slight fluctuations between clay content of SS (40.07%) and DS (39.14%). Cation exchange capacities (CEC) are low overall, with an average of 26.25± 10.61 ± meq/100g for surface soils (SS), 20.52 ± 8.89 meq/100g for sediments (RS) and 16.70 ± 2.96 meq/100g for deep soils (DS).

Figure 6 shows the average dissolved oxygen in the river and spring water at the site. This figure shows high levels of dissolved oxygen in the river water in zones 1 and 2, with an average of 4.53 ± 0.03 – 4.02 ± 0.07 mg/L, and low levels in the spring water (2.64 ± 0.02 mg/L). River water is more heterogeneous than spring water.

Figure 7 shows the temperatures of the various samples during the measurements. The figure shows that the temperature of the samples at the time of measurement was below 30°C, with the exception of SW (31.59°C).

Identifying of risk factors

Prospecting and data collection permitted to identify the following risk parameters: processing of gold-bearing ores (placers) in the deposits, transport of gold-bearing ores (veins and gravels) in camps, drying of these ores on the ground, presence of the population, crushers and sedimentation basins in these camps. Gold ores and inputs, particularly mercury, were the main source of TEs, with run-off and drainage water, crushers dust, wind-blown and mercury vapors emitted during the purification of Hg-Au amalgam being the main routes dissemination. The main disseminating agent of TEs are water, wind and man. The potential targets of TEs were the people living in the camps and the various ecosystems (soils, sediments and rivers) of the site.

Statistical analysis

Figure 8 shows the correlations between the various soil and sediment variables at the gold site. This figure shows that the pairs of variables pH and Eh redox power, sand content and clay content are highly dependent but in opposite directions, with respective correlation coefficients of -0.910 (p-value = 1.969e-11) and -0.902 (p-value = 5.975e-11), while the variables electrical conductivity and chloride content are highly correlated and move in the same direction (0.771) with a p-value of 1.956e-06. The low p-values confirm the existence of these correlations.

Figure 9 is a biplot of soils and sediments at the gold site. This figure shows a percentage of total inertia of 91.4% and a proportion of cumulative variances at PC2 of 0.9142, indicating that the two axes are sufficient to interpret the levels and distribution of TEs. The contributions of the variables to the construction of the first axis (PC1) are respectively 0.52 for pH, 0.51 for sand content and -0.51 for clay content. For axis 2, the significant contribution is 0.56 for redox power (ORP or Eh). The soil samples have high values for clay content and redox power (ORP or Eh), while the sediments have high values for pH and sand content. This figure illustrates the physico-chemical similarities between surface soils (SS) and deep sediments.

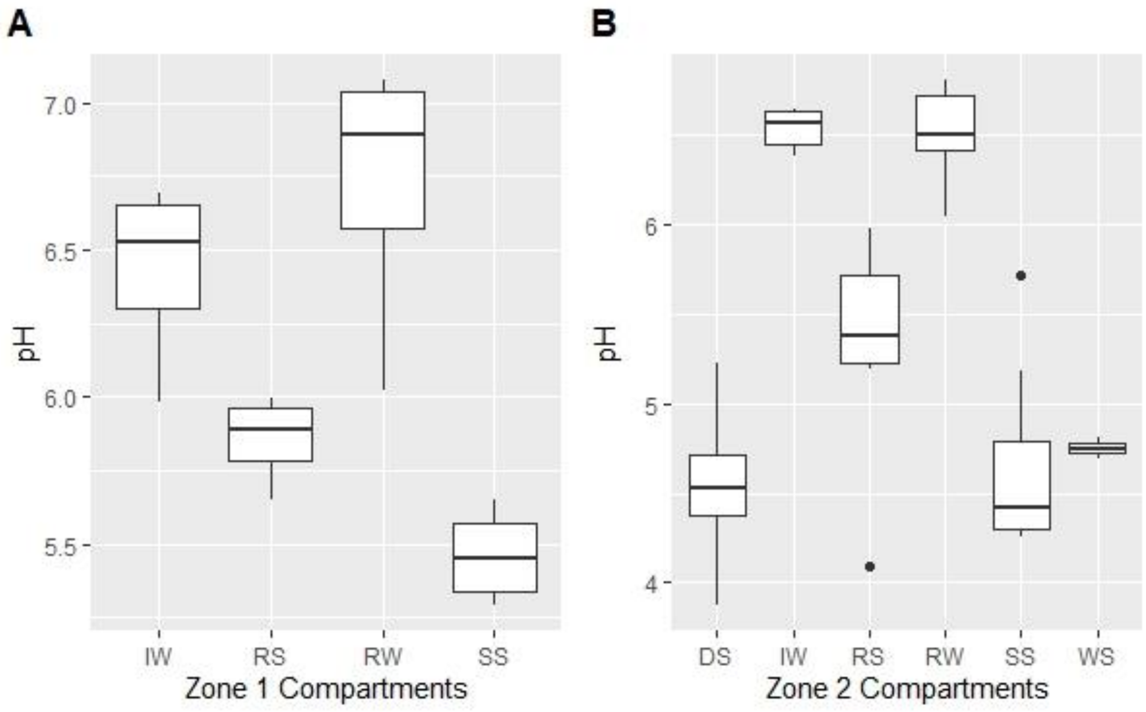

Figure 2: Acidity of the different compartments of the site.

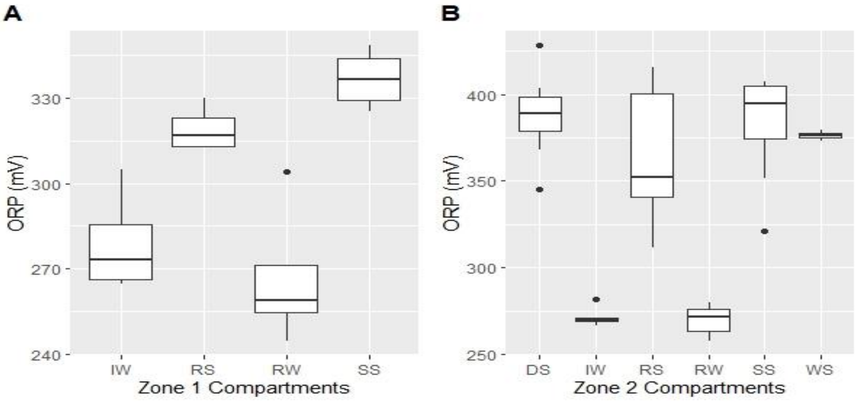

Figure 3: Oxidation-reduction capacity (ORP) of solutions in the different compartments.

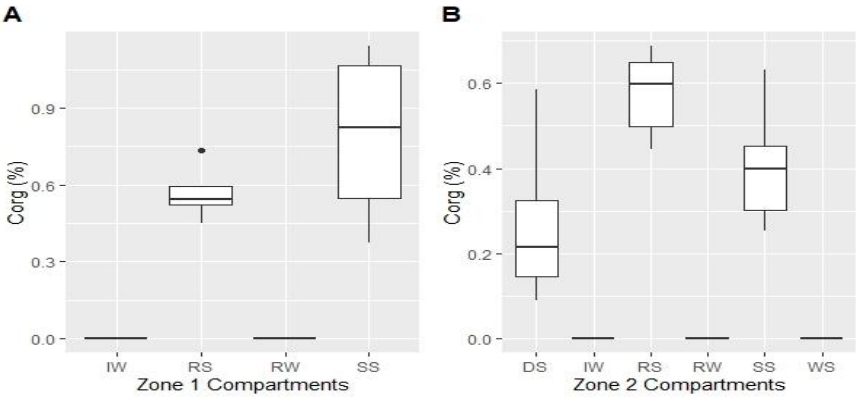

Figure 4: Organic carbon (Corg) contents of Lite-Bala soils and sediments.

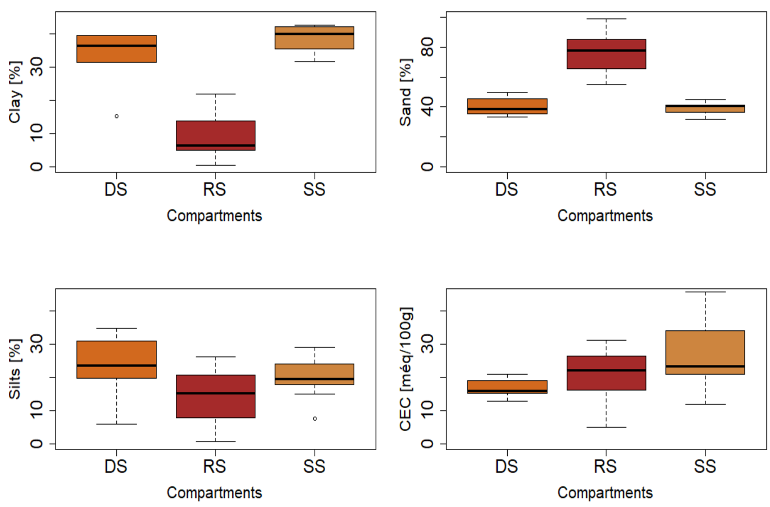

Figure 5: Clay contents and CEC of Lite-Bala soils and sediments.

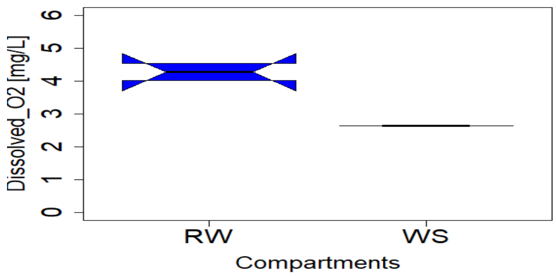

Figure 6: Dissolved oxygen contents of river and spring water.

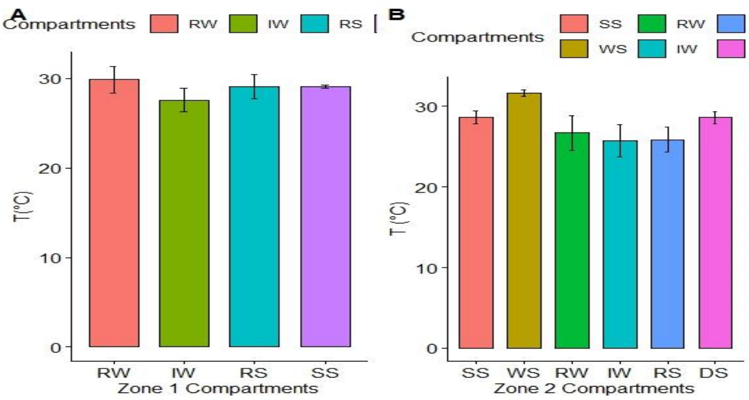

Figure 7: Temperature of samples during measurements.

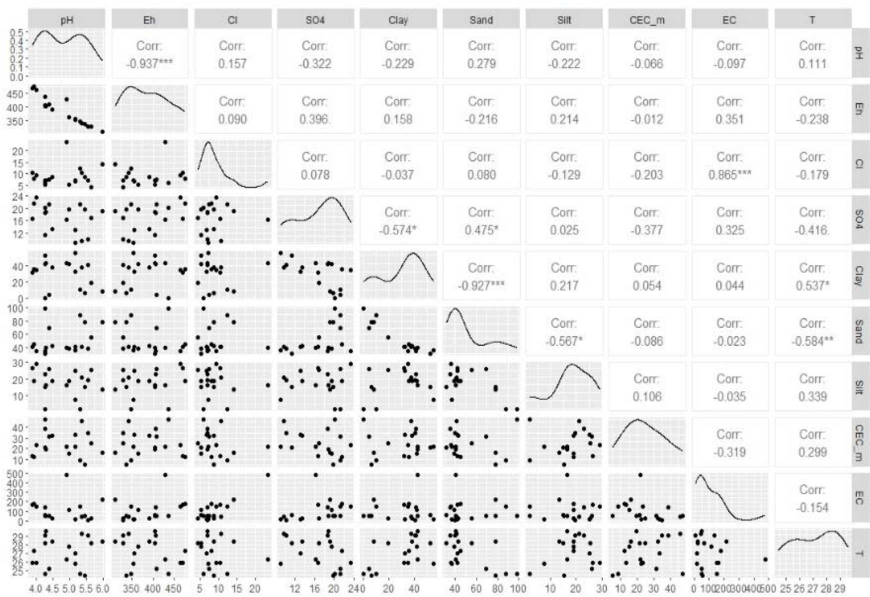

Figure 8: Soil and sediment physico-chemical parameter correlation matrix.

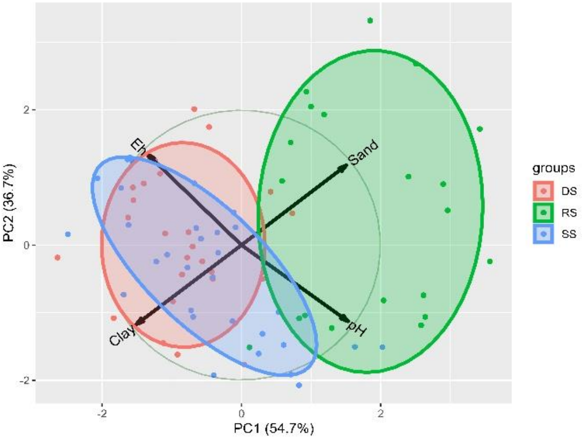

Figure 9: Biplot of Lite-Bala soil-sediments.

DISCUSSION

Soils are formed from bedrock, under the action of the climate and living organisms, and their evolution in time and space gives rise to different horizons with varied physico-chemical characteristics (colour, pH, redox potential, clay and organic matter content, Fe, Al or Mn oxides and hydroxides, etc.). The accumulation of TEs depends on the physico-chemical characteristics of each horizon (Coulibaly and Sako, 2024; Hamkary et al., 2024; Hullot, 2023; Quimeby et al., 2022; Lu et al., 2019; Bataillard et al., 2012).

The mobility and transfer of ETs from soil to plants and the relationships between the compartments are determined by the physico-chemical parameters of the soil, sediment and water (Coulibaly and Sako, 2024; Yuwono et al., 2023; Lu et al., 2019; Assad, 2017).

According to some authors, the soils of Lite-Bala are extremely acidic to strongly acidic. In addition, they belong to the group of ferralsols, soils with an acidity close to ~ 4.5 and low in mineral salts (TEs), developed on rocky substrates in flat lateritic landscapes covered by a dense hydrographic network (Figure 1) (Gasser et al., 2023; IUSS Working Group WRB, 2022; Ngongo et al., 2009).

Several authors have shown that the sorption and desorption of trace elements depend on the acidity of the compartments. In fact, the acidity at zero charge point (pH) of the trace element trap particles (iron, aluminium and manganese oxides and hydroxides, organic matter, clays, etc.) pH_{PCN} in relation to the acidity of the medium determines whether or not these elements are adsorbed. The pH_{PCN} of oxides and hydroxides varies between 6 and 9. In a medium with a pH below pH_{PCN}, the oxides or hydroxides are positively charged and can no longer bind the trace elements in solution. Unlike the situation where the pH is higher than pH_{PCN}, adsorption is maximal (Amel, 2020; Assad, 2017). At the Lite-Bala site, the pH values of the various compartments (Figure 2) indicate that adsorption is favourable for surface water and pore water. Trace elements will be more immobilised by trap particles suspended in surface water and pore water.

The oxidising character (Figure 3) is confirmed by the orange and yellow colour of the soils and sediments at Lite-Bala (IUSS Working Group WRB, 2022; Quimeby et al., 2022). Trace metals, naturally present in gold ores, with standard potentials (E_0) higher than the lowest ORP value on the gold site (240 mV) will be in a reduced state (Fe^{+2}, Ag, Hg_2^{2+}, Au, Hg, Pb^{+2}, etc.) while those with standard potentials (E_0) below this value will be in the oxidised state (Hg^{+2}, Hg_2Cl_2, Zn^{+2}, Cu^{+2}, Cd^{+2}, SiO_2) in solution (Brandely, 2022; Feix and Tremel-Schaub, 2020; Bruni and Hatert, 2017). In addition, the oxidising conditions of soil are very favorable to the formation of iron oxides, oxy-hydroxides and hydroxides, which are TEs trap particles whose surface charge varies with pH (Quimeby et al., 2022; Hullot, 2023; Coulibaly and Sako, 2024). In the case of soils and sediments, these particles are positively charged limiting the adsorption of TEs.

Several authors also maintain that the rate of transfer of trace metal from soil to plants is determined by pH, ORP/Eh and cation exchange capacity (CEC). Indeed, the acidity of the solutions favours the phyto-availability of certain TEs, while basicity leads to the formation of carbonates, oxy-hydroxides and bicarbonates of poorly soluble TEs. In addition, oxidative capacity modifies the charge of TEs, ligands and the solubility of particles in solution (Hamkary et al., 2024; Miravo et al., 2023; Lu et al., 2019; Tremel-Schaub and Feix, 2020).

Lite-Bala's compartments characterised by high acidity (soils and sediments) show average transfer rates for copper (Cu), lead (Pb), chromium (Cr), arsenic (As) but high rates for zinc (Zn), cadmium (Cd), mercury (Hg), cobalt (Co), nickel (Ni) and tantalum (Tl), while those with an oxidising character (ORP/Eh) (240 - 390 mV) have average transfer speeds for Cu, Co, Hg, Ni, Zn, Cd and As, and high speeds for molybdenum (Mo) and selenium (Se) according to Tremel-Schaub and Feix (2005, 2020).

Organic matter, which is very important for the adsorption or complexation of TEs (Hamkary et al., 2024; Gasser et al., 2023; Quimeby et al., 2022) is in very low quantities at the site (Figure 4). These low levels of Corg facilitate the migration of TEs towards watercourses and groundwater, increasing the risks for the population and various ecosystems. Organic carbon levels at the Lite-Bala site are low and close to those found by Hamkary et al. (2024) (0.62 - 0.75%) at a former gold mine in Kuang village, Taliwang district, West Sumbawa regency.

As for the texture of soils and sediments, several authors have shown that the clay texture of the soils favours pH values between 4.5 and 5, while the loamy sandy texture of sediments favours pH values close to 5.5. The pH values of the soils and the sediments at Lite-Bala (Figure 5) are within these pH ranges. However, the clay texture is favourable to the adsorption of TEs but has a negative effect on the percolation of water containing TEs (Gasser et al., 2023; Hullot, 2023; Bossé et al., 2022; IUSS Working Group WRB, 2022; Quimeby et al., 2022).

The transfer of TEs from the soil to the plant is also slowed down by this fine texture. These same authors state that the percentage of slopes and the texture of the site’s soils determine the resistance of a site’s surface layers to wind and water erosion (Gasser et al., 2023; Bossé et al., 2022; Quimeby et al., 2022; Tremel-Schaub and Feix, 2020; Tremel-Schaub and Feix, 2005). The surface layers of Lite-Bala soils, with a landscape of low slopes and high clay contents (≥ 40%) and low Corg content (< 1%), are not very vulnerable to wind and water erosion.

Several authors state that the soils of the Central Congo Basin belong to the group of ferralsols characterised by clay contents of between 20 and 45% and CECs close to 35 cmol(+)/kg or meq/100g at pH 4.5. These low CECs lead to high bioavailability of ETs (Hamkary et al., 2024; Hullot, 2023; IUSS Working Group WRB, 2022; Tremel-Schaub and Feix, 2005).

Under Lite-Bala conditions, contamination or pollution by ETs cannot persist after the deposits have been mined, and the extension of the ET-polluted zone could be very limited. The mobility of ET on the gold site is high and requires monitoring to identify the most informative compartment.

Others add that under Lite-Bala soil conditions (Figure 5), the transfer from soil to the plant is high for the following elements As, Co, Cr, Hg, Ni, Tl, Cd, Mo, Se, Zn and very high for Cu, Ni and Pb. The acidic nature of Lite-Bala’s soils and sediments reduces the cation exchange capacity (CEC) and increases the transfer of TEs from soils and sediments to plants. However, the transfer of a chemical element can be inhibited and/or stimulated by the presence of one or more chemical element

(Hullot, 2023; Tremel-Schaub & Feix, 2005, 2020; Lu et al., 2019).

Several authors have also demonstrated the important role played by dissolved O_2 levels on the distribution of biotic communities and the distribution of TEs between the immobile phase and the dissolved phase (water column). A decrease in dissolved O_2 levels can lead to a release of TEs (Vualu 2020). In addition, well aerated waters were a high oxidising power compared to less aerated waters. However, the oxidising-reducing power of water is also influenced by the pH of the solutions. Acidic waters are more oxidising than neutral or basic waters (Keddari et al., 2019; Dipakama et al., 2024). Although the river waters of Lite-Bala have high levels of dissolved O_2, they have low ORPs compared with spring waters that are low in dissolved O_2 but more acidic (Figure 6).

The temperature determines water-atmosphere exchanges, the solubility of gases (dissolved O_2, carbon dioxide, etc.) and salts, photosynthesis, respiration, the mobility of trap particles and the mineralization of organic matter (Tremel-Schaub and Feix, 2005; Tremel-Schaub and Feix, 2020; Vualu, 2020; Assad, 2017). However, several authors have shown that between 10 and 30°C, it has very little effect on the mobility of TEs, except in the presence of organic matter where it can be significant (Tremel-Schaub and Feix, 2005; Vualu, 2020; Tremel-Schaub and Feix, 2020). The temperatures of the samples taken from the gold site (Figure 7) oscillate around 30°C, except for SW in zone 2. The Lite-Bala site is located in a humic tropical zone, with wide variations in temperature between day and night. These temperature fluctuations affect the different compartments without, however, significantly modifying the mobility of trace elements, as suggested by various authors.

Health risks at the gold mining site are more than likely because many risk factors are present, in particular the presence of TEs from ores, potential targets (diggers, inhabitants of the camps, vegetation, etc.) and vectors for transferring TEs to points of exposure (diggers, runoff water, dust) as supported by several authors. These trace metals have various effects on human health and ecosystems in the short and long term (Dossou et al., 2022; Ye et al., 2020; Ibrahim et al., 2019).

The multivariate statistics indicate that the variables pH, ORP or Eh, sand content and clay content are determining factors in the dynamics of TEs on the site. The minus sign indicates that the variable evolves in the opposite direction with the mobility and transfer of TEs. In fact, several authors state that the more the oxidising character of the soils intensifies, the more oxides, hydroxides and mixed oxides are formed. These compounds interact with TEs by adsorption and/or absorption, thus reducing their mobility and transfer to plants depending on the pH of the environment. The mobility of TEs increases with sand content but decreases with clay content. Naturally, the various variables (pH, ORP or Eh, ligands, etc.) in soils and sediments are modulated and controlled by biological activities. However, anthropogenic activities generally disrupt the cycling of these elements, leading to contamination or pollution (Coulibaly and Sako, 2024; Hamkary et al., 2024; Gasser et al., 2023; Miravo et al., 2023; Bossé et al., 2022).

Conclusion

The Lite-Bala gold site, located in a humid tropical, is a highly altered zone, with soils, sediments and spring waters that are more acidic and oxidising than river and interstitial waters. Under these conditions, the mobility and transfer of TEs to plants is significant. In fact, the acidity of the site has a negative influence on the adsorption of TEs in soils and sediments as well as in river and interstitial waters. This low sorption increases the bioavailability of TEs and encourages their transfer to plants, watercourses and groundwater. The mobility of TEs is facilitated by the low organic carbon contents of the soils and sediments of Lite-Bala, organic matter being essential for the adsorption of TEs. The clay texture of the soils and sandy loamy sediments explains the acidity of these compartments, which also limits the permeability of run-off water containing TEs, increasing the mobility and bioavailability of TEs. The existence of all the risk factors on the site suggests that the risk to human health must be taken seriously.

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHORS' CONTRIBUTIONS

The draft of this article was submitted to the professors on the supervisory committee, as well as to the professors from the University of Kinshasa who took part in the field supervision (sampling campaign and processing of part of the data). Corrections concerned the wording of the introduction, the choice of bibliographical references, the choice of parameters and analytical methods. As the Lite-Bala gold site is located in the province of Nord-Ubangi, PKTNN had to intervene personally, financially and materially, to gain access to the site, carry out the sampling campaign and bring the samples back to Kinshasa. The gold site is located in the middle of the equatorial forest, and the diggers are wary of outsiders, particularly researchers. DDT is the initiator of this study. She supervised the champagne and sample analysis in Kinshasa, and contributed corrections to the presentation and discussion of the results. FAGD and NY were involved in finalizing the protocol (sampling and analysis methods) prior to the field trip, as well as correcting the title of the article and the discussion of results. CK coordinated the field trip (sampling and measurement equipment), the processing and interpretation of the data collected and the overall editing of the article.

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