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Analyzing Soil Pollution: Heavy Metals in Setif City Region Using ICP-OES Technique

Said Lifa[1,2], Seifeddine Sellami[3*], Ouahida Zeghouan[4], Omar Tebboub[5,6], Fares Zaamouche[2,7]

[1] Research Unit of Environmental Chemistry and Molecular Structural (CHEMS), University of the Brothers Mentouri—Constantine 1, 25000 Constantine, Algeria
[2] Mines Institute, University of Echikh Echahid Larbi Tébessi, 12002 Tebessa, Algeria
[3] Faculty of Process Engineering, Salah Boubnider University—Constantine 3, 25000 Constantine, Algeria
[4] Division Bioindustry, Biotechnology Research Center, 25000 Constantine, Algeria
[5] Department of SM, Faculty of SESNV, Echahid Cheikh Larbi Tebessi University, 12002 Tebessa, Algeria
[6] Research Unit, Valorisation of Natural Resources, Bioactive Molecules and Physicochemical and Biological Analysis (VARENBIOMOL), University of Brothers Mentouri—Constantine 1, 25000 Constantine, Algeria
[7] Laboratory of Signals and Smart Systems, Echahid Cheikh Larbi Tebessi University, 12002 Tebessa, Algeria

[*] Correspondence: Seifeddine Sellami (seifeddine.sellami@univ-constantine3.dz)

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Abstract: Heavy metal contamination is a serious issue that poses a significant threat to soil environments and human health worldwide. The rapid population growth in developing countries, together with challenging economic conditions, has led to uncontrolled urbanization. These activities have become major sources of environmental pollution, affecting soil, water, and air quality. The objective of this study was to analyze the concentration of heavy metals in the soil of Setif City. To achieve this objective, 16 soil samples were collected using a regular 3 $\times$ 3 km grid across the region. Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) was used to analyze these samples, and their pH , organic matter (OM), and limestone ($CaCO_3$) levels were also determined to assess their physical and chemical properties. Zinc (Zn), Copper (Cu), Nickel (Ni), and Cadmium (Cd) were selected as representative heavy metals for the study. The sixteen diffractograms obtained from powder X-ray diffraction (XRD) analysis showed the presence of calcite and quartz, along with elements such as Cd, Zn, Cu, and Ni . The results indicate that the soils in Setif City are alkaline, with pH values ranging from 8.00 to 8.47. The average concentrations of Zn, Cu, Ni, and Cd were 407.06, 55.85, 32.21, and 0.16 mg kg^{-1}, respectively, in the sixteen soil samples collected from Setif City. When compared with international standards (e.g., AFNOR NF X31-101 and CEPA), Zn concentrations in several samples exceeded acceptable thresholds, indicating moderate to high levels of contamination in specific zones. This finding is supported by the geoaccumulation index (Igeo) and contamination factor (Cf), both of which identified Zn as the main pollutant of concern. Contrary to the initial assumption of no contamination, the study reveals that localized Zn accumulation may pose potential environmental risks, highlighting the need for continuous monitoring and site-specific remediation strategies

Keywords: Setif; Pollution; Heavy metals; ICP-OES; XRD; Igeo; Cf

1 Introduction

While heavy metals are critical to humans, human activities have caused dangerously high levels of some elements to build up in certain places. The buildup of heavy metals, primarily in soil, is a major environmental concern because it can release toxic metals into living organisms [1, 2]. Heavy metals are highly harmful to both human health and ecosystems, as they can accumulate in the food chain and lead to serious health issues. Understanding their sources and impacts is essential for developing effective remediation strategies and protecting public health. These substances are harmful to humans, animals, microorganisms, and plants [3, 4].

These metals are non-biodegradable and have a long biological half-life, meaning they do not decompose over time. Once these metals contaminate the soil, mitigating their harmful effects becomes particularly challenging. If these metals are available to plants, toxic metals can accumulate in vegetation, posing a threat to humans and animals consuming them through the food chain [5–8].

Additionally, heavy metals can readily transfer into the atmosphere and groundwater. As a result, metal pollution increases the risk of exposure, whether through inhalation or ingestion of contaminated environments. Soil plays a crucial role as a substrate for many industrial, agricultural, and urban activities [9, 10]. Trace metals, also known as heavy metals, enter the soil through natural processes such as weathering and erosion of parent rocks and mineral deposits. Moreover, human activities such as industrial operations, urban areas (heating, wastewater, sewage sludge), transportation (roads, waterways), and agriculture (use of fertilizers and herbicides) also contribute to the release of these metals into the soil [11–14].

Pollution can be classified into two distinct categories. The first is point-source pollution, usually localized to a specific area and often caused by agricultural, industrial, and urban activities. The second category is non-point source pollution, which spreads regionally, with the primary vector often being atmospheric (thermal fumes, metallurgical factories, etc.) [15–18]. The increasing levels of heavy metals play a significant role as either nutrients or toxic elements in the biosphere [19–21].

The accumulation of heavy metals can reach toxic levels depending on the state of the environment [22, 23]. Zinc (Zn), Copper (Cu), and Cadmium (Cd) were selected as representative heavy metals, as their levels in the environment provide a reliable indicator of environmental pollution [24, 25]. These metals play a crucial role in the environmental ecosystem. Several techniques are used to analyze heavy metals in soils, including X-ray Diffraction (XRD), Total X-ray Fluorescence (TXRF), and Anodic Stripping Voltammetry (ASV), as well as Atomic Absorption Spectrophotometry (AAS). XRD, in particular, allows the determination of the mineralogical composition of samples by identifying crystalline phases, offering essential information to assess the interactions between heavy metals and soil [26, 27].

Despite the global concern regarding heavy metal contamination, research focusing on Setif, Algeria, remains limited. Setif is one of the most important agricultural and industrial regions in northeastern Algeria, where rapid urbanization, fertilizer use, and industrial activities may increase the risk of soil pollution. However, few studies have systematically quantified heavy metal concentrations in Setif's soils, and even fewer have employed advanced spectroscopic methods. In particular, the combined application of Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) for quantitative metal analysis and XRD for mineralogical characterization has not been adequately addressed in this region. This study aims to fill this gap by assessing the levels of Zn, Cu, Ni, and Cd in Setif soils using ICP-OES, while also considering the mineralogical background obtained through XRD.

The study's goal was to evaluate the use of ICP-OES to determine the concentrations of Zn, Cu, Ni, and Cd in sixteen soil samples collected from the city of Setif [28].

2 Materials and Methods

2.1 Study Area

Setif is one of the largest cities in northeastern Algeria. Located at an altitude of 1,080 meters, Setif lies on the High Plateaus separating the northern and southern Atlas Mountains, approximately 300 kilometers from Algiers and about 100 km from the Mediterranean coast. As the third-largest city in Algeria after Algiers and Oran, the city is known for its rich history, vibrant culture, and significant agricultural contributions. With a diverse population, Setif also boasts historical landmarks such as the ancient ruins of Timgad and offers captivating scenic views of the surrounding mountains.

The city covers an area of 127.3 km^2 and had a population of 1,686,845 inhabitants as of October 2022. Setif's geographical location results in a continental climate, with relatively cold winters and hot summers.

As a crossroads city, Setif is distinguished by notable urban expansion, driven by a combination of spatial and socioeconomic factors [29].

2.2 Sampling

As illustrated in Figure 1, a total of 16 surface soil samples (0–5 cm) were collected across the city of Setif during March and April 2024, representing various land uses, including industrial, residential, and recreational sectors [30].

Table 1 presents the GPS data and descriptions of the sampling sites. Using a stainless-steel scoop, surface soil samples were systematically collected using a regular 3 × 3 km grid across the study area, placed in polyethylene bags, and properly labeled. GPS devices were used to record the precise longitude and latitude of each sampling site.

Air-dried surface soil samples were homogenized using a pestle and mortar. The homogenized samples were then passed through a 2 mm mesh sieve and stored in polyethylene bags [31, 32].

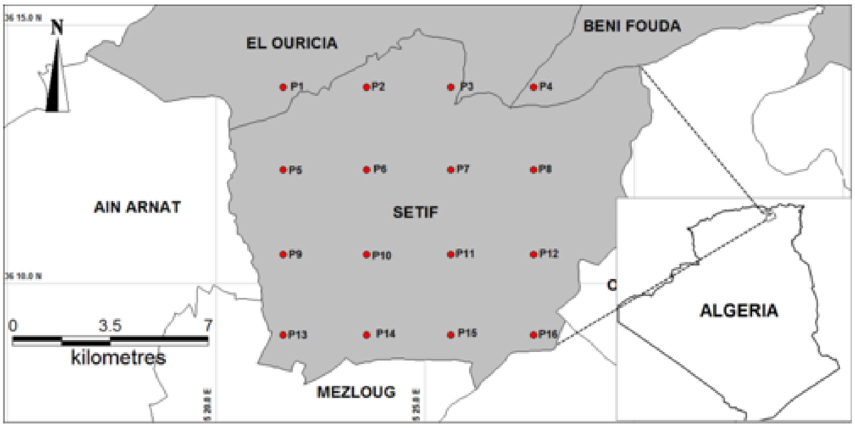

Figure 1. Sampling points of 16 soil samples from the Setif City region Algeria

Table 1. Description of 16 soil samples from the Setif City region Algeria

Sites	N Latitude	E Longitude
P01	36°13′48.00	5°21′36.00
P02	36°13′48.00	5°23′35.62
P03	36°13′48.00	5°25′36.68
P04	36°13′48.00	5°27′36.00
P05	36°12′11.95	5°21′36.00
P06	36°12′11.95	5°23′35.62
P07	36°12′11.95	5°25′36.68
P08	36°12′11.95	5°27′36.00
P09	36°10′33.94	5°21′36.00
P10	36°10′33.94	5°23′35.62
P11	36°10′33.94	5°25′36.68
P12	36°10′33.94	5°27′36.00
P13	36°09′00.00	5°21′36.00
P14	36°09′00.00	5°23′35.62
P15	36°09′00.00	5°25′36.68
P16	36°09′00.00	5°27′36.00

2.3 Physico-Chemical Analyses

Physical and chemical properties, including pH, OM, and $CaCO_3$, were determined in the samples [33].

Following two hours of stirring, the pH of the soil samples was measured using a pH meter in a 1:5 soil-water suspension [34].

The commonly used modified Walker-Black (WB) method was applied to determine OM content [35].

The Bernard calcimetry technique was employed to measure the $CaCO_3$ content.

Room-temperature XRD data were recorded for the sixteen samples using a PANalytical diffractometer.

All measurements were performed over an angular range of 5°–80° (2θ), with a step size of 0.025° (2θ) and a counting time of 5 seconds per step [36].

2.4 Soil Digestion

Based on the EPA Method 3051A developed by the U.S. Environmental Protection Agency [37], the soil samples underwent laboratory digestion using a microwave-assisted aqua regia digestion procedure. The process involved refluxing the samples. The digestion block was gradually heated from ambient temperature to 180°C, and the procedure continued until approximately 1 mL of acid remained.

After dilution of the digestion products with 10 mL of distilled water, the solutions were filtered through cellulose filter paper with a 0.45 μm pore size [37].

2.5 Instrumentation and Analysis

An inductively coupled plasma optical emission spectrophotometer (ICP-OES, Horiba Jobin-Yvon Ultima 2 CE) was used for the analysis of the elements Zn, Cu, Ni, and Cd [38]. Table 2 presents the specific instrumental operating parameters.

Table 2. ICP-OES instrumental operating conditions

Parameter	
RF generator power (W)	1200
Frequency of RF generator (MHz)	40.68
Plasma gas flow rate (l/min)	12
Auxiliary gas flow rate (l/min)	0.2
Nebulization gas flow rate (l/min)	0.85
Sample uptake rate (ml/min)	1
Type of detector	Solid state
Type of spray chamber	Cyclonic
Injector tube diameter (mm)	0.3
Measurement replicates	3
Element (λ/nm)	As 193.695; Ba 233.527 Cd 228.802; Co 228.616 Cr 267.716; Cu 324.754 Fe 259.939 ; Mn 257.610 Mo 202.301; Ni 231.604 Pb 220.353; Se 196.026 Sr 407.771; Zn 213.856

3 Results and Discussion

3.1 Soil pH

A crucial factor regulating metal chemical behavior, as well as other major soil processes, is pH. Table 3 shows the relatively wide variation in soil pH values in the Setif area, which range between 8.00 and 8.47. As shown in Figure 2, most of the soils exhibited pH values above 8.0. The presence of carbonates in the soil helps to explain its alkalinity [39, 40].

Table 3. pH of 16 soil samples from the Setif City region

Sites	pH
P01	8.18
P02	8.07
P03	8.30
P04	8.08
P05	8.47
P06	8.34
P07	8.00
P08	8.09
P09	8.18
P10	8.36
P11	8.38
P12	8.21
P13	8.14
P14	8.17
P15	8.11
P16	8.26

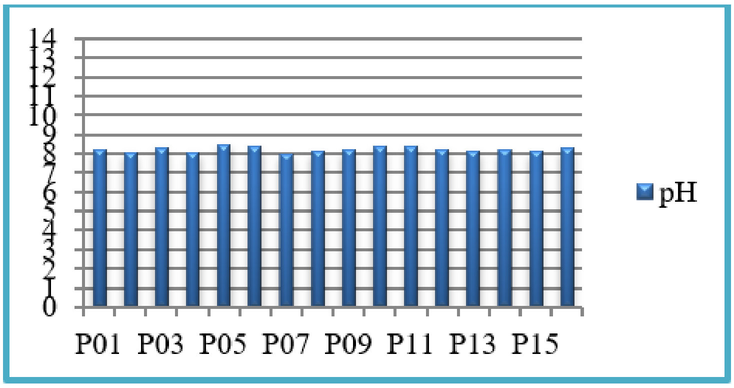

Figure 2. Soils pH in Setif City

The values for OM and $CaCO_3$ are summarized in Table 4.

Table 4. Physical and chemical characteristics MO and $CaCO_3$ 16 soil samples from the Setif City region

Sites	Organic Matter (%)	$CaCO_3$ (%)
P01	1.34	35.95
P02	0.28	37.48
P03	1.06	22.47
P04	0.96	34.83
P05	0.57	44.94
P06	1.34	35,95
P07	1.6	23.60
P08	1.45	43.82
P09	0.47	35.95
P10	0.96	38.20
P11	0.66	43.82
P12	2.32	33.70
P13	1.54	20.22
P14	1.45	30.33
P15	1.34	22.47
P16	1.06	33.70

For OM, the minimum, maximum, and average values were 0.28, 2.32, and 1.15, respectively. The abundance of plant and animal waste present in the topsoil layer likely accounts for the observed variation in OM content [41].

As shown in Figure 3, the minimum, maximum, and average values for $CaCO_3$ were 20.22, 44.94, and 33.59, respectively [42].

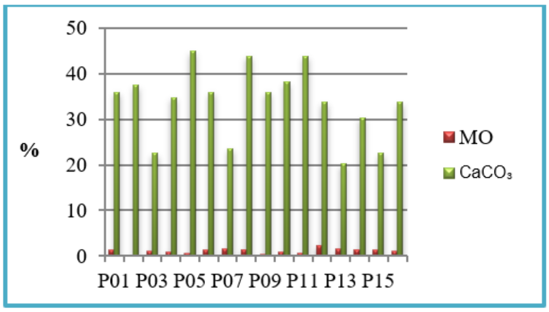

Figure 3. Soil physicochemical properties of Setif City top soils

3.2 Spectroscopic Analyses

3.2.1 X-ray diffraction (XRD)

Every diffractogram was analyzed to identify the phases present in the soils of the Setif region. The results revealed the presence of elements including Cd, Zn, Cu, and Ni in all samples, as well as calcite and quartz [43]. In addition, elements such as Fe, Ge, Se, and Mo were detected in several diffractograms.

Figure 4 illustrates the phase identification of sample 05.

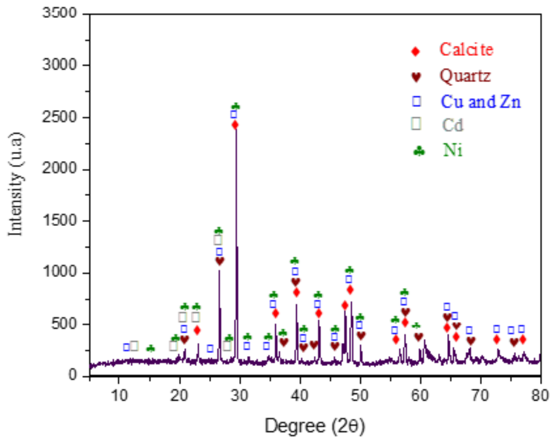

Figure 4. Identification of the phases in sample 05

The following phases were identified: the calcite phase, with characteristic peaks at $2\theta = 23.06°, 29.39°, 31.43°$, and $35.95°$, corresponding to reflections (102), (104), (006), and (110) (ICDD-PDF No. 96-900-9669), and the quartz phase, with characteristic peaks at $2\theta = 20.83°, 26.60°, 36.50°$, and $39.41°$, corresponding to reflections (100), (101), (110), and (102) (ICDD-PDF No. 96-901-0145).

Additionally, the presence of elements Cd, Zn, Cu, and Ni was observed in all diffractograms, with varying relative intensities. Cd is characterized by peaks at $2\theta = 12.53°, 19.88°, 20.83°$, and $23.06°$, corresponding to reflections (-203), (82-3), (51-5), and (44-4) (ICDD-PDF No. 96-723-7903) associated with the $C_{38}Cd_2N_{12}O_8$ phase.

Zn and Cu exhibit peaks at $2\theta = 11.77°, 20.83°, 25.29°$, and $29.39°$, corresponding to reflections (110), (112), (122), and (222) (ICDD-PDF No. 96-900-1251) attributed to the $Cu_{9.36}Fe_{3.56}Ge_{1.62}S_{16}Zn$ phase. Finally, Ni is identified by peaks at $2\theta = 16.23°, 19.88°, 20.83°$, and $23.06°$, corresponding to reflections (-111), (1-13), (0-14), and (005) (ICDD-PDF No. 96-710-0027) related to the $C_9H_4N_{0.5}NiS_{11}$ phase.

The mineralogical composition also influences metal mobility. Calcite, due to its alkaline buffering capacity, enhances the retention of heavy metals through adsorption and precipitation, whereas quartz, being chemically inert, exhibits limited retention capacity, potentially facilitating the mobility of metals in soil.

3.3 Concentrations of Trace Metals

Table 5 summarizes the minimum, average, and maximum concentrations of the investigated trace elements (Zn, Cu, Ni, and Cd) in the soils [44].

Table 5. Concentrations of heavy metals (mg kg^{-1}) in the soil of Setif City region

Sites	Concentration			
	Zn	Cu	Ni	Cd
P01	381.65	50.45	20.06	0.10
P02	246.15	36.12	35.47	0.30
P03	350.55	50.83	26.34	0.15
P04	184.55	46.69	15.92	0.25
P05	344.25	60.71	31.03	0.16
P06	222.85	49.11	21.60	0.01
P07	438.15	65.39	25.09	0.17
P08	443.65	48.75	36.01	0.23
P09	533.85	47.39	41.96	0.18
P10	428.25	62.87	36.98	0.06
P11	407.65	55.04	28.08	0.29
P12	399.85	61.41	44.00	0.07
P13	416.25	56.99	38.17	0.08
P14	458.25	53.53	27.14	0.14
P15	568.95	61.97	47.75	0.20
P16	688.25	86.42	39.81	0.18
Interval	184.55–688.25	36.12–86.42	15.92–47.75	0.01–0.3
Mean	407.06	55.85	32.21	0.16
Background values	59.5	22.2	122	0.2
Regulatory limit	300	100	50	2

With an average concentration of 407.06 mg kg^{-1}, Zn levels in the soils of Setif City range from 184.55 to 689.25 mg kg^{-1}; the regulatory limit is 300 mg kg^{-1}. Concentrations reached up to 689.25 mg kg^{-1} at locations P07, P08, P09, P10, P15 , and P16 , resulting in 68.75% of the sampling sites exceeding this limit, as illustrated in Figure 5.

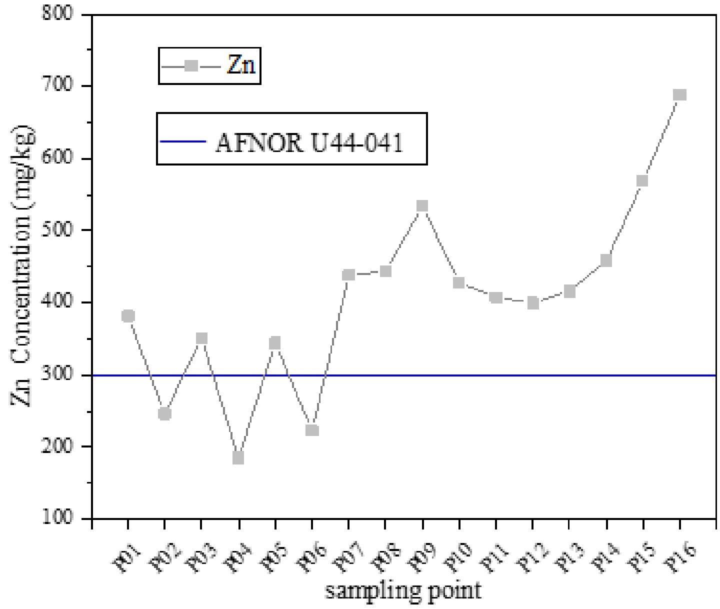

Figure 5. Zn concentration in 16 soil samples from the Setif City region

With an average concentration of 55.85 mg kg^{-1}, Cu levels in the soils of Setif City range from 36.12 to 86.42 mg kg^{-1}. The regulatory limit is 100 mg kg^{-1}. Although certain sites, such as P16, exhibit relatively high values, reaching 86.42 mg kg^{-1}, none of the samples exceeded this limit, as shown in Figure 6.

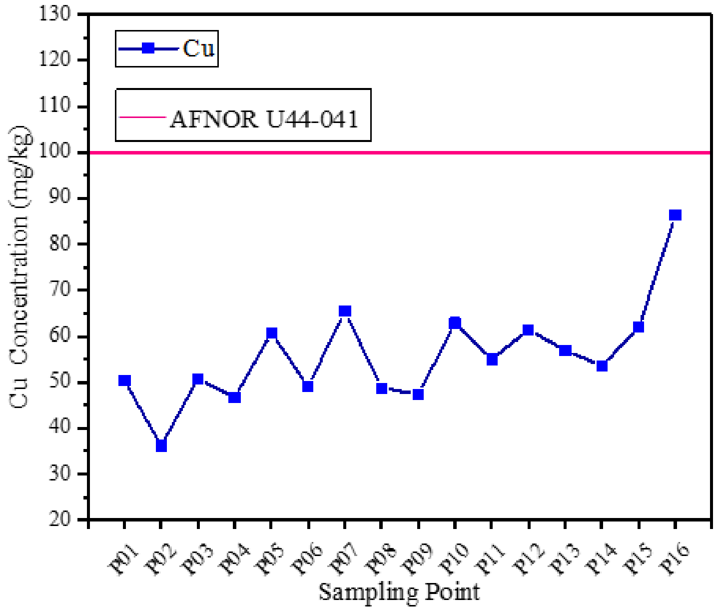

Figure 6. Cu concentration in 16 soil samples from the Setif City region

With an average concentration of 32.21 mg kg^{-1}, Ni contents in the soils of Setif City range from 15.92 to 47.75 mg kg^{-1}. Ni has a regulatory limit of 50 mg kg^{-1}. Although sites P15 and P16 approach this threshold, with values of 47.75 mg kg^{-1} and 39.81 mg kg^{-1}, respectively, as shown in Figure 7, none of the sites exceeded this limit.

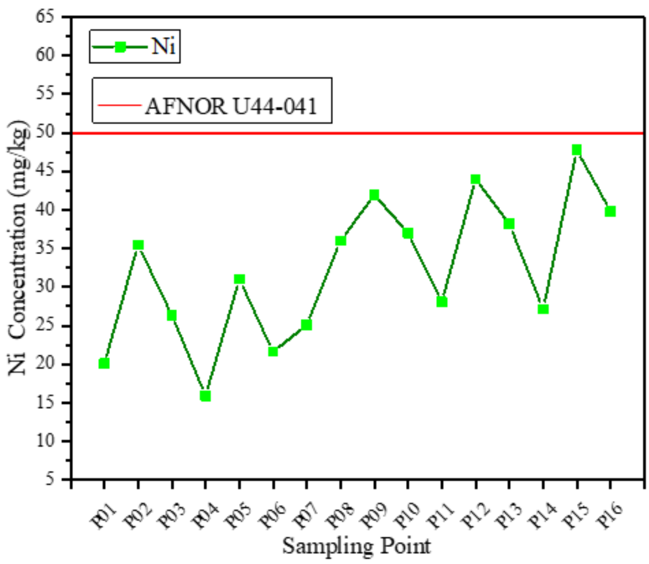

Figure 7. Ni concentration in 16 soil samples from the Setif City region

With an average concentration of 0.16 mg kg^{-1}, Cd contents in the soils of Setif City range from 0.01 to 0.30 mg kg^{-1}. Cd has a regulatory limit of 2 mg kg^{-1}. With concentrations between 0.01 mg kg^{-1} and 0.30 mg kg^{-1}, all samples remain well below this limit, as shown in Figure 8 [45].

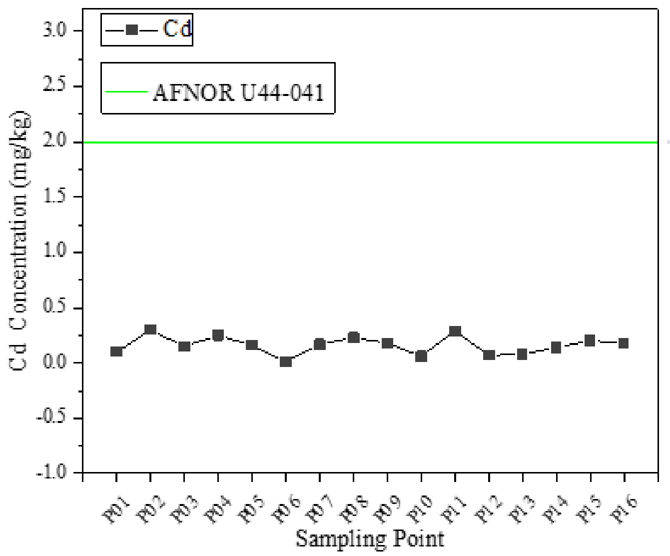

Figure 8. Cd concentration in 16 soil samples from the Setif City region

3.4 Geo-Accumulation Index (Igeo)

The Igeo is used to assess the degree of soil or sediment pollution by trace metals. It is calculated by comparing the measured metal concentration with its natural geochemical background value [46–49]. The index was proposed by Müller in the 1970s and is calculated using the following formula:

$$\text{Igeo} = \log_2(\text{Cn}/(1.5 \times \text{Bn}))$$

where,
- Cn is the concentration of the metal in the sample,
- Bn is the geochemical background concentration (natural level in the soil), and
- 1.5 is a correction factor accounting for natural variations in the geochemical background.

Table 6 presents the values of the Igeo for Zn, Cu, Ni, and Cd at the sixteen sampling points (P01 to P16). The Igeo index is commonly applied to evaluate the degree of soil or sediment contamination relative to a natural geochemical reference level.

Pollution levels are classified according to predefined thresholds as follows: an Igeo value of ≤ 0 indicates no pollution, whereas values between 0 and 1 correspond to unpolluted to lightly polluted conditions. When Igeo values range between 1 and 2, pollution is considered moderate, while values between 2 and 3 indicate moderate to high pollution. An Igeo value between 3 and 4 reflects strong pollution, and values ranging from 4 to 5 indicate very high pollution. Finally, an Igeo value greater than 5 denotes extremely high pollution [50, 51].

Table 6. Igeo of 16 soil samples from the Setif City region

Sites	Igeo			
	Zn	**Cu**	**Ni**	**Cd**
P01	2.10	0.60	-3.19	-1.58
P02	1.46	0.12	-2.37	0.00
P03	1.97	0.61	-2.80	-1.00
P04	1.05	0.49	-3.52	-0.26
P05	1.95	0.87	-2.56	-0.91
P06	1.32	0.56	-3.08	-4.91
P07	2.30	0.97	-2.87	-0.82
P08	2.31	0.55	-2.35	-0.38
P09	2.58	0.51	-2.12	-0.74
P10	2.26	0.92	-2.31	-2.32
P11	2.19	0.72	-2.70	-0.05
P12	2.16	0.88	-2.06	-2.10
P13	2.22	0.78	-2.26	-1.91
P14	2.36	0.68	-2.75	-1.10
P15	2.67	0.90	-1.94	-0.58
P16	2.95	1.38	-2.20	-0.74
Min	1.05	0.12	-3.52	-4.91
Max	2.95	1.38	-1.94	0
Mean	2.11	0.72	-2.56	-1.21

For Zn, the Igeo values range from 1.05 to 2.95, with an average of 2.12, indicating moderate to high pollution. Approximately 31.25% of the sampling points exhibit moderate pollution, such as P02 (1.46) and P06 (1.32), while 68.75% of the points, including P16 with an index of 2.95, show moderate to high pollution.

For Cu, the Igeo values range from 0.12 to 1.38, with an average of 0.72. Cu pollution levels are lower than those of Zn, with 93.75% of the points showing no to light pollution, whereas 6.25%, such as P16 (1.38), exhibit moderate pollution.

Regarding Ni, the Igeo values are negative, ranging from -3.52 to -1.94, with an average of -2.57, indicating the absence of nickel pollution across all sampled areas. These negative values, observed at 100% of the sampling points, indicate that nickel concentrations are below natural background levels, reflecting no contamination.

Finally, for Cd, the Igeo values range from -4.91 to 0, with an average of -1.21. The majority of the sampling points (93.75%) show negative values, indicating no pollution. However, 6.25% of the points, such as P02, exhibit an index value of 0, suggesting the presence of very low Cd traces without actual contamination [52–55].

Figure 9 illustrates the Igeo for the four investigated metals.

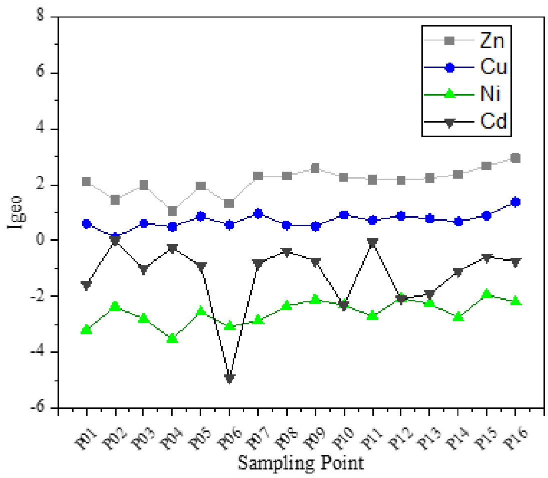

Figure 9. Igeo of 16 soil samples from the Setif City region

3.5 Contamination Factor (Cf)

The Cf is used to evaluate the level of pollution by comparing the concentration of heavy metals or other contaminants in environmental samples, such as soil, sediments, or water, with their natural background concentrations [56–59]. It helps identify the degree of contamination by relating the measured metal concentration to its natural reference value.

The Cf is calculated using the following formula:

$$\mathrm{Cf} = \mathrm{Cn}/\mathrm{Bn}$$

where,

• Cn is the measured concentration of the element in the sample, and

• Bn is the geochemical background concentration of the element in uncontaminated soil.

Table 7 presents the Cf values for the investigated trace metals (Zn, Cu, Ni, and Cd) measured at the sixteen sampling points (P01 to P16). The Cf is commonly used to assess each metal's impact relative to its natural background level, thereby determining the intensity of pollution.

A Cf value below 1 indicates low pollution, whereas values between 1 and 3 suggest moderate pollution. Significant pollution is indicated by Cf values ranging from 3 to 6, while values greater than or equal to 6 indicate extremely high pollution [60, 61].

Table 7. Cf of 16 soil samples from the Setif City region

Sites	Cf			
	Zn	**Cu**	**Ni**	**Cd**
P01	6.41	2.27	0.16	0.50
P02	4.13	1.62	0.29	1.50
P03	5.89	2.28	0.21	0.75
P04	3.10	2.10	0.13	1.25
P05	5.78	2.73	0.25	0.80
P06	3.74	2.21	0.17	0.05
P07	7.36	2.94	0.20	0.85
P08	7.45	2.19	0.29	1.15
P09	8.97	2.13	0.34	0.90
P10	7.19	2.83	0.30	0.30
P11	6.85	2.47	0.23	1.45
P12	6.72	2.76	0.36	0.35
P13	6.99	2.56	0.31	0.40
P14	7.70	2.41	0.22	0.70
P15	9.56	2.79	0.39	1.00
P16	11.56	3.89	0.32	0.90
Min	3.1	1.62	0.13	0.05
Max	11.56	3.89	0.39	1.5
Mean	6.83	2.51	0.26	0.80

For Zn, the Cf values range from 3.10 to 11.56, with an average of 6.83, indicating pollution levels ranging from moderate to very high. Approximately 31.25% of the sampling points exhibit moderate to high contamination, such as P03 (5.89) and P05 (5.78), while 68.75% of the points, including P16 (11.56), show very high contamination.

For Cu, the Cf values range from 1.62 to 3.89, with an average of 2.51, indicating moderate contamination. Approximately 93.75% of the sampling points exhibit moderate pollution, except for P16 (3.89), which shows moderate to high contamination.

For Ni, the Cf values are relatively low, ranging from 0.13 to 0.39, with an average of 0.26, indicating negligible to very low pollution across 100% of the sampling points.

Finally, for Cd, the Cf values range from 0.05 to 1.50, with an average of 0.80. Cd pollution levels are generally low, with 68.75% of the points showing low contamination and 31.25%, such as P02 and P11, exhibiting moderate contamination [62–64].

Figure 10 presents the Cf for the investigated metals.

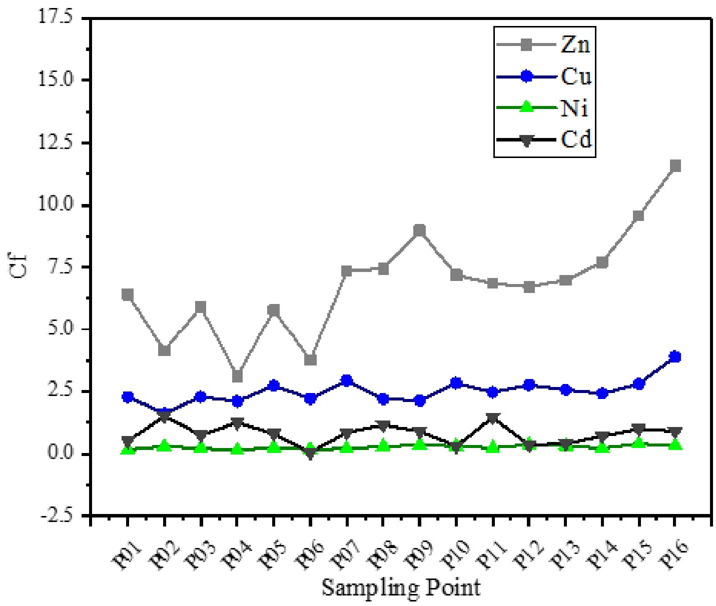

Figure 10. Cf of 16 soil samples from the Setif City region

The dominance of Zn contamination is most likely linked to anthropogenic sources, including the use of phosphate fertilizers, industrial emissions, and urban traffic. In contrast, Ni and Cd exhibit negligible pollution, reflecting their lower anthropogenic inputs and greater geochemical stabilization under alkaline conditions. Cu contamination, although moderate, may also originate from agricultural practices and industrial activities.

4 Conclusion

Generally alkaline in character, the soils under investigation exhibit pH values ranging from 8.00 to 8.47. With an average value of 1.15, OM contents range from 0.28 to 2.32, most likely derived from plant and animal litter present in the topsoil layers. The minimum, maximum, and average values for $CaCO_3$ are 20.22, 44.94, and 33.59, respectively.

Although some values, particularly for Zn, exceed regulatory limits at sites such as P09, P14, and especially P16, suggesting potential contamination sources that should be monitored, heavy metal concentrations (Zn, Cu, Ni, and Cd) generally comply with established regulatory standards.

With concentrations generally below contamination limits, Ni and Cd exhibit no significant pollution. The Igeo for the four metals indicates moderate to high Zn pollution in certain areas, while Cu shows comparatively low contamination.

The Cf results further identify Zn as the most significant contaminant, with particularly high values at P16. Cu displays moderate contamination, with elevated values at specific locations, whereas Ni shows negligible pollution and Cd exhibits low to moderate contamination. Overall, Zn pollution represents the greatest environmental concern, followed by Cu and Cd, while Ni remains minimally affected.

This study confirms that Zn is the primary contaminant, likely originating from fertilizer application, industrial activities, and traffic emissions. Ni and Cd show limited pollution due to their greater stability under alkaline soil conditions. Cu exhibits moderate contamination, potentially associated with agricultural practices and industrial sources.

Author Contributions

Conceptualization, S.S. and S.L.; methodology, S.S. and S.L.; software, F.Z.; validation, S.S., S.L., O.T., and O.Z.; formal analysis, S.S. and S.L.; investigation, S.S. and S.L.; resources, O.Z.; data curation, F.Z.; writing—original draft preparation, S.S.; writing—review and editing, S.S., S.L., and O.Z.; visualization, S.S.; supervision, OZ.; project administration, S.S. and S.L.; funding acquisition, S.L. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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