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Full Length Research Paper

Incurred environmental risks and potential contamination sources in an abandoned mine site

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The mineralogical characterization of Fedj Lahdoum mine wastes measured by X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) showed the presence of the following sulfide minerals: galena (PbS), sphalerite (ZnS), pyrite (FeS_2), cerussite ($PbCO_3$) and smithsonite ($ZnCO_3$). The wastes were stored in tailing ponds. The results showed that the concentration of metals from tailings were up to 10 460 mg.kg^{-1} for total Zn, 2 100 mg.kg^{-1} for total Pb and 62.08 mg.kg^{-1} for total Cd. The tailings have presented a fine unconsolidated texture that accelerated the dispersion of the particles rich in heavy metals. Geochemical analysis of soil has revealed high total contents of Pb, Zn and Cd, respectively: 3 646, 3 236 and 17 mg.kg^{-1}. Chemical analysis of cultivated and wild plants species inside the district contain high grades in heavy metals: 708.56 mg Zn. kg^{-1}; 16.24 mg Pb.kg^{-1} (*Thymus vulgaris* (L)); 500.44 mg Zn. kg^{-1}, 12.44 mg Pb. kg^{-1} (*Laurus nobilis* (L)); 128.33 mg Zn. kg^{-1} and 22.53 mg Pb.kg^{-1} (*Ficus* (L)) and 106.73 mgZn.kg^{-1} (pimento). The high levels detected in soil and plants have exceeded the Tunisian and Canadian standards. These results showed that the abandoned site was contaminated by the presence of tailing dumps which were exposed to significant water and/or wind erosion. To solve this problem, we proposed an environmental desulphurization by froth flotation.

Key words: Heavy metals, mine tailings, abandoned mining-district, plant contamination.

INTRODUCTION

The depletion has led to the closure of nearly all the mines in Tunisia, generating large amounts of tailings stored in tailing ponds near mining areas of the pool without supervision and subject to the Mediterranean climatic variations.

As a result, several areas contain large quantities of tailings which are rich in heavy metals such as Pb, Cd, Zn, Sb, As and Hg from the abandoned mine sites (Bhattacharya et al., 2006). These mining sites are areas where high levels of metals pollution can reach 10^2 to 10^4 times the normal content of a soil.

Exposure of tailings to air, oxidation and climatic conditions favored the release of heavy metals (Smuda et al., 2008) which are often a threat to the environment (Chiu et al., 2006; Chakroun et al., 2010; Concas et al., 2006). They have a negative impact on the concepts of sustainable development. In fact, many heavy metals remain in quantities that exceed the environmental standards in mining areas. Zinc in the form of sphalerite and lead as galena, are present in mine tailings owing to their release mesh that has not been reached).

Within the frame of abandoned mine sites remediation, fits this work, which is the environmental characterization

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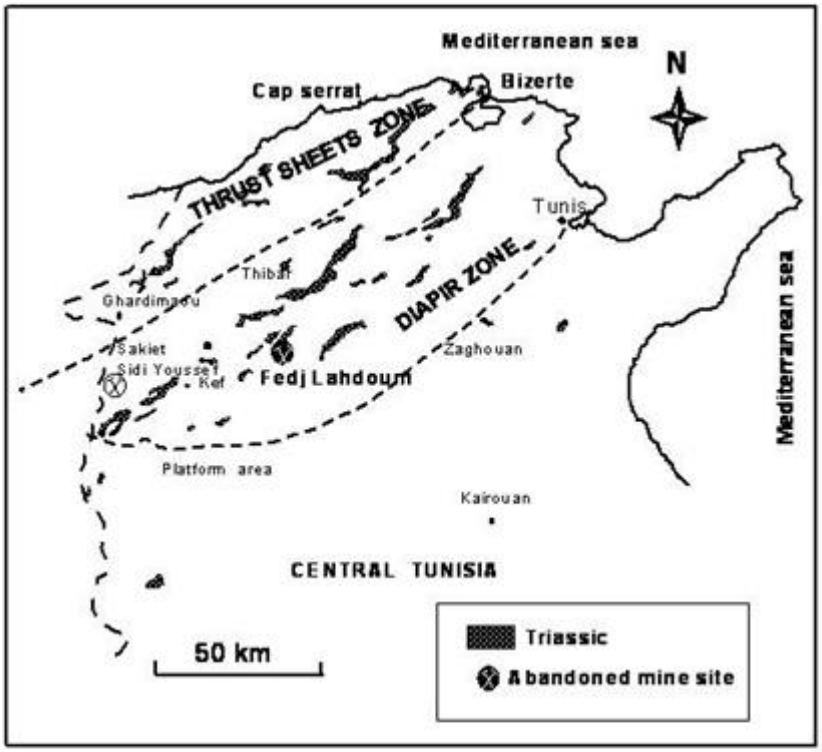

Figure 1. Location of Fedj Lahdoum mine site (Sainfeld, 1952).

of an abandoned mine site and potential sources of contamination and risks for a further purpose which will be the environmental desulphurization. Different techniques are applied to the restoration of sites contaminated by heavy metals such as: phytoremediation: biological method using green plants to remove, or render less toxic environmental contaminants (phytoextraction, phytostabilisation). Among the physicochemical methods: Confinement *in situ*; leaching with water and pumped on site; excavation and incineration; mineral processing separation by froth flotation: this process is becoming more useful for the management of certain mine tailings. the method consist on separating mineral particles non-selectively and economic by bringing them to the surface despite their high densities, in adhesion of hydrophobic particles to air bubbles blown into the pulp, while the hydrophilic particles remain into the pulp. This treatment process generates two products: a non reactive fraction and a reactive sulfide fraction. Management of this fraction is as a paste backfill or placed under a coverage made from desulfurized thin residue. This technology offers a great potential mineral processing to remove contaminants from mine tailings.

MATERIALS AND METHODS

Study area

The district of Jebel Fedj Lahdoum, a mining area of Pb-Zn has been exploited from 1892 to 2004 and since then it was abandoned. It is located in North West of Tunisia in the diapir zone (Figure 1) between the Medjerda plain and Krib plain one, located 120 km southwest of Tunis. This mineral deposit was one of the main Pb-Zn deposits in northwestern Tunisia (Sainfeld, 1952).

This mine deposit was the subject of several studies, which include those of Laatar (1980), Perthuisot (1981), Abidi and Abdelouahed (1986), Charef et al. (1987), Kassaa (1990), Bouhlel (1993), Vila et al. (2001), Sebei (2007) and Boussen et al. (2010). Fedj Lahdoum mine is located at the heart of a relatively high mountain peak at 954 m at the bottom of a valley drained (9°60'47''E and 36°22'06''N) by Tordfin wadi tributary of El-Mor Arkou wadi which flowed into the Tessa wadi about 11 km west of the deposit (Figure 2). The river system consisted of a large number of small ravines and wadis drained by the El-Mor-Arkou Tordfin wadi (deriving from the Tessa wadi) that passed north of the mining sector. The study area was located in a sub-humid field,

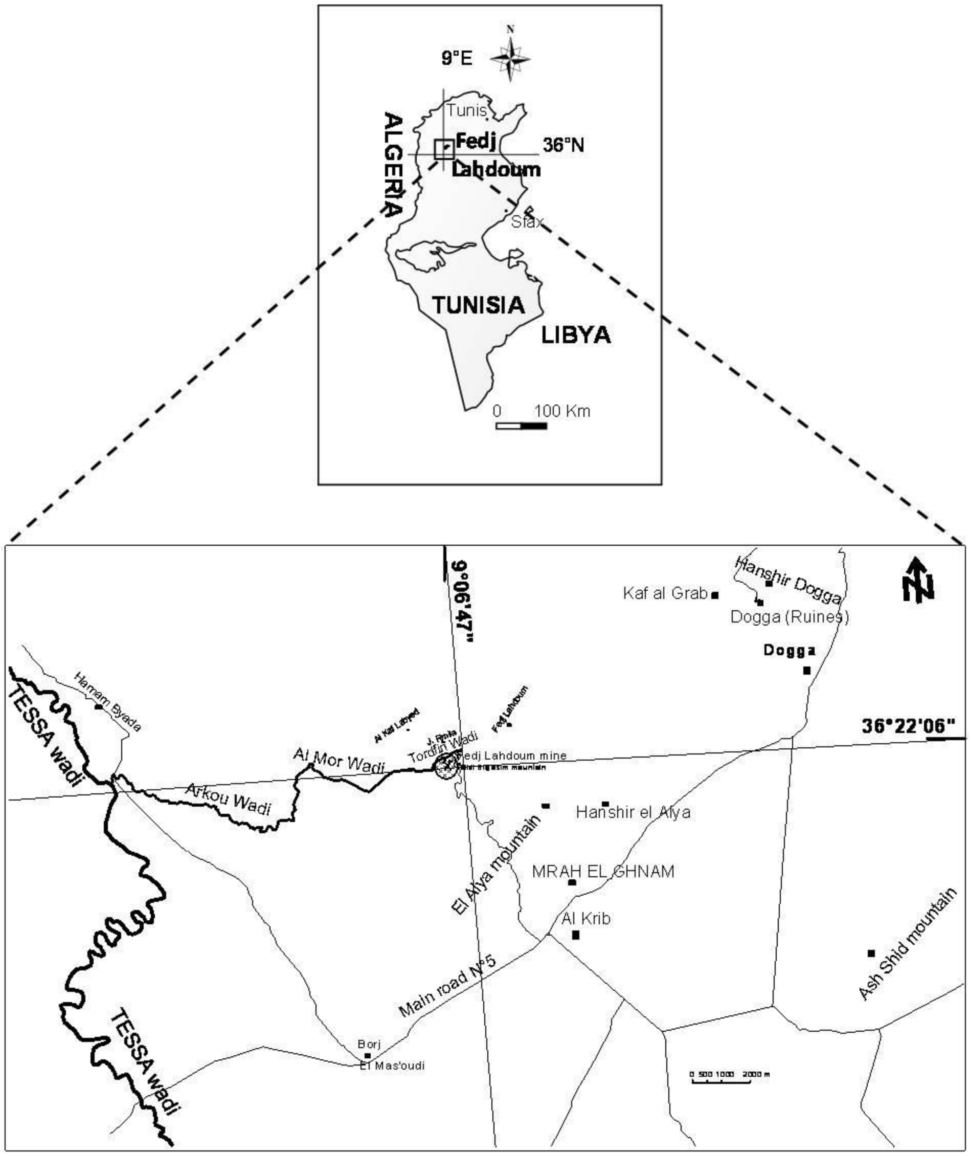

Figure 2. Fedj Lahdoum mining district from Tessa wadi.

characterized by a relatively abundant rainfall, which ranged between 400 and 600 mm/year.

Jebel Fedj Lahdoum is formed by a breach of Triassic dolomite. Its mineralization is of the type: Pb, Zn (Sr, Ba, S), Fe. The soils of Fedj Lahdoum region are characterized by a basic pH in the range of 8.29. They have a dominant clay texture of the order of 68%.

Extraction of metals has led to mining wastes. Discharges of Fedj Lahdoum occupy an area of 10 ha with a volume = 157,270 m^3; 393,175 tons (0.39 Mt). These wastes were deposited around the immediate vicinity of the Fedj Lahdoum site, which is a rural area exclusively. This zone is characterized by extensive agriculture based on a cereal production system associated with breeding (Figures 3 and 4).

Mine wastes sampling and characterization

The sampling is the crucial step in the process of tailings characterization. The purpose is to obtain a range of representative samples in terms of size and mineralogy, which reflect all the physical and chemical characteristics of all the dumps. The sampling method adopted is the release surface sampling on a square mesh screen 100* 100 m with 4 samples taken at 4 points

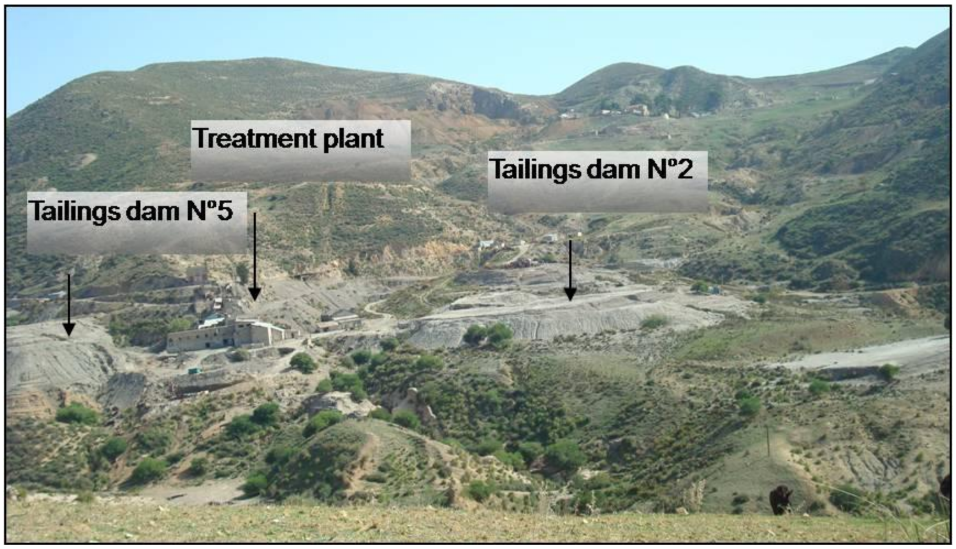

Figure 3. Tailings deposit in an agricultural area.

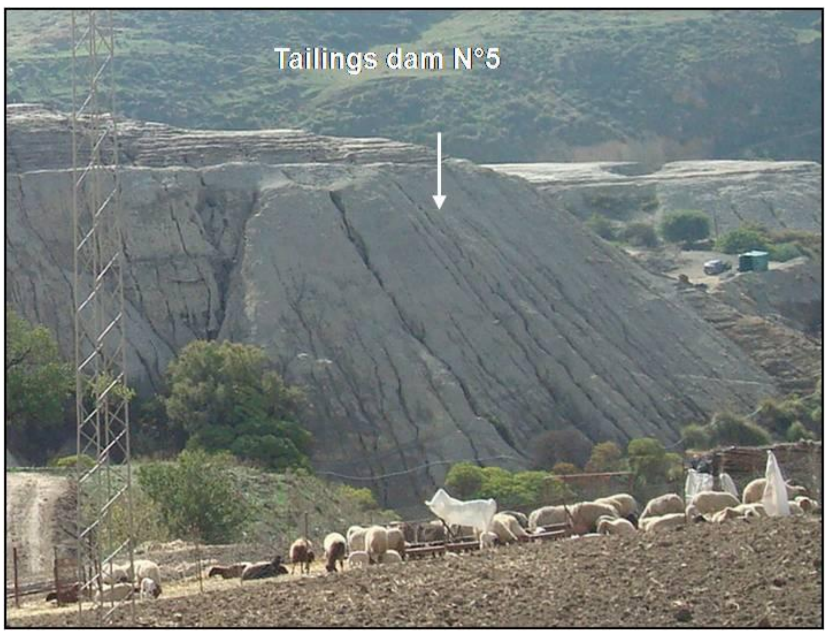

Figure 4. Breeding sheep in the vicinity of Fedj Lahdoum abandoned mine site.

arranged on a circle of 80 m around a central point fixed on the grid, with the directions SW, SE NW, NE according to the diagram (Figure 5). This grid is sufficiently flexible to be adjusted during sampling, tightened or relaxed depending on the constraints encountered in the field. Along the upright, samples were collected from the surface, half-height and base of each stock releases. All the samples were taken from different tailings dumps were mixed and then homogenized, quarted through a riffle sampler (Sample Splitter: splitter falls). All of the samples obtained are similar in content (Figure 6). They were kept in plastic bags until used for two purposes: the mineralogical characterization and treatment process by flotation. The representative sample must have the same grain

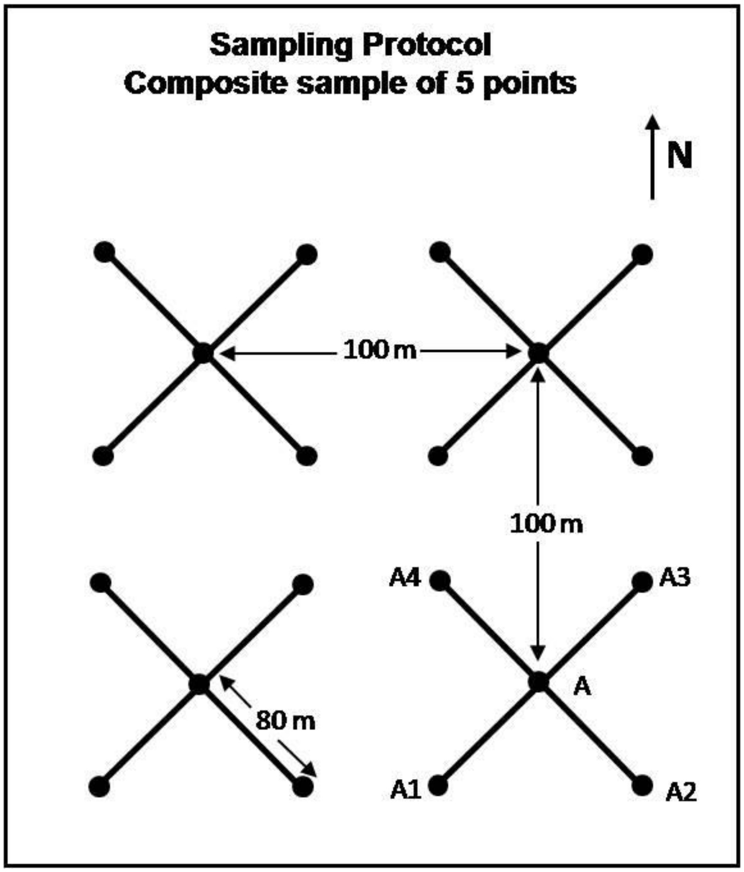

Figure 5. Diagram of Fedj Lahdoum sampling tailings.

size (by homogenization and quartering) to ensure that the flotation can be carried out.

In this study, the raw sample and the different size fractions of a representative waste sample were used for the characterization by XRD (X Ray Diffraction), SEM (Scanning Electron Microscope), chemical analysis which involved the determination of Pb and Zn total and other heavy metals. The samples were dissolved by triacid attack ($HClO_4$, HNO_3 and HF) whose purpose is to measure Zn, Pb, Fe, Mn, Cr, Co, Cd and Cu spectrometry atomic absorption (AAS) Thermo-elemental type.

Soils and plants sampling in the surrounding area and chemical analysis

Soil samples are collected around the mining district with a sample of control soil (control) outside the area (Figure 7). The determination of total contents of Pb, Zn and Cd in soils required a solution treatment and chemical analysis with the same protocol as for the solid waste.

To monitor the transport of PTE (Potentially Toxic Elements) at the first link in the food chain, wild and cultivated plant species were collected and represented (Figure 7) on the basis of their suitability to the inside or outside Fedj Lahdoum mining District: P1: olive tree (*Olea* (L)), upstream of the study area near the water source Ain Tordfin S1. P2: Plant shrub outside the mining district. P3: Aleppo pine (*Pinus halepensis* (L)), located far from tailings, upstream of the river Tordfin. P4: Aleppo pine (*P. halepensis* (L)), taken away from tailings. P5: pimento, plant along the left bank of the river Tordfin; P6: rosemary (*Rosmarinus officinalis* (L)), sampled on the left bank of the river Tordfin. P 7: fig tree (*Ficus* (L)) on the left bank of the wadi near the tailing dam N° 4. P8: Acacia (*Acacia* (L)), located on the right bank of the river Tordfin. P9: olive tree (*Olea* (L)), near the old gallery. P10: olive tree (*Olea* (L)), located near the old gallery and the tailing dump N° 1. P11: Cistus (*Cistus* (L)), located on the west bank of the river. P12: laurel (*Laurus nobilis* (L)) situated on the right bank of the river. P13: thyme (*Thymus vulgaris* (L)) on the right bank of the wadi.

The fresh material was washed with distilled water and treated with ultrasound to remove all dust and soil. The upper parts (leaves) are separated and then dried in an oven (40°C) for 48 hours, and then it was finely ground, calcined at 450°C for 12 hours. The calcination product was dissolved after an attack in pure nitric acid and pure perchloric acid [HNO_3 (70 to 71%): $HClO_4$ (70 to

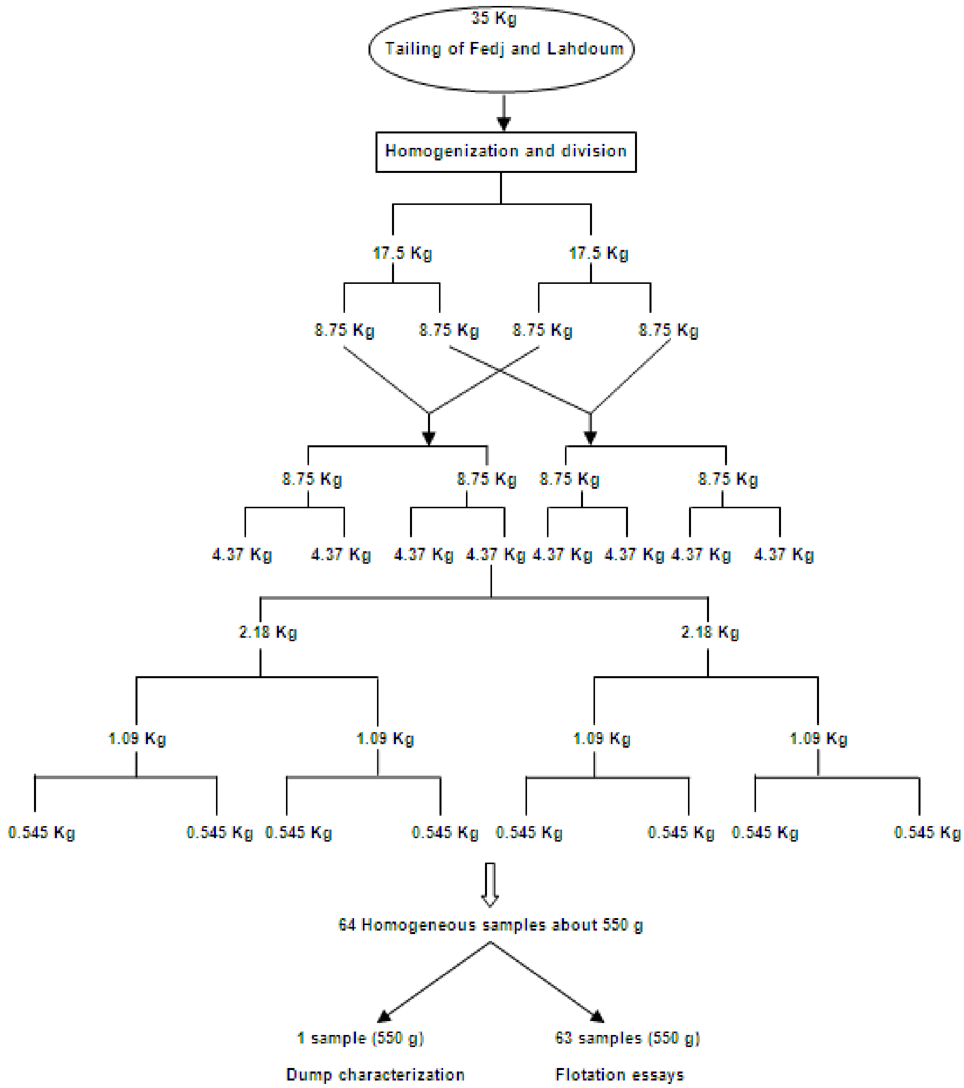

Figure 6. Representative samples through the homogenization and quartering.

72%), 2:1(v/v)]. The concentrations of heavy metals Pb, Zn and Cd in the plants were measured by atomic absorption spectrometry (AAS), type Solar Thermo Elemental.

RESULTS

Tailings

The analyzed mine waste samples showed a light gray color with a texture that is closely applied to the ore mineral processing. These mining wastes are poorly consolidated; unstable seat erosion with traces of gullies (Figures 8 and 9).

Particle size analysis of a representative sample of tailings dumps in the Fedj Lahdoum determined the size distribution ranging between 315 and 20 µm with the finest fraction (< 25 µm) 20% (Figure 10).

The observation under the binocular microscope of different size fractions (> 315 µm, [315 to 250 µm], [250 to 160 µm], [160 to 125 µm], [125 to 100 µm], [100 to 80 µm] and [80 to 63 µm]) showed the presence of grains of galena (PbS),

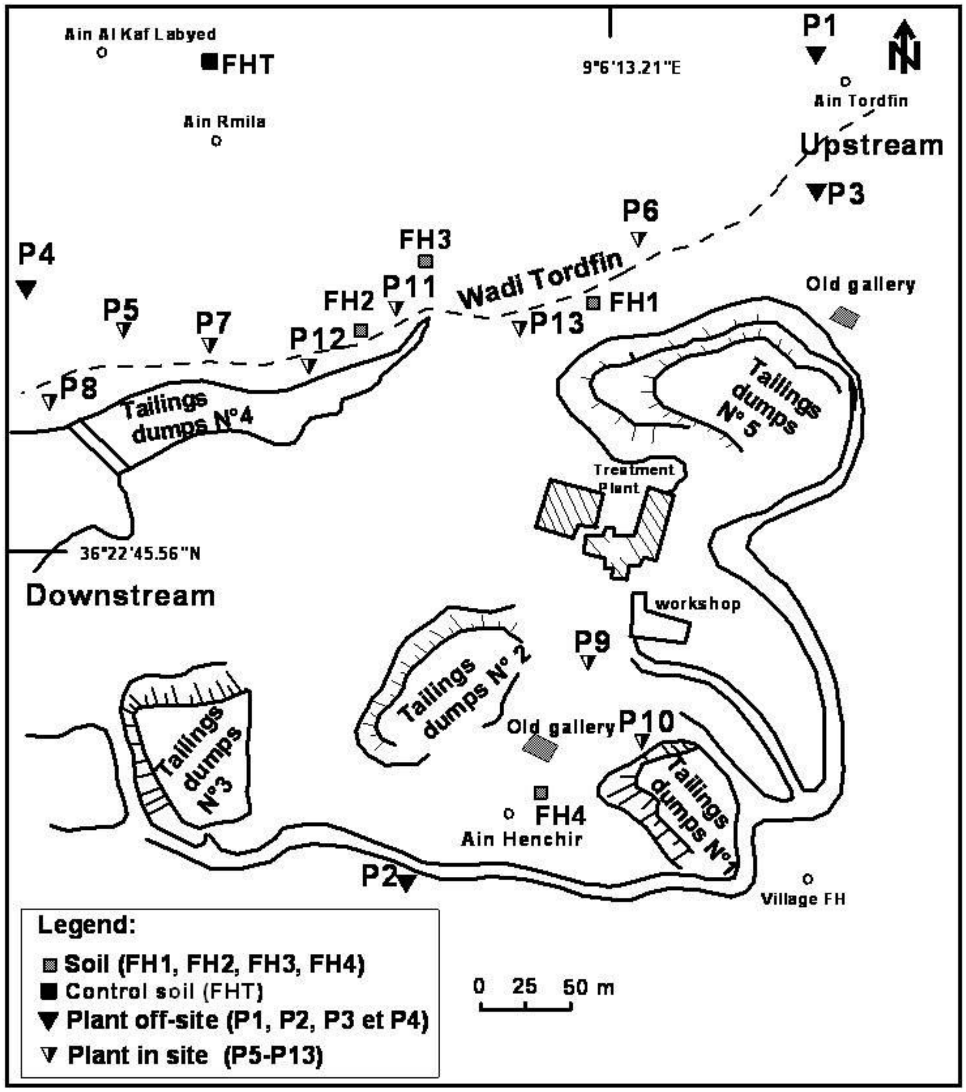

Figure 7. Location map of soil and plants sampling points.

sphalerite (ZnS), pyrite (FeS_2), calcite ($CaCO_3$), quartz (SiO_2) and dolomite (CaMg (CO_3)) (Figure 11) in a mixed form (formed from two or more mineral species), or free (only one mineral species). The finest fraction presented 20% which is the richest in sulfide minerals. The waste of fine texture is considered as a source of contamination of the entire mine site perimeter.

The observation under electron microscope (SEM) of fine particle size fractions confirmed the presence of galena, sphalerite and pyrite in the finest fractions of Fedj lahdoum tailings (Figure 12).

The total contents of heavy metals in the raw sample and a sieved sample in Fedj Lahdoum waste rock piles are presented in Table 1.

The raw sample showed levels of zinc of about 1.46% (14 600 $mg.kg^{-1}$), lead: 0.21% (2 100 $mg.kg^{-1}$) and iron: 3.2% (32000 $mg.kg^{-1}$). Strontium has a maximum of about 3.51% (35 100 $mg.kg^{-1}$), for manganese, the maximum (Figure 13) is about 1.63% (16 300 $mg.kg^{-1}$). The variation in grades, the contents of the other heavy metals are shown in the histogram (Figure 14).

The sieved sample showed that zinc concentrations ranged between 5,900 $mg.kg^{-1}$(0.59%) and 32,300 $mg.kg^{-1}$ (3.23%). The lead content ranged from 800 $mg. kg^{-1}$

Figure 8. Gullying process in the tailings.

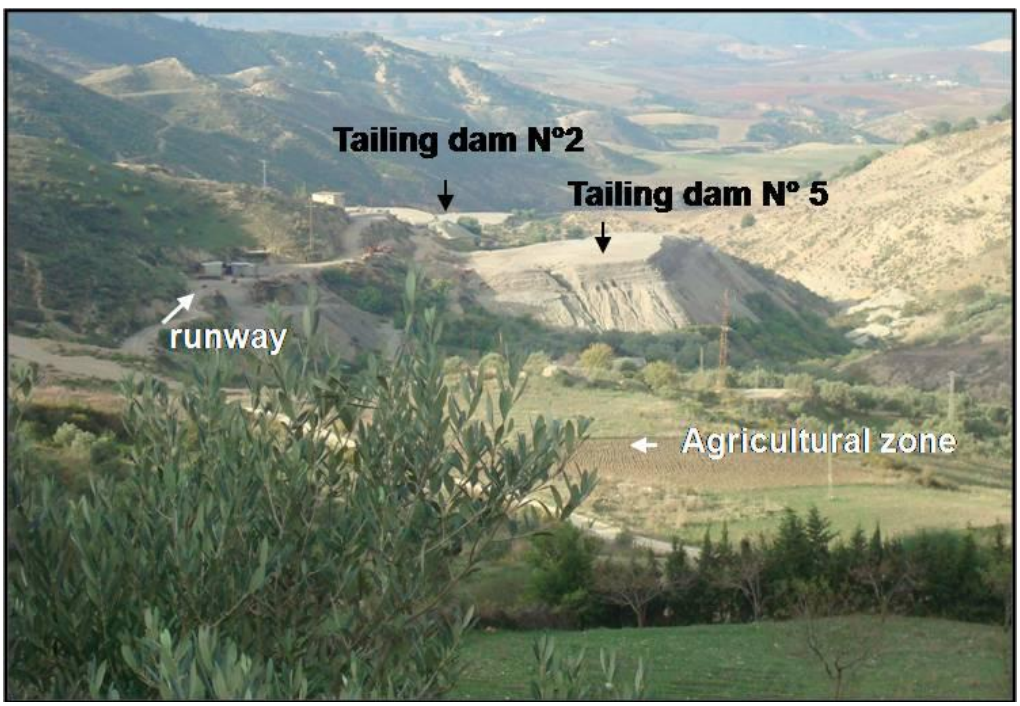

Figure 9. Fedj Lahdoum tailing.

(0.08%) to 6 200 mg.kg^{-1}(0.62%). Zinc and lead were concentrated preferentially in the fraction > 315 µm and that of < 25 µm (= 20 µm) (Figure 15). The iron has an average grade of about 32 000 mg.kg^{-1} (3,2%). The levels of manganese can reach 17 600 mg.kg^{-1}(1.76%). Iron and manganese showed a homogeneous distribution in all size fractions. The strontium levels high enough up to 61 800 mg.kg^{-1} (6.18%). Cadmium (Cd), cobalt (Co), chromium (Cr) and copper (Cr) are in small proportions (Table 1).

The correlation curves Zn / Cd and Pb / Cd (Figure16 and 17) showed a good positive correlation between zinc

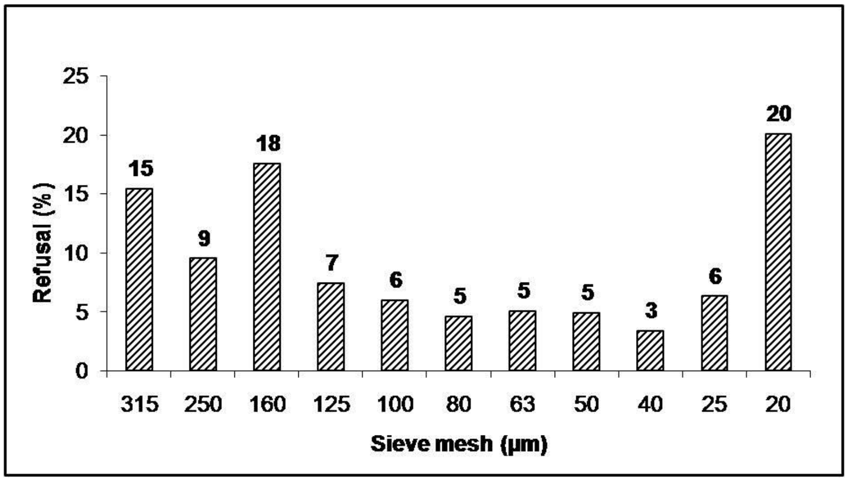

Figure 10. Histogram of size distribution.

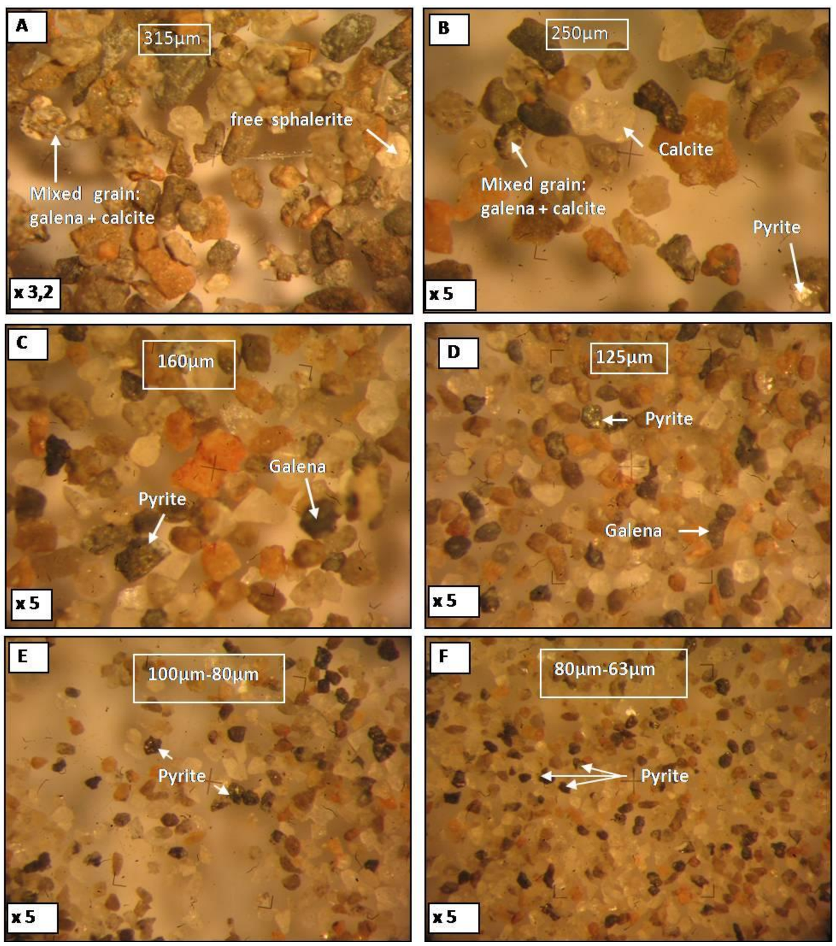

Figure 11. Different size fractions photographs of Fedj Lahdoum dumps.

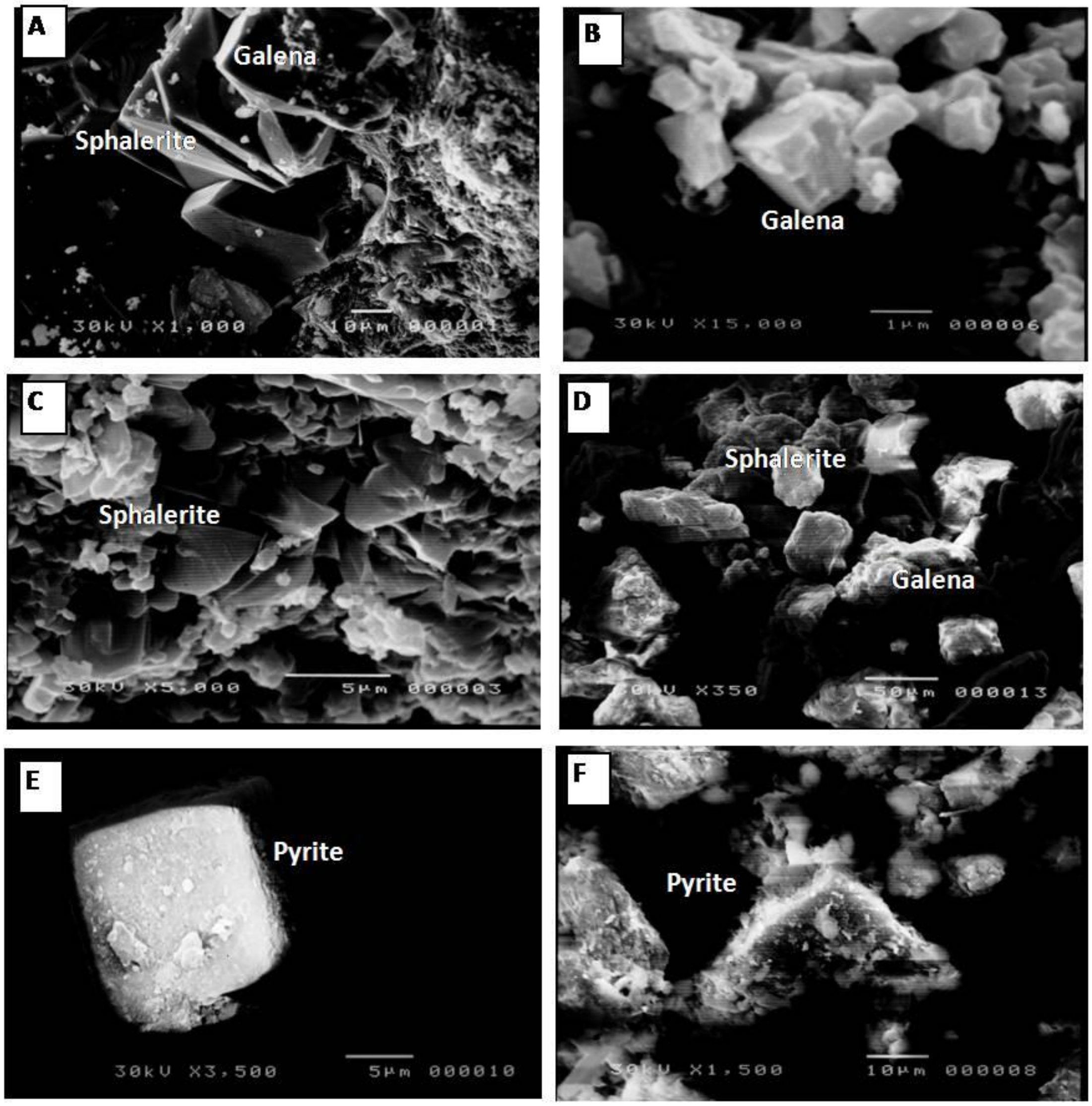

Figure 12. SEM images of cubic galena, sphalerite and pyrite in Fedj Lahdoum tailings (A): Galena (20 µm) in its cubic form in a sphalerite sample (30 µm). (B): Free galena grains (2 µm). (C): Free sphalerite (5 µm). (D): Mixed grain of galena-sphalerite (50 µm). (E): Free pyrite grain (20 µm). (F): Free pyrite graine (30 µm).

and cadmium, and between lead and cadmium.

Environment of the abandoned site soil analysis in the vicinity of the study area

The results of chemical analysis of different soils that are taken from topsoil (arable and pasture lands) and control soil are presented in Table 2.

Chemical analysis of soils (FH_1, FH_2, FH_3, FH_4) showed high levels of Pb, Zn and Cd from a soil sample collected far from the mine site considered as control (FHT) whose contents are: 118 $mgPb.kg^{-1}$, 312 $mgZn.kg^{-1}$, 1 $mgCd.kg^{-1}$. The contents of the heavy metal increased progressively outside Fedj Lahdoum district and the highest grades were found inside the mine site (Figure 18 (a), (b), (c)) at Soil FH_1: 3 646 $mgPb.kg^{-1}$, 3 236 $mgZn.kg^{-1}$, 17 mg $Cd.kg^{-1}$.

Table 1. Total content of heavy metals (mg.kg^{-1}) in a raw sample and in different size fractions of a representative sample from Fedj Lahdoum tailings.

Sample tailing	Zn	Pb	Fe	Sr	Mn	Cd	Co	Cr	Cu
Tailing raw sample (µm)	**14600**	**2100**	**32000**	**35100**	**16300**	**62.08**	**75.04**	**29.57**	**39.33**
+ 315	32300	6200	35000	51000	16700	77.17	28.21	32.48	17
-315 + 250	17000	4800	32000	44400	17500	44.21	23.93	35.96	11.67
-250 +160	10900	2200	32000	48100	17600	28.97	56.92	32.12	45.93
-160 +125	8200	1400	32000	54700	17000	22.27	25.29	29.59	23.31
-125 +100	7000	1100	34000	61000	16500	20.93	56.22	27.72	49.59
-100 +80	6300	1000	34000	61800	16100	19.71	9.33	23.39	23.09
-80 +63	5900	900	31000	52300	16200	20.51	25.66	25.66	35.23
-63 +50	5900	800	32000	50500	15900	19.40	36.91	26.48	31.56
-50 +40	6600	800	30000	42900	15600	18.82	18.16	28.16	40.69
-40 +25	6700	900	34000	46200	15200	19.86	29.21	30.45	10.62
< 25 (= 20)	30000	2000	36000	16900	14000	47.86	51.85	70.76	98.01
Min.	5900	800	30000	16900	14000	18.82	9.33	23.39	10.62
Max.	32300	6200	36000	61800	17600	77.17	75.04	70.76	98.01

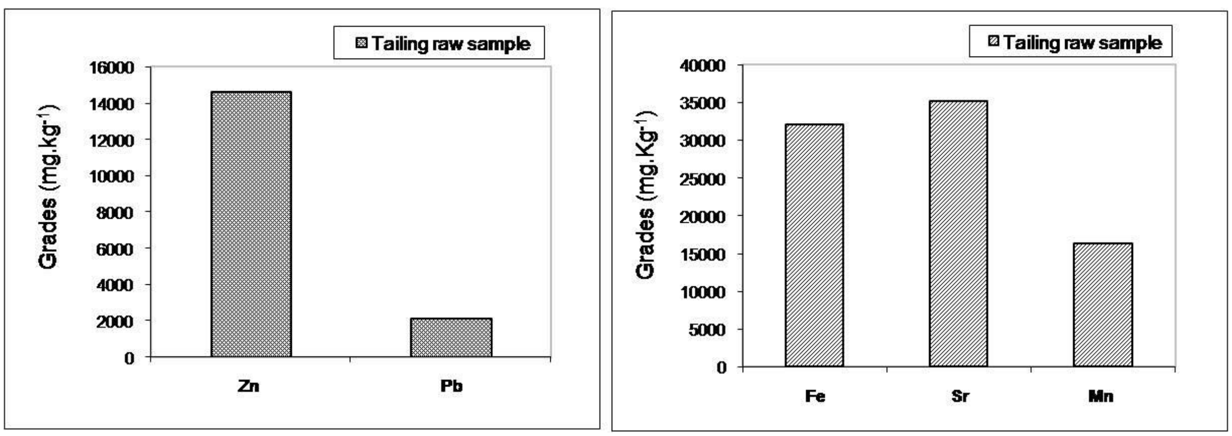

Figure 13. Variation in the contents of Pb, Zn, Fe, Sr and Mn from a raw sample of tailing.

Plants grades of metals at risks

The results of the chemical analysis of the aerial parts of these plants are shown in Table 3.

Plants that are located outside the mining district have shown low grades, while all plants located inside abandoned mining district are strongly contaminated (Figure19 (a), (b), (c)).

Zinc concentrations (Zn) in the plant species located inside Fedj Lahdoum mining district are extremely high (Figure 19(a)): Thyme (*Thymus vulgaris* (L)): 708.56 mgZn.kg^{-1}, laurel (*Laurus nobilis* (L)): 500.44 mgZn.kg^{-1}, pimento: 106.73 mgZn.kg^{-1}. High concentrations of lead (Pb) were also registered (Figure 19(b)): Olive (*Olea* (L)): 18.08 mgPb.kg^{-1}, fig tree (*Ficus* (L)): 22.53 mgPb.kg^{-1}. High grades of cadmium (Cd) were shown (Figure 19(c)): Olive: 5.62 mgCd.kg^{-1}, pimento: 3.23 mgCd.kg^{-1} laurel (*Laurus nobilis* (L)): 5.01 mgCd.kg^{-1}.

DISCUSSION

Tailings: Potential source of contamination

The mineralogical characterization of the tailings showed

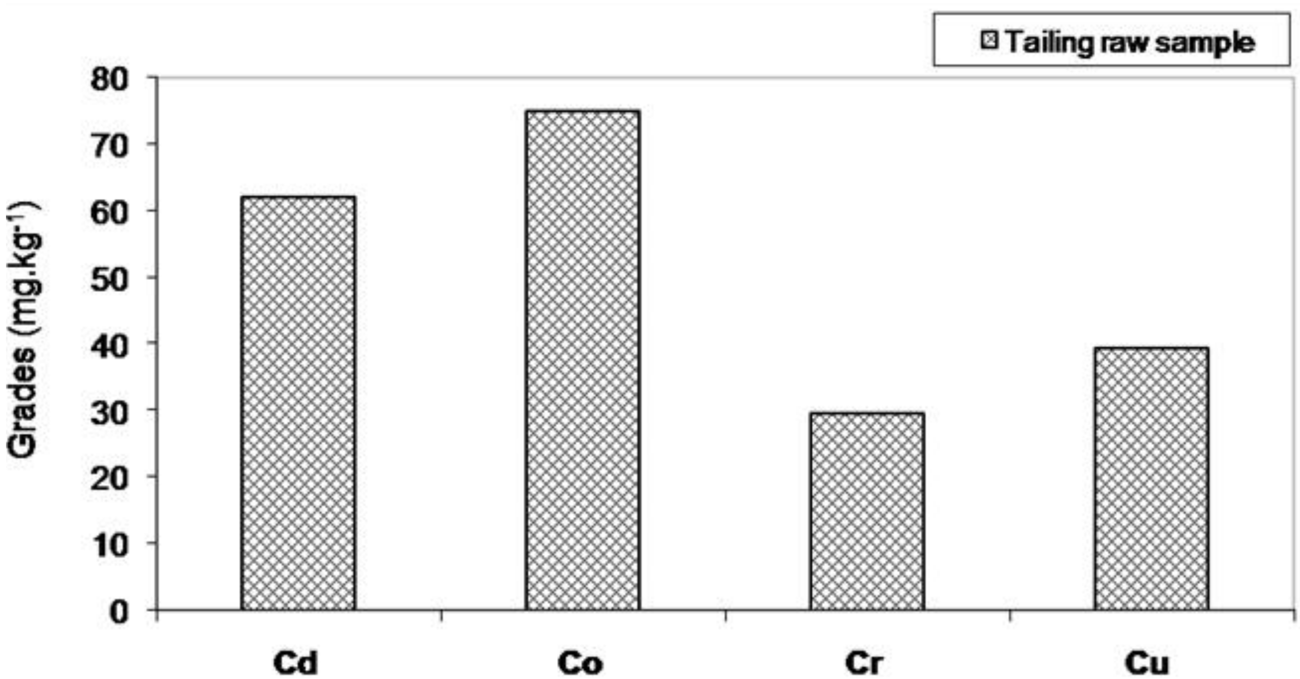

Figure 14. Grades variation of Cd, Co, Cr and Cu in a raw sample of tailing.

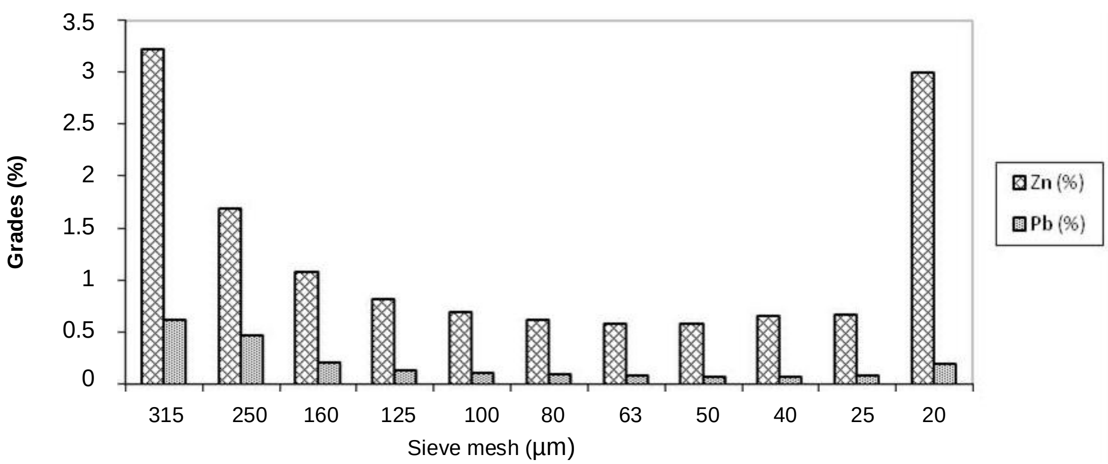

Figure 15. Histogram of Pb and Zn (%) concentrations in different size fractions of Fedj lahdoum waste dumps.

that bearing phases of lead and zinc are generally the size of about 20 microns, lead and zinc are mainly associated with sulfides and carbonates. In carbonate context and under a Mediterranean climate, Boussen et al. (2010) show that the environmental risks associated with mining activities are mainly related to the dispersion of fine particle that were emitted under the action of wind and to a lesser degree in erosion of the dumps and

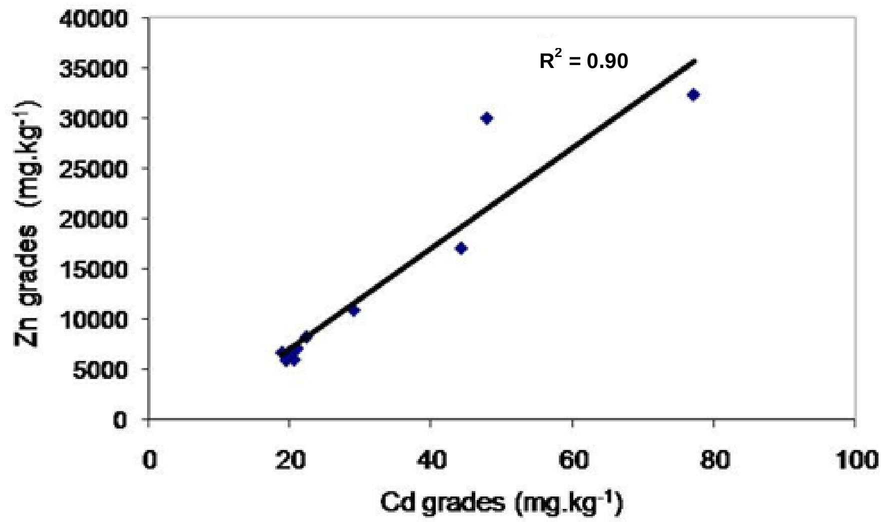

Figure 16. Correlation diagram of zinc-cadmium.

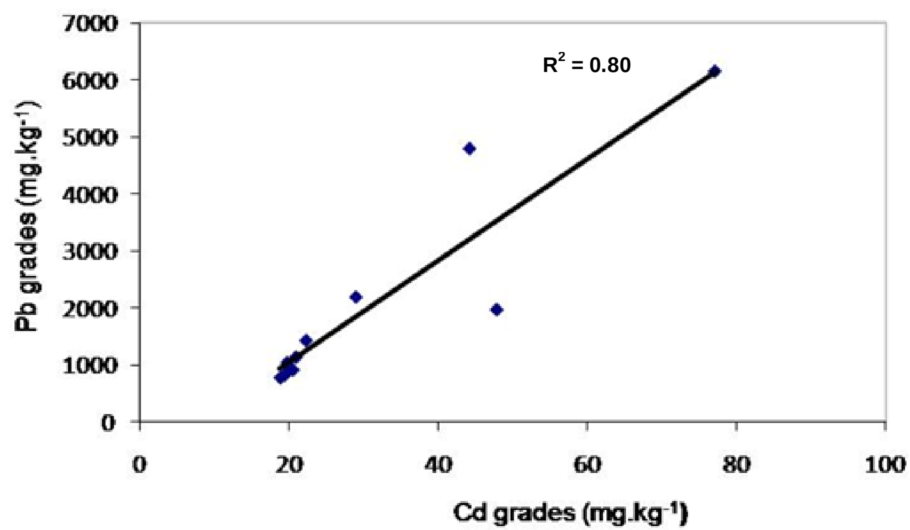

Figure 17. Correlation diagram of lead- cadmium.

Table 2. Concentrations of Pb, Zn and Cd ($mg.kg^{-1}$) in the soil of Fedj Lahdoum region.

Soil Sample	Pb	Zn	Cd
Soil FH_1	3 646	3 236	17
Soil FH_2	1 768	3 294	12
Soil FH_3	842	3 184	10
Soil FH_4	506	1 432	6
Control soil FHT	118	312	1

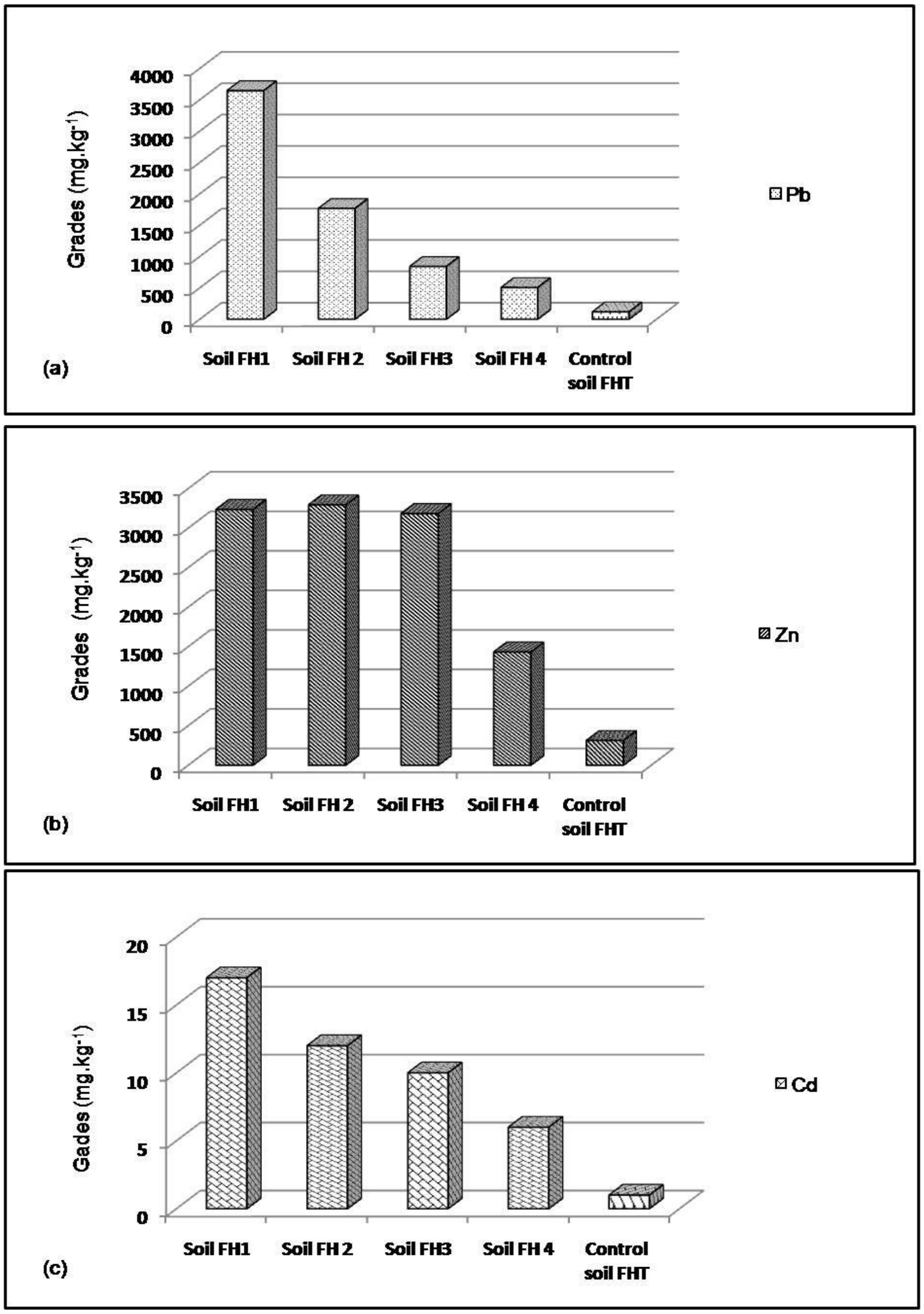

Figure 18. Fluctuations in grades of (a) Pb (b) Zn and (c) Cd as a function of distance from Fedj Lahdoum tailings dumps.

transport water from rivers during winter when it rains heavily.

High concentrations of zinc and lead in the 315 µm fraction were due to the presence of mixed grains of sphalerite and galena that were not broken (the mesh is not optimal liberation reached) during the enrichment. In

Table 3. Grades of Pb, Zn and Cd ($mg.kg^{-1}$) in plants located in the vicinity of the Fedj Lahdoum abandoned mine site.

Localisation	Plant leaves	Zn	Pb	Cd
Outside the mining district	P1 (*Olea* (L))	38.73	3.23	0.34
	P2 (*Plant shrub*)	67.98	2.53	0.44
	P3 (*Pinus halepensis* (L))	77.78	3.84	<0.001
	P4 (*Pinus halepensis* (L))	92.20	8.68	2.11
Inside the mining district	P5 (*pimento*)	106.73	2.25	3.23
	P6 (*Rosmarinus officinalis* (L))	113	4.98	0.25
	P7 (*Ficus* (L))	128.33	22.53	1.44
	P8 (*Acacia* (L))	130.68	7.92	0.5
	P9 (*Olea* (L))	181.70	4.98	2.32
	P10 (*Olea* (L))	212.20	18.08	5.62
	P11 (*Cistus* (L))	229.05	2.59	0.69
	P12 (*Laurus nobilis* (L))	500.44	12.44	5.01
	P13 (*Thymus vulgaris* (L))	708.56	16.24	<0.001

the finest fraction, the high content of zinc and lead owe their origin to overgrinding. It resulted in the production of a large quantity of fines making it difficult to flotation. Thus, these fines were found in the tailings. The positive correlations between Zn/Cd and Pb/Cd could deduce the possibility to recover cadmium simultaneously in the same phase with lead or zinc, in the reprocessing of tailings by flotation with the aim of environmental desulphurization. In fact, these elements have ionic radii neighbors, which allow partial replacement of Zn by Cd in sphalerite: R_{Zn}= 1.34 Å, R_{Cd} = 1.51 Å or partial replacement of Pb by Cd in galena Pb R_{Pb} =1.46 Å, R_{Cd} = 1.51 Å (Rosler and Lange, 1972).

Kovacs et al. (2006), in Gyöngyösoroszi, North Hungary, show that the contamination of the site by mining activity is the result of the transfer of trace elements by wind and water processes.

Recent studies conducted by Conesa et al. (2007) and Liao et al. (2008) prove that mining waste fine textured rich in heavy metals pose serious environmental problems. Once released into the environment, these heavy metals have a potentially negative impact on the quality of the environment (Jang and Kim, 2000). The toxicity of heavy metals (Pb, Zn, Cu and Cd) is one of the main constraints to remediation (Lan et al., 1998).

A recent study similar to the present work was carried out by Rashed, 2010 shows that when processed mine minerals are finely divided, there is a potential risk that such materials may find their way through the environment and food chain to animals/humans, and can be toxic to plants, animals and humans through their interaction with the environment. The contamination of heavy metal has been reported in the vicinity of mining and smelting sites.

The tailings (from the fine grinding of ore and processed material) can seriously pollute the surrounding land with toxic dust due to the wind erosion. Jacob and Otte (2004a) and Ritcey (1989) confirms that the tailings deposits, the crushed and processed ore material, can severely pollute the surrounding land with toxic dust from wind erosion.

Contamination of agriculture soil

All concentrations detected in soil inside and outside the Fedj Lahdoum mining district have exceeded the maximum allowable tolerance in soils: 100 $mgPb.kg^{-1}$, 300 $mgZn.kg^{-1}$ and 0.7 $mgCd.kg^{-1}$ (Henin, 1983).

According to the Canadian Environmental Quality Standard International for soils (CCME-EPC-CS34, 1991), grades of Pb, Zn and Cd in soil samples analyzed (FH_1, FH_2, FH_3, FH_4) greatly exceeded the tolerance contents in agricultural areas (50 $mgPb.kg^{-1}$, 100 $mgZn.kg^{-1}$, 3 $mgCd.kg^{-1}$) tolerance limits and in residential areas (300 $mgPb.kg^{-1}$, 500 $mgZn.kg^{-1}$, 5 $mgCd.kg^{-1}$). For soil FH_4, it can be considered below the tolerance levels in industrial areas (600 $mgPb.kg^{-1}$, 1 500 $mgZn.kg^{-1}$, 20 $mgCd.kg^{-1}$). The levels detected in soil samples (FH_1, FH_2, FH_3 and FH_4) also exceeded the Tunisian standard (INNORPI (2002, 2003 (a), (b), (c)), NT 106.20, NT 91.12; NT 91.33; NT 91.10) in agricultural areas (100 $mgPb.kg^{-1}$, 300 $mgZn.kg^{-1}$, 3 $mgCd.kg^{-1}$).

Control soil contained significant grades of heavy

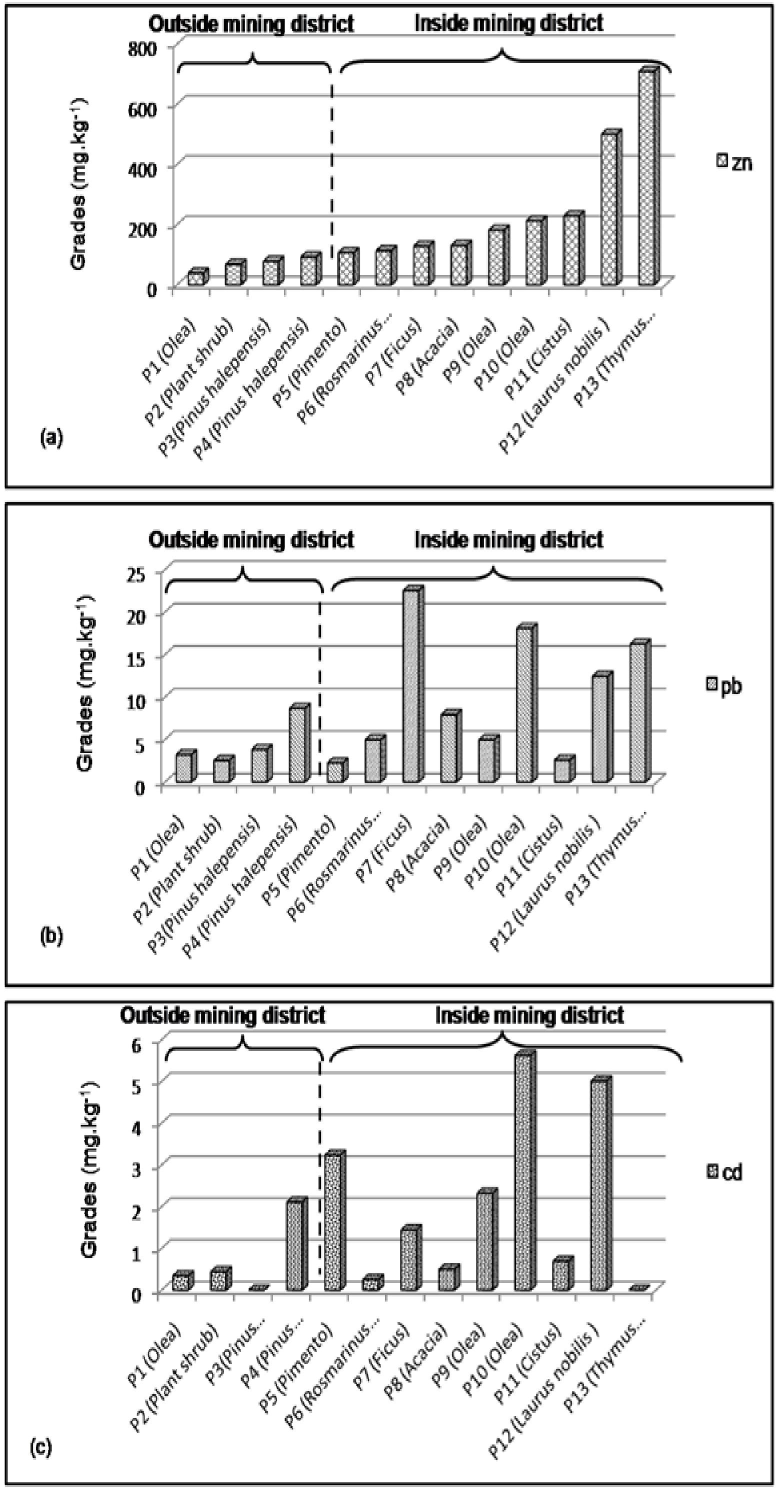

Figure 19. Grades variations of Zn (a), Pb (b) and Cd (c) according to plants approximity from mining site.

metals that exceed the standards, which proved that contamination exceeded the internal territory of the former mine and progresses to the vicinity of the mine site. Simon et al. (2001) show that the soil contamination is related to the distance from the storage site and fine texture of tailings.

High concentrations of heavy metals in soil samples reflect the blocking of these metals risk surface, from the input of mineral dust from operating activities of the mining field and the deposit of waste around the site (Schippera, 2008).

Tailings dumps were subject to atmospheric transport under wind action and presenting a dust emission source and an inhalation risk for people (Haneef and Yanful, 2003; Conesa et al., 2007). Mining waste are subject to water erosion that results in a transport of rich particles in toxic elements in particulate form or dissolved form causing degradation of soil quality (Boussen et al., 2010). These tailings (from the fine grinding of ore and processed material) can seriously pollute the surrounding land with toxic dust due to wind erosion (Ritcey, 1989; Jacob and Otte (2004b).

Soil pollution by lead, zinc and cadmium were characterized in an old Spanish mine Pb-Zn (Rodriguez et al., 2009), in abandoned mine sites Tunisia: Jalta (Boussen et al., 2010), Jebel Sidi-Hallouf Bouaouane (Chakroun et al., 2010). In the same context, Lee et al. (2001) showed that the soil located around an abandoned mine site in Korea is less contaminated than those detected in Fedj Lahdoum (northern Tunisia).

Other previous studies on this topic led by Shu et al. (2001), Liu et al. (2007), Yang et al. (2003) and Schipper et al. (2008) have shown that the tailings that are deposited in agricultural areas are suspected of being sources of heavy metals to the environment. The potential toxicity and the risk of contamination of the food chain have been described in the USA by Pichtel et al. (2000), in New Zealand by Taylor and Percival (2001), in the Rio Pilcomayo basin, Bolivia by Miller et al. (2004) and in China by Liu et al. (2006). The exploitation of mineral deposits is a major anthropogenic source of soil pollution by heavy metals which is confirmed by Wang et al. (2008), Jiménez et al. (2009), Wang et al. (2009), Wei et al. (2009) and Schindler et al. (1987).

Heavy metal concentrations in plants

Plants located outside the mining district have grades below the limits of tolerance. While all plants located inside the abandoned mining district were highly contaminated.

These concentrations of Zn, Pb and Cd exceeded the limits of toxicity in plant tissues: 100 $mgZn.kg^{-1}$, 5 $mgPb.kg^{-1}$ and 2 $mgCd.kg^{-1}$ (Bedell et al., 2006).

Plants react differently depending on the variety. Some are less tolerant than others and die on contact with heavy metals. Other defense reactions and prevents the absorption by secreting acids that will increase the pH and therefore reduce the mobility of toxic elements. Others are tolerant to metals and even accumulate and concentrate them. These plants are called: hyperaccumulators and metallophilic (Bhattacharya et al., 2006). Several studies have demonstrated that heavy metals (Pb, Zn, Cu, Cd) are preferentially absorbed by certain plants hyperaccumulator such as: *Thlaspi caerulescens* and *Brassica napus:*Colza (Ben Ghnaya et al., 2006); *Rhododendron annae* (L*), Llex plyneura* (L*), Fargesia dura* (L), *Arundinella yunnanensis* (L*)* (Yanqun et al., 2004).

In fact, these plants accumulate heavy metals that can be assimilated by humans and can cause the contamination of the whole food chain (Kabata-Pendias, 2004).

Heavy metals are absorbed by the roots and remain the most often. The shift in aerial parts (stems, leaves) vary depending on the metal and are indicators of an increased concentration of metals in the soil. Lead remains in the roots, cadmium and zinc pass more easily into the aerial parts (Boularbah, 2006).

Plant contamination by heavy metals is done: either through root and in this case only the mobile fraction (phytodisponible) can be assimilated by the plant (Vangronsveld et al, 1995; Pratas et al,2005), or through passive contamination: it is the wind transportation. The performed analysis showed that the plants were contaminated at the leaves. Mine wastes are suspected to be a source of plants contamination and therefore contamination of the environment (Rodriguez et al., 2009; Yang et al., 2003; Lan et al., 1998). In Mediterranean countries, and in the case of Tunisia, aeolian transport plays an important role in the dispersion of fine particles when released around former mine sites (Boussen, 2010). Plants and crops can uptake toxic elements through their roots from contaminated soils and even leaves can absorb toxic elements deposited on the leaf surface (Rashed, 2010).

Diffusion process of contamination to the environment

The Mediterranean climate is characterized by long dry periods interspersed with heavy rains, high winds and high temperatures that induce wind and erosion. They are the two major processes of the spread of contamination to the various compartments of the environment and to local populations. The relative importance of wind and water processes depend on the climate zone that varies greatly according to a north-south gradient. In addition, in a changing climate where the frequency of droughts and extreme rainfall events are increasing, the spread of contamination becomes a more prevalent concern.

The transfer through wind plays a leading role in the spread of contamination in semi-arid climatic conditions in arid areas around the Mediterranean. Aeolian transport depends also on weather events and surface characteristics subjected to wind erosion. All natural resources are vulnerable to anthropogenic assaults and for this reason, the ecological balance had been broken.

The cultivation of almost all land is originally starting the process of malfunction and degradation of all components of the landscape: changing the water balance of land with higher rates of runoff, erosion of land sloping (Cappuyns et al., 2006) and siltation in low areas. These phenomena are still shaping the abandoned mine site of FH and determine its regressive evolution marked by:

(i) Extensive land degradation;
(ii) Shaping the landscape by water runoff and erosion which cause environmental risks arising from this dynamic resident, a very special way, the potential transfer by runoff, contaminating mineral particles that could settle the land surface and landing in areas of spreading or in waterways.

The starting points of potential dust hazards are all located inside the territory of the former mine, spread out along the route of the treatment with ore from its extraction to its shipment outside the region, the following steps: at the exit of the ore mining galleries and its transport to the area for crushing and stockpiling of material along the transport path of the ore to the ore processing plant, loading of ore processed for evacuation to the outside.

As for potential vectors of dust dispersal into the abandoned mine environment, they were:

(i) Wind: Its ability to transport these particles depends on its speed and humidity. In areas considered particularly windy, only the wind in the wet season was potentially able to disperse the load and potential pollutants in the territory of the former mine and in the vicinity of mine (Haneef and Yanful, 2003; Conesa et al., 2007).
(ii) Runoff: Potentially, these waters are important vectors of dispersal of dust hazards in the absence of specific arrangements for rainwater retention that does not infiltrate immediately locally. Potential areas of dust transported landing zones are spreading flood waters and waterways.
(iii) The drainage water: The fraction of rainwater that infiltrates into the soil must first saturate the topsoil prior to percolate deeply and eventually reach the groundwater (Pinte, 2000). In reality, the risk of leaching of heavy metals by vertical drainage are virtually zero for several reasons: the minerals at risk are insoluble in high pH calcareous soils, rainfall averages, even in the wet season, are not sufficient to saturate the soil and cause a drainage material in the context of Fedj Lahdoum soil. Previous mining activities caused a serious heavy metal contamination of surface waters, groundwater in different sites throughout the world.The effluent from mine site consists of mine drainage, water that flows at the outfall of tailings accumulation area , of runoff from waste rock pile or a combination of these types of water. The mine water is pumped to the surface to keep the mine dry and to permit the exploitation. It may contain contaminants emitted by blasting operations, the use of vehicles and other equipment, as well as by biological or chemical reactions that occur on the surface of the bedrock. In Sardinia (Italy) water is contaminated under the impact of mining activities (Concas et al., 2006). The same phenomena is detected in British Cohnnhia ,Canada (Azcue et al., 1995) and in south Africa (Winde and van der Walt, 2004).

Contamination of the aquatic environment caused by mining and ore processing metal comes mainly from the oxidation of sulphide minerals contained in the exposed walls of the underground galleries, the walls of the extraction sites, areas of accumulation of tailings and waste rock dumps. Sulphide minerals, when exposed to air, first undergo a relatively slow chemical oxidation and then gradually become more acidic environment: pyrite.

Oxidation of iron sulfide (FeS_2) in the presence of water is the starting reaction process. The first reaction is the conversion of sulfides to sulfates by means of an oxidation reaction (Pint, 2000) and the water is acidic values (pH 3 to 4).

$$FeS_2+\frac{7}{2}O_2+H_2O \rightarrow Fe^{2+}+2SO_4^{2-}+2H^+$$

The second reaction is with the progressive acidification of the medium (H^+) and processing of ferrous iron to ferric iron (Fe^{3+}), which produces a fast cyclical process and forms large amounts of acid (Toulhoat, 1996).

$$2FeS_2+\frac{15}{2}O_2+3H_2O\leftrightarrow 2Fe^{3+}+4HSO_4^-+2OH^-$$

This acidification allows the growth of bacteria that act as catalysts in oxidation reactions, thereby causing an increase in the rate of acidification (Masson and Rice, 2002).

$$4Fe^{2+}+O_2+4H^+\rightarrow 4Fe^{3+}+2H_2O$$

They are acidophilic bacteria that are involved in the oxidation of metal sulfides: Thiobacillus ferrooxidans, is a Gram-negative (optimal growth T: 30 to 35°C and low pH=2), chemolithotrophic bacterium able to derive energy for growth from the oxidation of ferrous to ferric iron and elemental sulfur or reduced inorganic sulfur compounds to sulfate using oxygen as electron acceptor. In waters strongly acidic (pH 2 to 3) mines, the iron type oxidation is bacterial (Buonfiglio et al., 1999).

Therefore, there is a production of highly acidic water that dissolves the heavy metals from sulphide minerals which generates acid mine drainage: AMD (Lawrence et al., 1991). Sulfidic mine tailings are the major source for AMD and contamination of the mine environment (Sima et al, 2011). In Kristineberg, northern Sweden and near Selebi-Phikwe, Botswana; Kock and Schippers (2006) reported the impact of microbiological metal sulfide oxidation on acid mine drainage generation. Sulfide oxidation is predicted to continue for centuries in the absence of remedial actions.

(iv) The work and the reversal of the surface layers of soil: ploughings could actually mix the possible pollutants that contaminate the surface of cultivated land.

(v) Direct contamination of natural and cultivated vegetation types through dust dispersion by the wind: it is possible inside the mine, particularly as a result of transport along the tracks inside the mine site. This is the case of contamination of aerial parts (leaves) of forestry training, relics of scrubland, and the remaining olive groves inside the territory of the mine.

(vi) The export of plant products, potentially contaminated harvested or consumed by sheep flocks: contamination could occur directly by deposition of dust risks on bodies consumed, or due to absorption of metal pollutants in contaminated soil and their concentration in parts consumed or collected. But the potential export of plant products contaminated outside the risk zone was extremely high. For the surrounding area the risks of plants contamination, directly or indirectly by dust from the mine are high.

Thus, Fedj Lahdoum abandoned mine site has vulnerable components but the environmental risks were very serious. However, if the risks were probable over short distances inside the mine, they were maximum for possible contamination of the surrounding land in view to the humidity of air, land and materials exposed to air in relatively rainy season. In this case, tailings are suspected being the source of contamination.

The methods that are available to decontaminate the toxic metals contained in the tailings include phytoremediation such as phytoextraction: use of plants to extract organic pollutants from soil and metals and concentrate in the organs of the plant for harvest (Wong, 2003) and phytostabilisation: use of plants to reduce erosion and immobilize pollutants in the surface layers, in particular avoiding their migration to the water surface and groundwater (Doumett et al., 2008; Ruttens et al., 2006); soil flushing; pneumatic fracturing; solidification/stabilization; vitrification; electrokinetics; electromigration (Zhongming et al., 1997), phytodegradation: use of the combination plant/micro-organisms to degrade organic pollutants from the soil; chemical reduction/oxidation; soil washing and excavation, but these methods are usually expensive (Chiu et al., 2006). The most profitable method in the long term and less expensive is froth flotation using the appropriate collector chosen according to the mineralogical and chemical characterization of mine wastes (López Valdivieso et al., 2006).

Froth flotation is a separating process, by bringing them to the surface despite their high densities, particles of searched minerals (galena, sphalerite, pyrite and even cerussite, anglesite, smithsonite), by adhesion of these particles (hydrophobic particles) to air bubbles blown into the pulp, while the other particles of these minerals (hydrophilic particles) does not cling to the air bubbles and remain in the pulp (Fuerstenau, 1976; Herrera-Urbina et al., 1999). In a pulp, the most important factor to separate particles of the gangue is useful to the specific surface behavior versus the products that are added to the air and some chemical agents: collectors, depressants, activators and regulators of pH (Blazy, 1970).

To apply the flotation process, it is necessary to mill the representative sample in a steel rod mill during the required time (up to the mesh liberation minerals) in the presence of water and the necessary reagents.The milled slurry was transferred to a Denver flotation stainless steel cell , the impeller speed is fixed depending on the cell size, at a constant air flow rate (the maximum permitted by the system). Pulp density is adjusted by tap water. The pulp is conditioned in the flotation cell for few minutes with the appropriate reagent after adjustment of pH. The collector is added to the pulp for few minutes. The global flotation is carried out to have finally: total concentrate and a final tailing (non reaction fraction). The froth height was kept constant at 2 cm throughout using frother. Feeds, concentrates and tails were filtered, dried and weighed before analysis for heavy metals (Havre, 1952).

This technique is essential to the prosperity of several mines producing ore complex. It can lead to open new mines or to reprocess tailings from old mines (Benzaazoua et al., 2000). With flotation, dumps of old mines in Canada have been treated by the flotation process for an environmental desulphurization (Benzaazoua et al., 2003). Hesketh et al. (2010) developed a conceptual integrated approach for sulfide removal from flotation tailings in AMD mitigation and presents preliminary findings in the technical feasibility of flotation desulfurization.It is the aim in North Africa, especially in Tunisia: desulfurization of abandoned mine sites by froth flotation. This method was chosen for possible decontamination of Fej Lahdoum mine site after the mineralogical study which has shown the finesse of mine waste and mineralogical complexity (mixed minerals).

Conclusion

This study showed that Fedj Lahdoum abandoned mine site was contaminated with heavy metals originating tailings. The concentrations of mine wastes were: 10,240 $mgZn.kg^{-1}$ and 2,100 $mgPb.kg^{-1}$ and 62.08 $mgCd.kg^{-1}$.

Tailings are suspected of being the primary source of environmental contamination. The soils of the former mining site of the deposit and various materials were contaminated by zinc, lead and cadmium (3 646 $mgPb.kg^{-1}$, 3 236 $mgZn.kg^{-1}$ and 15 $mgCd.kg^{-1}$). As for the plants growing inside this abandoned mine, they had already revealed significant accumulations of Zn, Pb and Cd, particularly in the leaves of thyme (*Thymus vulgaris* (L)): 708.56 $mgZn.kg^{-1}$; 16.24 $mgPb.kg^{-1}$, Laurel (*Laurus nobilis* (L)): 500.44 $mgZn.kg^{-1}$, 12.44 $mgPb.kg^{-1}$ and 5.01 $mgCd.kg^{-1}$. Heavy metals concentration in pepper was: 106.73 $mgZn.kg^{-1}$, 3.23 $mgCd.kg^{-1}$. Fedj Lahdoum area is strongly contaminated by mineral dust rich in Zinc and Lead. In Tunisia, several mine sites are located in rural zones where the population depends on agriculture. In this environmental context, the contaminants were dispersed from mining sites (transfers wind, water) to land surrounding the areas. Therefore, there has been a transfer from soil to plant of these contaminants and their accumulation in plants. The spread of contamination into the food chain via local agriculture can then lead to people exposure to a health risk in relation to regulatory limits. Environmental risks inherent in mining activities reside in the potential dispersal of dust from zinc materials exploited and stored in tailings ponds without any precautions previously. The former mining activity can generate pollution from mining.

Current methods to combat this problem remain limited, often very costly and environmental guarantee is never assured in the very long term. Assistance in the management of contaminated sites and the choice of modes of prevention and protection is already started in our laboratory involving the environmental remediation. Therefore, we suggest adapting the method of environmental desulphurization by froth flotation.

REFERENCES

Abidi A, Abdelouahed B (1986). The deposit Fedj Lahdoum. Geological data with estimated reserves. Campaigns survey 1979-1985, Unpublished Report. CO.MI.NO., 54 p., 28 tab.

Azcue JM, Mudroch A, Rosa F, Hall GEM, Jackson TA, Reynoldson T (1995). Trace elements in water, sediments, porewater, and biota polluted by tailings from an abandoned gold mine in British Columbia, Canada. J. Geochem. Expl., 52(1-2): 25-34.

Bedell J Ph, Briant A, Delolme C, Lassabatère L, Perrodin Y (2006). Evaluation of the phytotoxicity of contaminated sediments deposited “on soil”:II. Impact of water draining from deposits on the development and physiological status of neighbouring plants at growth stage. Chemosphere, 62 (8): 1311-1323.

Ben Ghnaya A, Gilbert CH, Ben Hamida J, Branchard M (2006). Phytoremediation: *In vitro* selection of Rapeseed (*Brassica napus L.*) tolerant of toxic metals. Geo-Eco-Trop., 30(2): 69-86.

Benzaazoua M, Bussière B, Kongolo M, McLaughlin J, Marion P (2000). Environmental desulphurization of four Canadian mine tailings using froth flotation. Int. J. Miner. Process., 60(1): 57-74.

Benzaazoua M, Kongolo M (2003). Physico-chemical properties of tailing slurries during environmental desulphurization by froth flotation. Int. J. Miner. Process., 69(1-4): 221-234.

Bhattacharya A, Routh J, Jacks G, Bhattacharya P, Mörth M (2006). Environmental assessment of abandoned mine tailings in Adak, Västerbotten district (northern Sweden). Appl. Geochem., 21(10): 1760–1780.

Blazy P(1970). The valuation of minerals. Manual of Mineral, Paris, 404 p.

Bouhlel S (1993). Ore deposit, mineralogy and mineralization modeling test to F-Ba-Sr-Pb-Zn associated with the carbonates (Jurassic and Cretaceous) and the Triassic diapirs: Deposit of Stah, Kohl, Zriba, Guebli, Boujaber and Fedj Lahdoum (Northern Tunisia). PhD, thesis,

Tunis. 293 p.
Boussen S (2010). Evolution of lead-zinc dumps in Northern Tunisia: The example of a carbonate environment. Ph.D thesis in cotutelle. Tunis, 226 p.
Boussen S, Sebei A, Soubrand-Colin M, Bril HF, Chaabani, Abdeljaouad S (2010). Mobilization of lead-zinc rich particles from mine tailings in northern Tunisia by aeolian and run-off processes. Bull. Soc. Géol. Fr., 181(5): 371-379.
Buonfiglio V, Polidoro M, Soyer F, Valenti P, Shively J (1999). A novel gene encoding a sulfur-regulated outer membrane protein in *Thiobacillus ferrooxidans.* J. Biotechnol., 72(1-2) : 85-93.
Canadian Council of Ministers of the Environment (1991). Interim Canadian Environmental Quality Criteria for contaminated Sites. CCME-EPC-CS34, p. 9.
Cappuyns V, Swennen R, Vandamme A, Niclaes M (2006). Environmental impact of the former Pb-Zn mining and smelting in East Belgium. J. Geochem. Explor., 88: 6-9.
Chakroun HK, Souissi F, Bouchardon JL, Souissi R, Moutte J, Faure O, Remon E, Abdeljaoued S (2010). Transfer and accumulation of lead, zinc, cadmium and copper in plants growing in abandoned mining-district area. Afr. J. Environ. Sci. Technol., 4(10): 651-659.
Charef A, Bouhlel S, Sheppard SMF (1987).The stratabound Pb-Zn deposit and salt bearing diaper of Fedj el Hadoum (Northern Tunisia Geological frame, fluid inclusions, isotopic data and genetic model 8th Regional meeting of sedimentology, pp. 145-146.
Chiu KK, Ye ZH, Wong MH (2006). Growth of Vetiveria zizanioides and *Phragmities australis* on Pb/Zn and Cu mine tailings amended with manure compost and sewage sludge: A greenhouse study. Bioresour. Technol., 97(1): 158-170.
Concas A , Ardau C, Cristini A, Zuddas P, Cao G (2006). Mobility of heavy metals from tailings to stream waters in a mining activity contaminated site. Chemosphere, 63(2): 244-253.
Conesa H M, Faz A, Arnaldos R (2007). Initial studies for the phytostabilization of a mine tailing from the Cartagena-La Union Mining District (SE Spain). Chemosphere, 66: 38-44.
Doumett S, Lamperi L, Checchini L, Azzarello E, Mugnai S, Mancuso S, Petruzzelli G, Del Bubba M (2008). Heavy metal distribution between contaminated soil and *Paulownia tomentosa*, in a pilot-scale assisted phytoremediation study: Influence of different complexing agents. Chemosphere, 72(10): 1481-1490.
Fuerstenau MC (1976). Flotation, A.I.M.E, New York, Ist edition, 621 p.
Haneef M, Yanful EK (2003). Tailings erosion and resuspension in two mine tailings ponds due to wind waves. Adv. Environ. Res., 7: 745-765.
Havre H (1952). Mechanical preparation and concentrations of minerals by flotation and on dense liquors, 2nd edition, Paris, 759 p.
Henin S (1983). Trace elements in soil. A.F.E.S.2 Newslett., pp. 67-71.
Herrera-Urbina R, Sotillo FJ, Fuerstenau DW (1999). Effect of sodium sulfide additions on the pulp potential and amyl xanthate flotation of cerussite and galena. Int. J. Miner. Process. 55(3): 157-170.
Hesketh AH, Broadhurst JL, Harrison STL (2010). Mitigating the generation of acid mine drainage from copper sulfide tailings impoundments in perpetuity: A case study for an integrated management strategy. Min. Eng., 23(3): 225-229.
National Institute of Standardization and Industrial Property INNORPI (2002). Fertilizers, slurry and treatment of municipal wastewater. NT 106.20520021, p. 12.
National Institute of Standardization and Industrial Property INNORPI (2003a). Soil quality, vocabulary. Part 1: Terms and definitions related to the protection and soil pollution. NT, p. 91. 10 p.
National Institute of Standardization and Industrial Property INNORPI (2003b). Soil quality, vocabulary. Part 4: Terms and definitions related to rehabilitation of soils and sites. NT 91. 12 p.
National Institute of Standardization and Industrial Property INNORPI (2003c). Soil quality: Extraction of trace elements soluble in nitrohydrochloric solution, NT 91.33 p.
Jacob DL, Otte ML (2004a). Long-term effects of submergence and wetland vegetation on metals in a 90-year old abandoned Pb-Zn mine tailings pond. Environ. Pollut., 130(3): 337-345.
Jacob DL, Otte ML (2004b). Influence of Typha latifolia and fertilization on metal mobility in two different Pb-Zn mine tailings types. Sci. Total Environ., 333(1-3): 9-24.
Jang A, Kim S (2000). Technical note solidification and stabilization of Pb, Zn, Cd and cu in tailing wastes using cement and fly ash. Min. Eng., 13(14-15): 1659-1662.
Jiménez EM, Penalosa JM, Manzano R, Carpena-Ruiz RO, Gamarra R, Esteban E (2009). Heavy metals distribution in soils surrounding an abandoned mine in NW Madrid (Spain) and their transference to wild flora. J. Hazard. Mater., 162: 854-859.
Kabata-Pendias A (2004).Soil–plant transfer of trace elements - An environmental issue. Geoderma, 122(2-4): 143–149.
Kassaa S (1990). Thermo-optical characterization and physico-chemical fluid inclusions in minerals, application to celestite from the transition zone of Fedj Lahdoum Pb-Zn mine (Northern Tunisia). Master, FST, 76 p.
Kock D, Schippers A (2006). Geomicrobiological investigation of two different mine waste tailings generating acid mine drainage. Hydrometallurgy, 83(1-4): 167-175.
Kovacs E, Dubbin WE, Tamas J (2006). Influence of hydrology on heavy metal speciation and mobility in a Pb-Zn mine tailing. Environ. Pollut., 141: 310-320.
Laatar E (1980). Lead-zinc deposits and saline Triassic diapirism in northern Tunisia: Concentrations peridiapiric of Nefate Fedj El-Adoum mining district (Tebousouk region). Ph.D, Univ.Pierre and Marie Curie (Paris VI). 234 p + appendices.
Lan CY, Shu WS, Wang MH (1998). Reclamation of pb/zn mine tailings at Shaoguan, Guangdong province, People's Republic of china: The role of river sediment and domestic refuse. Biores. Technol., 65: 117-124.
Lawrence RW, Poling GP, Marchant PB (1991). Acid rock drainage prediction manuel. Report on DSS Contract No. 23440-9-9149/01-SQ, Energy Mines and Resources, Canada, MEND/NEDEM project 1.16.1b.
Lee CG, Chon HT, Jung MC (2001). Heavy metal contamination in the vicinity of the daduk Au–Ag–Pb–Zn mine in Korea. Appl. Geochem., 16: 1377-1386.
Liao G, Liao D, Li Q (2008). Effect of solids concentration on removal of heavy metals from mine tailings via bioleaching. Trans. Non Ferrous. Met. Soc. China, 18: 207-211.
Liu Y, Zhang H-Z , Zeng G-M, Huang B-R, Li X (2006). Heavy Metal Accumulation in Plants on Mn Mine Tailings. Pedosphere, 16(1): 131-136.
Liu YG, Zhou M, Zeng GM, Li X, Xu WH, Fan T (2007). Effect of solids concentration on removal of heavy metals from mine tailings via bioleaching. J. Hazard. Mater., 141(1): 202–208.
López Valdivieso A, Sánchez López AA, Ojeda Escamilla C, Fuerstenau MC (2006). Flotation and depression control of arsenopyrite through pH and pulp redox using xanthate as the collector. Int. J. Min. Process., 81(1): 27-34.
Mason LJ, Rice NM (2002). The adaptation of *Thiobacillus ferrooxidans* for the treatment of nickel–iron sulphide concentrates. Min. Eng., 15 (11): 795-808.
Miller JR, Hudson-Edwards KA, Lechler PJ, Prestond D, Mackline MG (2004). Heavy metal contamination of water, soil and produce within riverine communities of the Rio Pilcomayo basin, Bolivia. Sci. Tot. Environ., 320: 189–209.
Perthuisot V (1981). Diapirism in northern Tunisia. J. Struct. Geol., 3: 231-235.

Pichtel J, Kuroiwa K, Sawyer HT (2000). Distribution of Pb, Cd and Ba in soils and plants of two contaminated sites. Environ. Pollut., 110(1): 171-178.

Pinte F (2000). The acid mine drainage. Note BRGM, p. 12.

Pratas J, Prasad MNV, Freitas H, Conde L (2005). Plants growing in abandoned mines of Portugal are useful for biogeochemical exploration of arsenic, antimony, tungsten and mine reclamation. J. Geochem. Explor., 85(3): 99-107.

Rashed MN (2010). Monitoring of contaminated toxic and heavy metals, from mine tailings through age accumulation, in soil and some wild plants at Southeast Egypt. J. Hazard. Mater., 178: 739-746.

Ritcey GM (1989). Tailings management: Problems and solutions in the mining industry. Amsterdam: Elsevier, p. 970.

Rodriguez L, Ruiz E, Alonso- Azcarate J, Rincon J (2009). Heavy metal distribution and chemical speciation in tailings and soils around a Pb–Zn mine in Spain. J. Environ. Manage., 90(2): 1106-1111.

Rosler HJ, Lange H (1972). Geochemical tables. Ed.Elsevier, New York.

Ruttens A, Colpaert JV, Mench M, Boisson J, Carleer R, Vangronsveld J (2006). Phytostabilization of a metal contaminated sandy soil. II: Influence of compost and/or inorganic metal immobilizing soil amendments on metal leaching. Environ. Pollut., 144(2): 533-539.

Sainfeld P(1952). The lead-zinc deposits of Tunisia. Annals of Mines and Geology N°9. S.E.F.A.N.Tunis, 252 p.

Schindler PW, Liechti P, Westall JC (1987). Adsorption of copper, cadmium and lead from aqueous solution to the kaolinite water interface. Netherlands J. Agric. Sci., 35: 219-230.

Schippera PNM, Bonten LTC, Plette ACC, Moolenaard SW (2008). Measures to diminish leaching of heavy metals to surface waters from agricultural soils. Desalination, 226(1-3): 89–96.

Sebei A (2007). Impacts of mining wastes on the environment, cases watershed of Wadi Mellegue and Tessa (Northern Tunisia). Ph.D Thesis. FST, 259 p.

Sima M, Doldb B, Frei L, Senilad M, Balteanua D, Zobrist J (2011). Sulfide oxidation and acid mine drainage formation within two active tailings impoundments in the Golden Quadrangle of the Apuseni Mountains, Romania. J. Hazard. Mater., 189(3): 624-639.

Simon M, Martin F, Ortiz I, Garcia I, Fernandez J, Fernandez E, Dorronsoro C, Aguilar J (2001). Soil pollution by oxidation of tailings from toxic spill of a pyrite mine. Sci. Total Environ., 279(1-3): 63-74.

Smuda J, Dold B, Spangenberg JE, Pfeifer HR (2008). Geochemistry and stable isotope composition of fresh alkaline porphyry copper tailings: Implications on sources and mobility of elements during transport and early stages of deposition. Chem. Geol., 256(1-2): 62-76.

Taylor MD, Percival HJ (2001). Cadmium in soil solutions from a transect of soils away from a fertilizer bin. Environ. Pollut., 113(1): 35-40.

Toulhoat P (1996). Chemical evolution of the deep water and surface water. The Techniques, Special Issue "Mines and Quarries", Dec., 96: 26-29.

Vangronsveld J, Van Assche F, Clijsters H (1995). Reclamation of a bare industrial area contaminated by non-ferrous metals: *In situ* metal immobilization and revegetation. Environ. Pollut., 87(1): 51-59.

Vila JM, Ghanmi M, Ben Youssef M (2001). The "salt glaciers" underwater of passive continental margin in the northeast of the Maghreb (Algeria, Tunisia) and the Gulf Coast (USA): Comparisons, special view on the "salt glaciers" composite illustrated by that of Fedj el Adoum (Northwest Tunisia) and global review. Ecloga geol. Helv. In Ghanmi M (2003). Geodynamics of the Saharan platform and its northern margin during the Cretaceous. Its evolution towards the northern Atlas, interference of rifting and halokinesis. University accreditation, Geology Specialty. FST, 347 p.

Wang J, Zhang CB, Jin ZX (2009). The distribution and phytoavailability of heavy metal fraction in rhizosphère soils of Paulowniu fortunei (seem) Hems near a Pb/Zn smelter in Guangdong, PR China. Geoderma, 148 (3-4): 299-306.

Wang X, Liu Y, Zeng G, Chai L, Xiao X, Song X, Min Z (2008). Pedological characteristics of Mn mine tailings and metal accumulation by native plants. Chemosphere, 72 (9): 1260-1266.

Wei C, Wang C, Yang L (2009). Characterizing spatiam distribution and sources of heavy metals in the soils from mining–smelting activities in Shuikoushan, Hunan province, China. J. Environ. Sci., 21(9): 1230-1236.

Winde F, van der Walt IJ (2004). The significance of groundwater–stream interactions and fluctuating stream chemistry on waterborne uranium contamination of streams - A case study from a gold mining site in South Africa. J. Hydrol., 287(1-4): 178-196.

Wong MH (2003). Ecological restoration of mine degraded soil, with emphasis on metal contaminated soils. Chemosphere, 50(6): 775–780.

Yang B, Shu WS, Ye ZH, Lan CY, Wong MH (2003). Growth and metal accumulation in vetiver and two Sesbania species on lead/zinc mine tailings. Chemosphere, 52(9): 1593–1600.

Yanqun Z, Yuana L, Schvartzc CH, Langladec L, Fand L (2004). Accumulation of Pb, Cd, Cu and Zn in plants and hyperaccumulator choice in Lanping lead–zinc mine area, China. Environ. Int., 30(4): 567-576.

Zhongming L, Ji-Wei Y, Ivars N (1997). Removal of Pb (II), Cd(II) and Cr(III) from sand by electromigration. J. Hazard. Mater., 55(1-3): 295-304.