Eurasian J Soil Sci 2017, 6 (1) 28 - 36

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org

Influence of the artisanal gold mining on soil contamination with heavy metals: A case study from Dar-Mali locality, North of Atbara, River Nile State, Sudan

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Article Info

Received : 03.03.2016
Accepted : 25.05.2016

Abstract

Twenty soil samples were collected from North of Atbara (Dar-Mali locality),River Nile State, Sudan (17.82289 to 17.82389N and 33.99974 to 34.02127E) inside and outside gold mining area in order to assess the influence of the gold mining on the concentrations of selected heavy metals (Co, Cu, Fe, Mn, Ni, Pb, Zn, Hg) in study area. The soil contamination by heavy metals of study area was studied using two parameters; (i) Comparison of the heavy metals concentrations with mean concentrations in most world soils, (ii) Enrichment Factor (EF). Results revealed that the concentrations of heavy metals were varying in the study area, the highest concentrations were obtained at the center of mining area particularly inside the mining basins of gold extraction. The concentrations of Cu, Fe, Mn, Zn, Co, Ni, and Pb were ranged from (4.85 to 34.65 mg kg^{-1} soil), (6,355 to 14,635 mg kg^{-1} soil), (37.35 to 655 mg kg^{-1} soil), (11.85 to 42.7 mg kg^{-1} soil), (0 to 16.5 mg kg^{-1} soil,) (2.5 to 47.3 mg kg^{-1} soil) and (2.65 to 823.5 mg kg^{-1} soil), respectively. The results also indicated that the soil samples which collected from inside mining basins have a highest EF for most heavy metals particularly Pb, which showed EF value of (676.3), suggesting that the Pb may be derived from anthropogenic source. This study recommends regular monitoring of heavy metals in the soils around the Artisanal gold Mining for conservation and protection from pollution.

Keywords: Sudan, River Nile State, gold mining, enrichment factor, mining basins.

Introduction

The development in the world in various fields such as industry, agriculture and other technology led to contamination the surrounding environment. The most important of these contaminants are heavy metals contamination such as lead, arsenic, cadmium, and mercury which using in extraction of gold in the most mining areas worldwide (Mandal et al., 2011).

Mining has been identified as one of the human activities which can have a negative impact on the quality of the environment (Donkor et al., 2005). It causes the destruction of natural ecosystems through removal soil and vegetation and burial beneath waste disposal sites funeral (Cooke and Johnson, 2002). Mining waste can

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e-ISSN: 2147-4249
DOI: 10.18393/ejss.284261

be divided into two categories: (i) mine tailings, generated during processing of the ore, and (ii) waste rock produced when uncovering the ore body (Ledin and Pederse, 1996).

Anthropogenic sources not only lead to increasing heavy metals concentrations in the environment, but also it can cause an unnatural enrichment, leading to metal pollution of the surface soils. The soil enriched with heavy metals can significantly cause an adverse impact on the population via inhalation, ingestion and dermal contact. The soil-accumulated heavy metals can also pose potential long-term hazards to plants and animals as well as humans that consume these plants (Singh and Kumar, 2006).

To our knowledge, in Sudan (especially at the gold mining areas), there is no research on soil contamination with heavy metals derived as a result of anthropogenic activities (gold mining activities) and its impacts. Thus, there is a need for proper assessment of heavy metals in the soils to ensure environmental sustainability. Therefore, the main objectives of the present study are to assess the influence of mining industry on the concentrations of soil heavy metals in the Dar-Mali locality, North of Atbara city, River Nile State, Sudan and to study the effect of vicinity and distance from mining zone on concentration of heavy metals in the study area.

Material and Methods

Site description and soil sampling

The study area is located at North of Atbara city, River Nile State, Sudan, with an altitude of (336-358 meters) above sea level. The study area covered about 8.0 $km^2$and it is located within coordinates of17.82289 to 17.82389 N and 33.99974 to 34.02127 E. The study area falls within the arid climatic zone (Van der Kevie, 1973). The average annual rainfall varies from 0 to 100 mm. Mean maximum temperature of the hottest months (May and June) is 43˚C. Mean minimum temperature of the coldest month (January) is less than 13˚C. The mean annual relative humidity ranges between 15 to 21% (January to February), and less than 15% (March to June). The predominant natural vegetation consists of the following species;Tundub (*Capparis decidua*), Seyal (*Acacia tortilis*), Usher, Musket (*Prosopischilensis*), Heglig (*Balanitesaegypiaca*) and Seder (*Zizyphusspina-christi*). The calculated soil temperature regime is hyperthermic and soil moisture regime is aridic. The soils of the study area belong within Entisols and Aridisols orders (Soil Survey Staff, 2014a).

Twenty soil samples were collected from three different Nile river terraces (Table 1). At each site, approximately 5kg of soil sample was collected from the depth of 0-30cm using an auger and kept in a plastic bag. The study area completely descends towards the river Nile. Highest elevation was recorded at the instructional farm for Agricultural College (358 masl) and lowest elevation recorded at recent Nile River terrace (349 m asl), which may increase the possibility of pollutants transition from mining area towards the river Nile (especially at raining season) or via wind through transition and sedimentation processes. The descriptive and geographical locations with the textural classes of samples sitesare presented in (Table 1). The soil texture ranged from sandy loam at the first terrace, silt loam at the second Instructional (Nile Valley University). By contrasting to that, the soil texture for samples at the Agricultural College farm was sand. This could be due to the fact that these soils fall in the mining area are truncated soils.

Determination of soil properties

In the laboratory, soil samples were air-dried (25± 2°C) and passed through 2 mm mesh sieve to obtain the fine earth fraction. The particles-size distribution of the soil samples was determined using particle size analyzer model (Mastersizer 2000, Malvern) and the textural class was obtained by using the USDA textural triangle according to (Soil Survey Staff, 2014b). Soil chemical properties were measured according to standard methods (Sparks et al., 1996). Soil pH was measured in 1:5 soil suspensions using a digital pH meter Jenway Model 3510 (U.S. Salinity Lab. Staff, 1954), and the results were compared according to the classification of Horneck et al. (2011). The electrical conductivity (EC dS/m at 25˚C) was determined in 1:5 soil extract using a conductivity meter Jenway (Model 4510), and the results were compared according to the classification of Rhoades (1996). Calcium carbonate percent was estimated by calcimeter. The samples were treated with 0.1N HCl; the volume of CO_2 from pure calcium carbonate and samples were recorded. The percent of calcium carbonate was then calculated according to (Horváth et al., 2005). Ion Chromatography Model (Dionex 5000) was used to determine the soluble cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) and anions (F^-, Cl^-, SO_4^{2-} and PO_4^{3-}) in the extracted solutions.

Table 1. Description of the studied samplesand sites within the study area

Sample Site No.	Descriptive Locations	Geographical coordinates		Elevation (m asl)
		N	E	
1	Instructional farm (Nile Valley University)	17.82289	34.02127	356
2	Instructional farm, Nile Valley University	17.82283	34.02044	354
3	Instructional farm, Nile Valley University	17.82062	34.0203	351
4	Instructional farm, Nile Valley University	17.82044	34.02142	353
5	near wells of the instructional farm	17.82214	34.02237	358
6	Farm near mining mills	17.82503	34.01473	354
7	Outside the farm in the mining zone	17.82503	34.01473	354
8	Outside the mills in mining zone	17.82578	34.01468	356
9	Outside washing basin and the gold extraction	17.82288	34.01498	352
10	Outside washing basin and the gold extraction	17.82288	34.01498	352
11	Outside washing basin (red color)	17.82145	34.01407	351
12	Inside washing basin (red color)	17.82145	34.01407	351
13	middle of mining zone	17.82167	34.01612	357
14	Farm near mining zone	17.82483	34.00957	351
15	recent Nile River terrace	17.81779	33.99229	349
16	recent Nile River terrace	17.81779	33.99229	349
17	Inside Residential zone	17.81763	33.99478	351
18	Inside Residential zone	17.82344	33.99523	352
19	Inside Agric. College (Nile Valley Uni.)	17.82389	33.99974	356
20	Inside Agric. College (Nile Valley Uni.)	17.82389	33.99974	356

Determination of heavy metals in the soil samples

Microwave digestion oven model (CEM Mars 5) was used to digest soil samples to estimate the heavy metals, 0.5 gram of air-dried soil was used after a well-milled, and then placed in a microwave oven pipes. 10 ml of nitric acid was added to each pipe containing soil sample and well closed, then introduced into the microwave oven, and digested using (EPA-3051A) method described by (Link et al., 1998). After samples digestion, extracted samples were transferred quantitatively into 50 ml volumetric flask and the volume was completed by deionized water to the mark. All digested samples filtered using filter paper (Whatman No. 42) and then transferred to (ICP-Optima 4300 DV) in order to estimate the heavy metals (Mn, Cu, Pb, Cd, Zn, Fe, Ni, Hg).

Assessment of heavy metal pollution levels in the soil samples

In order to verify the quantity of heavy metal pollution levels in the soil samples; the enrichment factor (EF) has been applied. The EF was calculated by using the equation described by Sutherland (2000), as follows:

$$\mathrm{EF}m = \frac{\mathrm{Cm(sediment)/CFe\ (sediment)}}{\mathrm{Cm\ (earth\ crust)/CFe(earth\ crust)}}$$

Where: C_m (sediment) is the metal concentration in the sediment sample; C_{Fe} (sediment) is the concentration of the reference metal (Fe) in the sediment sample; C_m (earth crust) is the metal concentration in the earth crust; and C_{Fe} (earth crust) is the concentration of the referenced metal (Fe) in the earth crust. The EF values are classified into five categories: deficiency to minimal (EF<2), moderate (2<EF<5), significant (5<EF<20), very high (20<EF<40), and extremely high enrichment (EF>40).

Statistical analysis

The values of maximum, minimum, and means were calculated, and Tukey significant difference was tested for means separation (*P*< 0.05). All statistical analyses were performed by using statistical package for social science software SPSS Statistics version 16.0 (IBM Corp., 2012).

Results and Discussion

Physico-chemical properties of soil samples

Data in Table 2 presents maximum, minimum, and average of some physico-chemical properties of the studied soil samples.The soil reaction varied from alkaline to strongly alkaline (Horneck et al., 2011), with a pH values ranged from 7.46 to 8.8. The composite sample (Figure 1) taken from outside washing basin showed least value of soil reaction (pH 7.46). This could be due to the washing of soil bases through mining process and their later removal during gold extraction. The EC values ranged from 0.13 to 20.9 dS m^{-1}, suggesting non-saline to extremely saline conditions at the different sites (Rhoades, 1996). The content of the calcium carbonate ($CaCO_3$) varied in the soil samples from non calcareous to moderately calcareous (FAO, 2006) at different sites and the $CaCO_3$ranged from 2.58 to 10.32%. By contrast, the $CaCO_3$ was disappeared in the samples taken from inside washing basin. This could be due to possibility of $CaCO_3$ dissolution and transported inside soil depths via washing water. The texture of the studied samples at different sites is dominantly by sand fraction and ranged from 5.61 to 87.99 %.

Table 2. Some physico-chemical soil properties

Sampling sites		Characteristics						
		pH	EC (dSm^{-1})	$CaCO_3$ %	Sand %	Silt %	Clay %	Textural Class
Instructional farm (Nile Valley University)	Max	8.73	4.57	7.4	52.57	61.14	6.66	SL
	Min	7.86	0.15	2.75	32.61	41.57	5.49	SL
	Average	8.26	1.06	4.78	39.44	54.61	5.95	SL
Agricultural College (Nile Valley University)	Max	8.8	0.57	3.44	87.99	12.13	1.75	S
	Min	8.35	0.46	2.58	86.12	11.78	0.23	S
	Average	8.58	0.51	3.01	87.06	11.96	0.99	S
Inside Residential zone	Max	8.8	4.64	4.64	58.07	37.78	12.0	SL
	Min	8.15	2.58	2.58	56.0	32.0	4.16	SL
	Average	8.48	3.61	3.61	57.04	34.89	8.08	SL
Mining zone	Max	8.68	0.19	10.32	86.79	49.96	64.33	S
	Min	8.19	0.09	3.44	7.32	13.24	5.74	S
	Average	8.48	0.13	5.59	52.38	30.87	20.95	S
Recent Nile River terrace	Max	8.42	0.25	5.5	48.38	62.98	31.41	SCL
	Min	8.01	0.23	4.47	5.61	47.77	3.85	SCL
	Average	8.22	0.24	4.98	26.99	55.38	17.63	SCL
Outside washing basin	Max	8.76	20.9	6.02	77.8	37.21	9.85	SL
	Min	7.46	0.14	2.58	57.21	20.53	1.66	SL
	Average	8.15	7.43	4.3	62.65	31.55	5.8	SL
Inside washing basin	Max	8.11	0.41	ND	81.48	18.28	0.24	S
	Min	-	-	ND	ND	ND	ND	ND
	Average	-	-	ND	ND	ND	ND	ND

ND not detectable

Soil heavy metals concentrations of the study area

Data in Table 3 present the maximum, minimum, and mean of heavy metals (Cu, Fe, Mn, Zn, Co, Ni, and Pb) concentrations (mg kg^{-1} soil) in the soils of the study area. Among all heavy metals, the concentration of Cd was detected only in one sample at inside washing basin, and Hg was not detected in all studied soil samples. Results revealed that concentrations of heavy metals were varying in the study area, and highest concentrations were obtained in the mining area particularly inside washing basin and gold extraction. The concentrations of Cu, Fe, Mn, Zn, Co, Ni, and Pb were ranged from (3.65 to 33.55 mg kg^{-1} soil), (6,355 to 14,635 mg kg^{-1} soil), (42 to 655 mg kg^{-1} soil), (11.85 to 40.85 mg kg^{-1} soil), (2.8 to 16.15 mg kg^{-1} soil), (2.5 to 44.95 mg kg^{-1} soil) and (2.65 to 823.5 mg kg^{-1} soil) respectively. Overall, the heavy metals in the study area were rated as to following sequences: Fe>Mn>Zn>Ni>Cu>Co>Pb>Cd>Hg.

Figure 1. Composite sample represents contaminated soil after extraction of gold.

Table 3. Maximum, minimum and mean concentrations of heavy metals in the soil samples of the study area

Sampling sites		Heavy metals concentrations (mg kg^{-1}soil)								
		Cu	Fe	Mn	Zn	Co	Ni	Pb	Cd	Hg
Instructional farm (Nile Valley University)	Max	18.100	10995	345.50	40.15	8.500	23.35	4.200	ND	ND
	Min	14.350	9485.0	302.25	17.10	6.300	18.15	2.650	ND	ND
	Mean	16.390	9820.0	319.35	23.95	7.350	20.63	3.360	ND	ND
Agricultural College (Nile Valley University)	Max	22.050	11885	396.10	28.65	9.100	25.00	7.050	ND	ND
	Min	11.800	8335.0	242.20	18.50	5.700	15.90	4.550	ND	ND
	Mean	16.925	10110	319.15	23.575	7.400	20.45	5.800	ND	ND
Inside Residential zone	Max	15.850	9755.0	345.10	29.15	7.100	20.65	8.250	ND	ND
	Min	15.400	8930.0	330.35	29.05	6.500	20.15	4.050	ND	ND
	Mean	15.625	9342.5	337.73	29.10	6.800	20.40	6.150	ND	ND
Mining zone	Max	31.750	9985.0	350.10	28.75	8.600	22.95	39.65	ND	ND
	Min	4.8500	6355.0	42.000	ND	ND	2.150	ND	ND	ND
	Mean	19.000	8473.0	238.11	20.85	5.200	15.33	12.46	ND	ND
Recent Nile River terrace	Max	3.6500	14635	655.00	42.70	16.50	47.30	6.150	ND	ND
	Min	32.500	14390	454.50	39.00	15.80	44.60	5.000	ND	ND
	Mean	33.550	14513	554.75	40.85	16.15	45.95	5.575	ND	ND
Outside washing basin	Max	21.650	9485.0	221.35	77.70	6.250	18.10	823.5	ND	ND
	Min	17.95	3566	37.35	18.45	-	2.5	14.4	ND	ND
	Mean	20.23	7262.00	149.37	39.07	3.88	11.78	285.00	ND	ND
Inside washing basin	Max	21.15	8135	203.65	11.85	2.8	8.45	3.55	0.521	ND
	Min	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Mean	ND	ND	ND	ND	ND	ND	ND	ND	ND

[ND] not detectable

Comparison of soil heavy metals concentrations with common concentrations in most world soils

Comparing the heavy metals concentrations with most world soils concentrations (Table 4), we obtained that the Cd concentration inside washing basin (0.521 mg kg^{-1} soil) as shown in Table 3 was nearly to its maximum concentration in most world's soil (0.7 mg kg^{-1} soil), and this may increase the possibility to exceeds its maximum when using same washing basin more times. Pb concentration at outside washing basin (823.5 mg kg^{-1} soil) exceed 4 times the concentration in most world's soils, and Zn atsamesite (77mg kg^{-1} soil) exceed one half times the concentration in most world's soils. Likewise, Pb concentrations in all sites were in their concentrations limits in soil except outside washing basin (Riley et al., 1992). Similarly, the same sitealso exceeded the regulatory limits (NIDEP, 2012) and intervention value (DPR-EGASPIN, 2002) which means, Pb seriously contaminates this site (Outside washing basin of gold extraction). Furthermore, according to Dutch standard same sample exceeded the target and intervention values.Cu concentration exceeds the average concentration in all studied sites. According to DPR-EGASPIN (2002) Cu concentrations exceeded the intervention value in all studied sites, except for recent Nile River terrace (Table 3) which means these soils are seriously contaminated so theyneed to be remediated in order to be suitable for sustainability for human, animals and plants life. On the other hand, Ni, Co and Mn concentrations were obtained at their average concentrations in most tested sites, except for Ni concentration in recent Nile Riverterrace site (mean of 45.95 mg kg^{-1} soil) which was exceeded the target value according to Dutch standard. Mn concentrations in recent Nile River terracesite (mean of 554.75 mg kg^{-1} soil) exceeded the average limits of worldwide. This could be due to intensive utilization of mineral fertilizers enriched in these heavy metals as impurities. Contrasting, Hg was disappeared in all samples detected by ICP despite for its intensive utilization in gold extraction (Figure 2). This could be due to its evaporation during exposed to the ICP plasma heat when its estimation. This finding in agreement with Almasoud et al. (2015).

Table 4. Heavy metals concentrations in most world soils (Lindsay, 1979).

Element	Common rang in soils (mg kg^{-1} soil)		
	Max	Min	Average
Cd	0.7	0.01	0.06
Co	40	1	8
Cu	100	2	30
Fe	55000	7000	38000
Mn	3000	20	600
Ni	500	5	40
Pb	200	2	10
Zn	300	10	50

Figure 2. Utilization of Hg in gold extraction processes in the mining area.

Use of Enrichment factor (EF) to assess the soil contamination in the study area

The EF is appropriate measure of geochemical trends and is applied for contemplating on lithogenic or anthropogenic origin of heavy metals (Sutherland, 2000; Ye et al., 2011). The results of EF values for different heavy metals in the study area are presented in Table 5. Results revealed that EF for cobalt (Co) according to (Sutherland, 2000) was in its minimum limit for all sites; except recent Nile terrace site was in medium concentrations with EF of 2.35 and 2.21 respectively. EF for Cu showed medium concentrations in mining zone sites, outside and inside washing basin (3.3, 4.98 and 2.13, respectively). In contrast, EF for Mn and Ni were obtained at the minimum limits. In addition, EF for Pb showed that Agricultural College, Residential zone, mining zone and out washing basin sites were polluted. Nevertheless, EF value was least in sites 17 and 19. This could be due to transition of pollutants via wind (northeast) from mining area to nearest areas especially southwest areas at same wind direction (Figure 3). Contrary to all studied sites, site No.10 (from inside washing basin and gold extraction) showed highest EF (676.3). Reason for this may due to combustion of the fuel used in gold extraction mills in the study area. This infrared confirmed that washing basins and gold extractions were severe polluted in Pb, which may increase dramatically with frequent use. Based on our results all tested sites were polluted with Zn except for site No. 8. However, samples No. 7 (mining zone) and 11 (outside washing basin) showed highest EF values (137.36 and 6312.11 respectively), which means these sites could be described as highly concentrated with contaminated element (Zn), and this confirmed that the washing basins were severe dangerous.

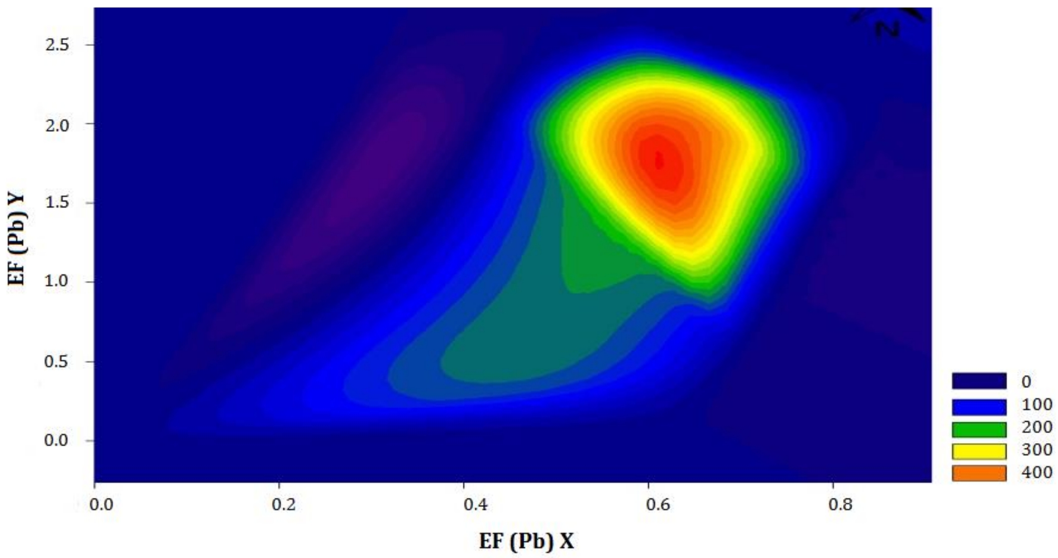

Figure 3. Distribution of Pb pollution in the study area based on EF values (red color is the center of mining area)

In order to facilitate comparison between enrichment values for various zones in our study, we selected the recent Nile River terrace site as control site due to the fact that it's receives seasonally deposits from Ethiopian Plateau and for its distance from the mining area. EF values for heavy metals more than 2 considered as major concern contaminant as suggested by some researchers (e.g. Yongming et al., 2006; Ye et al., 2011). In this context as shown in Table 5, the EF values for Co and Cu (in 90% of sites), Mn and Ni (in all sites) and Pb (in 65% of sites) were less than two, suggesting that their contaminations may be not a major concern. By contrast, the EF values for Zn (in 65% of sites) ranged from 5-20. In contrast, around 15% of sitesreached very high enrichment (20<EF<40) and 20% of sites had EF values >40 for Zn, which indicate a severe degree of Zn contamination may possible in the study area.

Table 5. Enrichment values for heavy metals in the study area

Sites	Co	Cu	Mn	Ni	Pb	Zn
1	1.70	1.45	0.13	1.17	0.94	8.81
2	1.47	1.34	0.15	1.06	0.88	8.25
3	1.51	1.30	0.13	1.03	0.95	8.83
4	1.51	1.40	0.14	1.07	1.28	11.95
5	1.46	1.36	0.16	1.05	0.96	8.93
6	1.77	1.70	0.15	1.18	2.04	19.03
7	1.14	3.30	0.14	0.90	14.72	137.36
8	0.00	0.63	0.03	0.17	ND	ND
9	1.27	1.98	0.11	0.87	5.73	53.51
10	0.00	4.98	0.05	0.36	676.30	6312.11
11	1.35	1.55	0.09	0.98	4.45	41.50
12	0.71	2.13	0.11	0.53	1.28	11.93
13	1.51	1.84	0.14	1.10	4.21	39.25
14	1.43	1.59	0.12	1.03	0.97	9.05
15	2.35	1.85	0.14	1.68	1.02	9.50
16	2.21	1.94	0.19	1.56	1.23	11.49
17	1.49	1.46	0.16	1.16	2.71	25.25
18	1.49	1.29	0.15	1.08	1.22	11.35
19	1.40	1.16	0.13	0.98	2.48	23.12
20	1.57	1.52	0.14	1.08	1.12	10.46

According to (Hernandez et al., 2003), EF≤2 indicates that the heavy metals may be as resulting from crustal materials or as product of natural weathering processes. However, EF ≥2 indicate that a major proportion of the heavy metals are mainly due to anthropogenic inputs. Therefore, the heavy metals of Co, Cu, Mn, and Ni in most sites having EF values less than 2, suggesting that these heavy metals may be as a result of crustal materials or natural weathering processes. While, the heavy metals of Pb (in 40% of sites) and Zn (in all investigated soil samples) having EF higher than 2, indicating that these heavy metals may be enriched as a result of anthropogenic inputs (especially mining activities). Overall, it was observed that the mean EF values of Co and Ni in the soil samples atthe inside washing basin and the mining zones were lower when compared tothe recent Nile River terrace (Figure 4). This may be due to the fact that the soils at recent Nile River terrace are used for agricultural purposes which mean these heavy metals were added during fertilization with trace elements as impurities. In addition, the mean EF of Zn at mining site were lower compared to the recent Nile River terrace (control zone). The same previous justificationmay occur. By contrast, the EF of Cu, Mn and Pb in all sites were higherthan those at the recent Nile River terrace (Figure 4). This suggests that the sites located far away from the Nile River and near the activities of mining may have probability to enrich soil with some heavy metals (Almasoud et al., 2015).

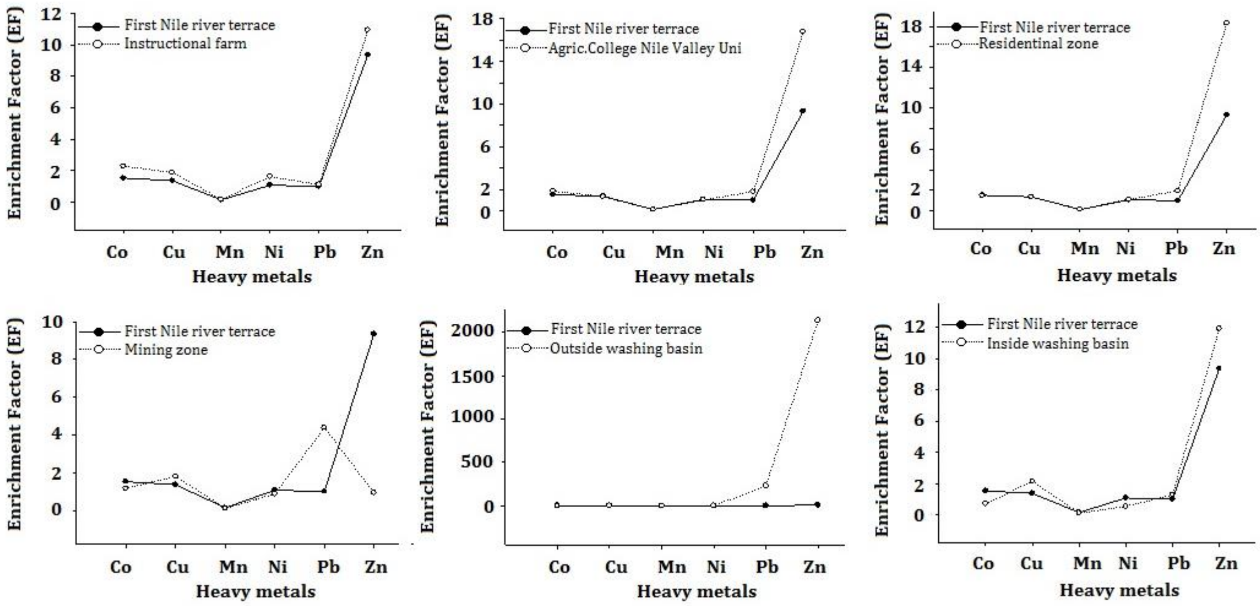

Figure 4. Enrichment values for heavy metals at different studied sites.

Conclusion

After studied the influence of artisanal gold mining on heavy metals concentration at Dar-Mali locality, we concluded that the heavy metals concentration in study area were obtained according to the following sequence; Fe>Mn>Zn>Ni>Cu>Co>Pb>Cd. In addition to that, mining zone was clearly affected by high concentration of heavy metals, particularly Pb inside mining basins; indicate that the latter was more prevalent in study area with wind direction. Applying of EF indicated that, cobalt (Co) was in its minimum limit in most studied sites; Cu showed medium concentrations in mining zone sites, outside and inside washing basin, Mn and Ni were obtained at the minimum limits, and Pb showed that Agric. College, Residential zone, mining zone, and out washing basin sites were polluted.

Acknowledgements

The authors are greatly indebted to dean of Agriculture College and general manager of Educational Farm - Nile Valley University, and Special thanks to the head of soil sciences department, King Saud University, Riyadh, Saudi Arabia, for availing their laboratories facilities and for their technical advice.

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