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An investigation of mercury distribution in the soils around gold mining area at Dar-Mali locality, river Nile State, Sudan

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Abstract

An artisanal gold mining region located in North of Atbara (Dar-Mali locality), River Nile State, Sudan (17.82289 to 17.82389N and 33.99974 to 34.02127E) has been studied with the aim to evaluate the soil contamination with mercury (Hg) using two parameters; (i) Comparison of the Hg concentration with the mean concentrations in world soils, (ii) Enrichment Factor (EF). The results revealed that, the concentrations of the Hg are varying in the studied area and the highest concentrations were obtained inside the mining basins used for gold extraction (2.62 mg kg^{-1} soil) it is around 29 times more than mean Hg concentration in world soils, while the lower concentrations are found at recent Nile River terrace (0.10 mg kg^{-1} soil). The results also indicated that the soil samples collected from inside mining basins had a highest E.F value (352.84) that means, this site must be closed and remediation process should be started immediately. While the E.F value of recent Nile River terrace site was 8.74, means, all studied sites have significant contamination with Hg. The mobility of Hg may have influenced by northeast wind, or water runoff from mining zone to nearest areas at same wind direction or water flow direction.

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

Introduction

Soil is not only a medium for plants growth or waste disposal but also a transmitter of many pollutants to surface water, ground water, atmosphere and food. Soil pollution may threaten human health not only through its effect on hygiene quality of food and drinking water, but also through its effect on air quality (Wong, 1996).

Informal gold mining constitutes an important source of income for many people in Africa, Southeast Asia and China. this growing industry employs more than 10 million people around the world, and there is a generalized environmental menace to human health because most of the gold is extracted by Hg amalgamation, leading to Hg contamination of the ecosystems by releasing more than 650.000 tons of Hg annually (Olivero and Solano, 1998; Guedron et al., 2009).

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

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Mercury (Hg) is consider an important pollutant due to its global distribution, bioaccumulation and toxicity (Yin et al., 2014), soils can accumulate up to 75% of the Hg present in the biosphere (Mason and Sheu, 2002), mostly as a result of the affinity of Hg for soil organic matter and Al and Fe (Schuster, 1991; Skyllberg et al., 2006). Hg is a very toxic and insignificant element of life. Nevertheless, elemental Hg and its compounds are highly volatile and can easily migrate to environments that enter the food chain, which can cause irreversible damage to people and animal life, the risk for mercury exposure is significant, elemental mercury exposure can be toxic to multiple organ systems, including the nervous and dermatologic systems (Fernandes et al., 2012).

The Hg is widely used for the gold extraction in our study area, so, a high concentration of it are expected will be found in the mining zone and other adjacent areas at same wind direction or water flow direction in the study area. The main objectives of this study were to assessing the distribution of Hg in soils around gold mining area with the hypothesis that it could be leaching from tailings and deposition at mining area to nearest locations at Dar-Mali locality, River Nile State, Sudan, this study also aim to investigate the effect of vicinity and distance from mining zone on concentration of Hg in the study area.

Material and Methods

The investigated area is located at North of Atbara city, River Nile State, Sudan, with an altitude of (336-358 meters) above sea level. The studied area covered around 10.0 km^2 and it is located within coordinates of 17.82289 to 17.82389N and 33.99974 to 34.02127E Fig1 The study area falls within the arid climatic zone. The average annual rainfall varies from 0 to 100 mm. the mean maximum temperature of the hottest months (May and June) is 43˚C. The mean minimum temperature of the coldest month (January) was 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 (Elfaki et al., 2015). The soils of the study area belong within Entisols and Aridisols orders (USDA, 2014a).

Twenty soil samples were collected from different sites around gold mining area at Dar-Mali locality, (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 cloth bag. Each sample was labeled with; collected data, site coordinates, sample number, then, subjected to physical and chemical analyses at the soil laboratories.

Table 1. Geographical coordinates, elevation, and texture class of the study sites

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

In order to calculate to the distances between mining zone and other studied areas which may affected by Hg pollution which used in mining zone for extraction of gold, Sinnott, (1984) equation Eq. (1) was used to

convert the longitudes and latitudes coordination to distances. Then, the Sigma plot v12 software was used to draw the distribution of Hg concentration to all studied areas.

$$\Delta\tilde{\sigma} = 2\arcsin\left(\sqrt{\sin^2\left(\frac{\Delta\phi}{2}\right) + \cos\phi_s \cos\phi_f \sin^2\left(\frac{\Delta\lambda}{2}\right)}\right)$$

Where	$\Delta\sigma$	Interior Spherical Angle
	$\Delta\phi$	Latitude1 - Latitude2
	ϕ_s	Latitude1
	ϕ_f	Latitude2
	$\Delta\lambda$	Longitude1 - Longitude2

Eq. (1) Sinnott, (1984) equation used to calculate the distance between two points.

Enrichment factor (EF)

The enrichment factor (EF) was calculated using Dragovic et al. (2008) formula

$$EF = (\left(\frac{C_x}{C_{Fe}}\right) sediment)/(\left(\frac{C_x}{C_{Fe}}\right) Earth'scrust)$$

Eq. (2) Dragovic et al. (2008) Enrichment factor formula

Where;

(C_x/C_{Fe}) sediment = the concentration of an element / the concentration of Fe in the sample (C_x/C_{Fe}) earth's crust = concentration of a metal in the earth crust /the concentration of Fe in the earth crust.

Dragovic et al. (2008) classified the EF in to classes as the following scale; EF (2-5) is moderate contamination, EF (5-20) means significant contamination, EF (20-40) high contamination and EF (>40) classified as very high contamination.

Figure 1. Google map image of study area

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 pipette method which was recommended by Elfaki et al. (2016b), and the textural class was obtained by using the USDA textural triangle according to (USDA, 2014b). Soil pH was measured in 1:5 soil suspensions using a digital pH meter Jenway Model 3510, The electrical conductivity (EC dS/m at 25°C) was determined in 1:5 soil extract using a conductivity meter Jenway (Model 4510), Calcium carbonate percent was estimated by Calcimeter which recommend by Elfaki et al. (2016a).

Determination of Hg in the soil samples

Microwave digestion oven model (CEM Mars 5) was used to digest soil samples, 1gram of air-dried soil was used after a well-milling, and then placed in a microwave oven pipes. A 10ml aliquot of nitric acid was added to each pipe containing soil sample and well closed, then placed into the microwave oven, and digested using (EPA-3051A) method described by (Link et al., 1997). After samples digestion, extracted samples were transferred quantitatively into 100 ml volumetric flask and the volume was completed by deionized water to the mark. All digested samples were filtered using filter paper (Whatman No. 42) and then transferred to

(Perkin Elmer 350D ICP mass spectrometer) after standard curve was prepared from different concentrations (1 ppb, 5 ppb, 10 ppb, 25 ppb, 50 ppb, 100 ppb) of Hg in order to achieve accurate results of Hg concentration at ppb levels.

Results and Discussion

General characteristics and topography of the study area

Highest elevation in the study area was recorded at the instructional farm for Agricultural College (358m ASL) and lowest elevation recorded at recent Nile River terrace (349m ASL), which means the study area was completely slopes towards the River Nile. That may increase the risk of pollutants to transfer from mining zone towards the River Nile (especially at raining season) or via wind through transition and sedimentation processes. The descriptive and geographical locations, textural classes, calcium carbonate percentage of all sites were presented in (Table 2). The soil texture ranged from sandy loam at the recent terrace, silt loam at the second instructional farm - Nile Valley University (NVU).

Table 2. Some soil physico-chemical properties of the study area

Site	Rate	pH	EC, dS m^{-1}	$CaCO_3$, %	Sand, %	Silt, %	Clay, %	Dominant Textural Class
Instructional farm (NVU)	Max	8.73	4.57	7.4	52.57	61.14	6.66	
	Min	7.86	0.15	2.75	32.61	41.57	5.49	Silt loam
	Average	8.26	1.06	4.78	39.44	54.61	5.95	
Faculty of Agriculture (NVU)	Max	8.80	0.57	3.44	87.99	12.13	1.75	
	Min	8.35	0.46	2.58	86.12	11.78	0.23	Sand
	Average	8.58	0.51	3.01	87.06	11.96	0.99	
Inside Residential area	Max	8.80	4.64	4.64	58.07	37.78	12.00	
	Min	8.15	2.58	2.58	56.00	32.0	4.16	Sandy loam
	Average	8.48	3.61	3.61	57.04	34.89	8.08	
Mining area	Max	8.68	0.19	10.32	86.79	49.96	64.33	
	Min	8.19	0.09	3.44	7.32	13.24	5.74	Sandy loam
	Average	8.48	0.13	5.59	52.38	30.87	20.95	
Recent Nile River terrace	Max	8.42	0.25	5.5	48.38	62.98	31.41	
	Min	8.01	0.23	4.47	5.61	47.77	3.85	Silt loam
	Average	8.22	0.24	4.98	26.99	55.38	17.63	
Outside gold extraction basins	Max	8.76	20.9	6.02	77.8	37.21	9.85	
	Min	7.46	0.14	2.58	57.21	20.53	1.66	Sandy loam
	Average	8.15	7.43	4.3	62.65	31.55	5.80	
Inside gold extraction basins	Max	8.11	0.41	ND	81.48	20.53	1.66	
	Min	-	-	ND	77.8	18.28	0.24	Loamy sand
	Average	-	-	ND	79.6	19.41	0.95	

Soil properties of study area

Table 2 shows the soil physio-chemical properties, the soil reaction at the study area was varied from alkaline to strongly alkaline according to Marx and Stevens (1999), with a pH values ranged from 7.46 to 8.8. The composite sample 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 different sites according to Rhoades (1996). The content of the calcium carbonate (%$CaCO_3$) was varied in all sites from non-calcareous to moderately calcareous according to FAO (2006) guidelines, while $CaCO_3$ was disappeared inside gold extraction basin (Figure 2), this could be due to possibility of dissolution and transportation of $CaCO_3$ inside soil depths via washing water. the dominant texture of the studied sites was sand fraction (up to 87.99 %).

Mobility and distribution of Hg in soils of the study area:

According to table3, which present the maximum, minimum, and mean of Hg concentrations (mg kg^{-1} soil) in the soils of the study area. The highest concentrations were obtained at the mining zone particularly inside gold extraction basins (2.62 mg kg^{-1} soil), and the minimum concentrations were found at recent Nile River terrace (0.10 mg kg^{-1} soil). Generally, the Hg concentration in the study area were rated as to following sequences; Inside gold extraction basin s> Outside gold extraction basins > around gold mining zone > Instructional farm (Nile Valley University) > Inside residential zone> Agricultural college (Nile Valley University) > Recent Nile River terrace.

Figure 2. Gold extraction basin

Table 3. Maximum, minimum and mean concentrations of Hg in the study area

Sites		Hg Concentrations (mg kg^{-1} soil)
Instructional farm (Nile Valley University)	Max	0.10
	Min	0.21
	Mean	0.16
Agricultural College (Nile Valley University)	Max	0.31
	Min	0.26
	Mean	0.29
Inside Residential zone	Max	0.65
	Min	0.13
	Mean	0.39
Around gold mining zone	Max	1.32
	Min	0.31
	Mean	0.90
Recent Nile River terrace	Max	0.21
	Min	0.10
	Mean	0.16
Outside gold extraction basins	Max	1.52
	Min	0.65
	Mean	0.97
Inside gold extraction basins	Max	2.62
	Min	1.02
	Mean	1.82

Comparing the mean of Hg concentrations in studied sites with the mean of Hg concentrations in world soils (0.09 mg kg^{-1} soil), all studied sites are above of Hg concentration in the world soils even in recent terrace site (0.16 mg kg^{-1} soil) it is near to couple times more. While comparing between Hg concentrations inside gold extraction basins at mining zone (1.82 mg kg^{-1} soil) with the mean concentrations in world soils, it is more than 20 times more! That means that site must be closed and remediation process should be started immediately. However, the average concentration of total Hg in study area was lower than concentrations found in some gold mines around the world such as Almadén (Spain). Where Hg soil concentrations were

found ranging between 0.13 and 2695 mg kg^{-1} (Molina et al., 2006); Idrija (Slovenia) and in alluvial soils range between 0.595 and 1970 mg kg^{-1} (Gosar and Žibret, 2011) or Wanshan (China) with total Hg contents in soils ranging between 5.1 and 790 mg kg^{-1} (Horvat et al., 2003). This may be attributed due to the fact the gold mining in the study area was started recently before 5 years ago.

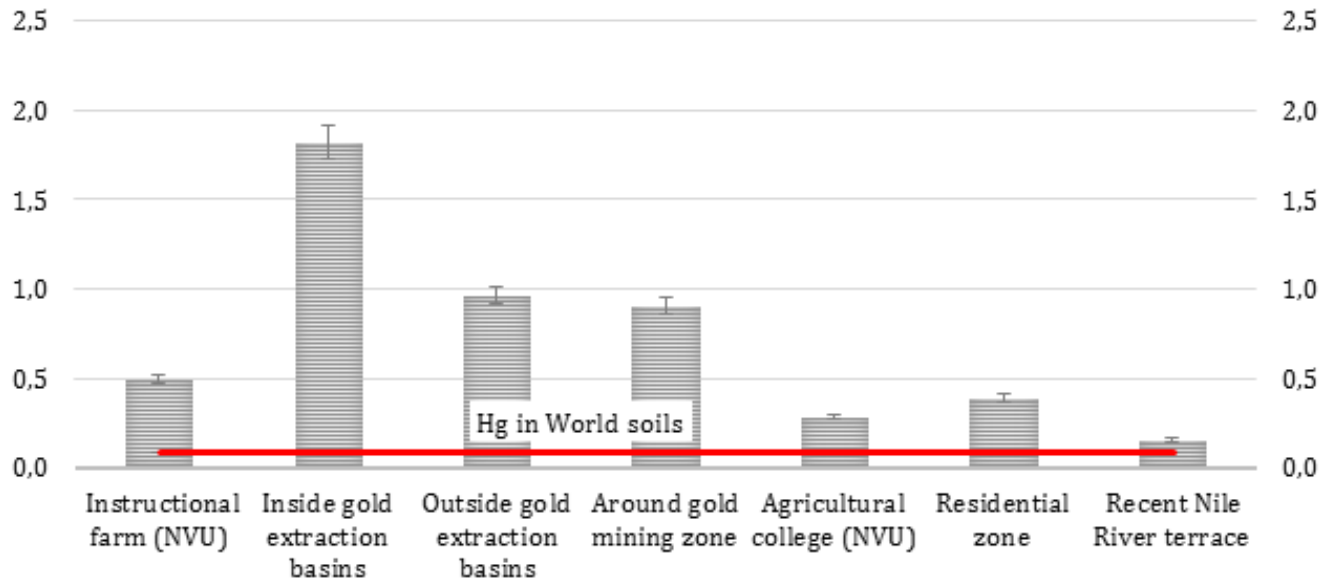

Figure 3. Hg concentrations (mg kg^{-1}) in studied sites comparing with world soils

Use of Enrichment factor (EF) to assess the Hg concentration in the study sites:

According to Dragovic et al. (2008) classification, the EF value at studied sites were ranged from 8.7 – 352.8 (Table 4), that means there is a significant contamination even at the recent Nile River terrace site (E.F 8.74) although, this area are renewed annually by transition and precipitation process from Nile River. The high contamination are classified in %71 of studied sites, whereas the highest EF value are observed inside gold extraction basins (E.F 352.84).

Table 4. EF values in studied sites

Studied sites	EF
Recent Nile River terrace	8.740273
Residential zone	33.22241
Agricultural college (NVU)	23.63295
Around gold mining zone	83.44194
Outside gold extraction basins	107.1644
Inside gold extraction basins	352.8417
Instructional farm (NVU)	41.15672

When distribution of Hg in studied sites was drawn using sigmaplot v12 software (Figure 4). We found that the distribution of Hg ranged from mining zone (highest concentration of Hg) to southwest sites, this agreed by Ali et al. (2017) when studied the distributions of heavy metals in the same area, they interpreted that this was due to transition of pollutants via northeast wind, from mining zone to nearest areas at same wind direction.

On other hand, the distribution of Hg in our study looks like the distribution of the lead (Pb) in Ali et al. (2017) study (Figure 5), where they studied the distribution of some heavy metals in the same area, this may be due to non-purity of Hg which used in gold extraction Figure 6, this hypothesis was supported by the ability of Hg to dissolve other metals like lead. This will be done by rubbing lead filings with Hg in a mortar or by pouring molten lead into Hg; this amalgam has no definite composition. It possesses a brilliant gray color and remains liquid with as much as 33% of lead and 67% Hg although, lead is less dense than Hg (density of Pb is 11.340 kg/m^3 and density of Hg is 13.534 kg/m^3) (Mortazavi and Mortazavi, 2015). Finally, it was noticed that the appearance of Hg which using by miners it is seem mixed by other minerals, the one of it might be Pb.

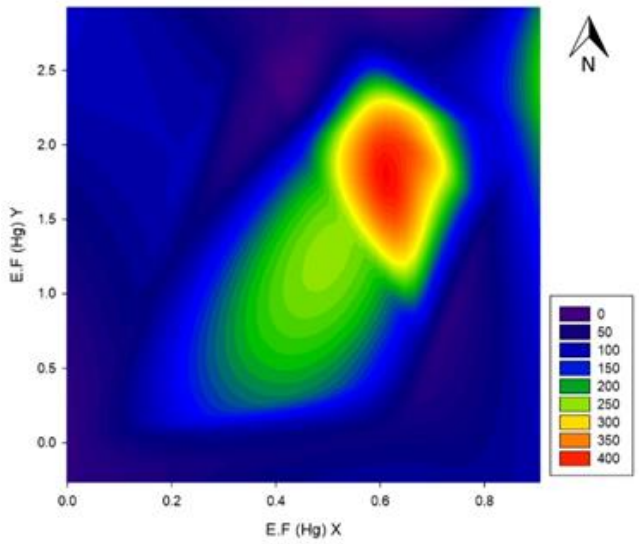

Figure 4. Hg distribution in studied area based on EF values (red color is the center of mining zone).

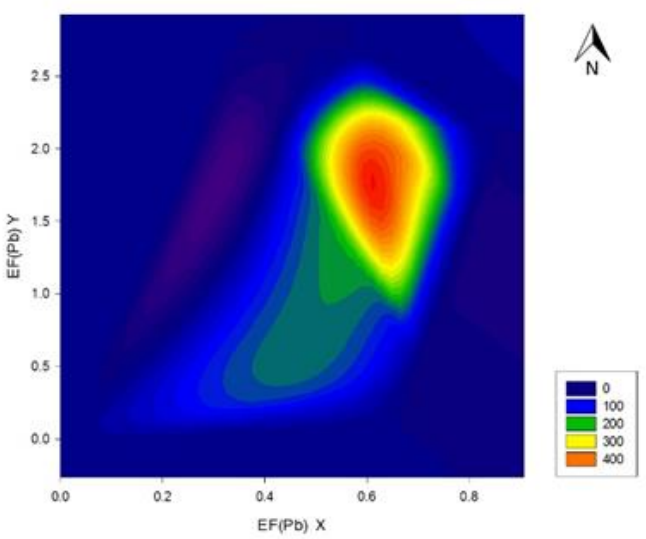

Figure 5. Distribution of Pb pollution in the study area based on EF values (red color is the center of mining area).

Figure 6. Utilization of Hg in gold extraction processes in the mining area.

Conclusion

After studied the mobility and distribution of Hg in soils around gold mining area at Dar-Mali Locality, River Nile State, it can be concluded that the Hg concentration in all sites are above the mean concentration of Hg in world soils. In addition, the distribution of Hg concentrations around the studied sites dispersed via northeast wind, from mining zone to nearest areas at same wind direction. Finally, the Hg concentrations inside gold extraction basins at mining zone (1.82 mg kg^{-1} soil) about 20 times more the mean Hg concentration in world soils! That means this site must be close and remediation possess should be stat immediately.

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