

# Heavy Metal Contamination in Soil and Purslane (*Portulaca oleracea*) in Bassa Industrial Zone, Douala-Cameroon: Implications for Environmental Health and Ecosystem Sustainability

Roland Lemlack Londe<sup>1</sup>, Ebot Veronica Manga<sup>1</sup>, Lawrence Tatanah Nanganoa<sup>2\*</sup>, Guilen-Noel Nghokapin Tataw<sup>1</sup>, Levai Nuvadga Fofung<sup>1</sup>

<sup>1</sup>Department of Environmental Science, Faculty of Science, University of Buea, Buea, Cameroon

<sup>2</sup>Soil Section, Institute of Agricultural Research for Development, Ekona, Cameroon

Email: \*tatanah2002@yahoo.fr

**How to cite this paper:** Londe, R. L., Manga, E. V., Nanganoa, L. T., Tataw, G.-N. N., & Fofung, L. N. (2025). Heavy Metal Contamination in Soil and Purslane (*Portulaca oleracea*) in Bassa Industrial Zone, Douala-Cameroon: Implications for Environmental Health and Ecosystem Sustainability. *Journal of Geoscience and Environment Protection*, 13, 44-64.

<https://doi.org/10.4236/gep.2025.138003>

**Received:** June 28, 2025

**Accepted:** August 15, 2025

**Published:** August 18, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

## Abstract

The contamination of soils with heavy metals (HMs) and their accumulation in local plants has become an increasing issue because of industrial activities. This study investigated the extent of HMs contamination in soils and Purslane (*Portulaca oleracea*) in the Bassa Industrial Zone, Douala-Cameroon, focusing on the implications for environmental health and ecosystem sustainability. We collected 17 surface soil samples and 4 composite purslane leaf samples from different sampling locations in the industrial site. The HMs (Cd, Pb, As, Cr, Cu and Ni) were analyzed with an Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES). The results revealed that, the HM concentrations (except for Cd and Ni) in most locations exceeded the Soil Quality Guidelines for industrial land use. The Pollution Load Index confirmed the presence of heavy metal pollution in all the sample locations. Potential Ecological Risk Index highlighted varying levels of risk across locations, presenting moderate, high, and significantly high ecological risk. The primary contributors to ecological risk were Pb, Cd, and Cu. Furthermore, the geo-accumulation index revealed heavily to extremely high contamination in several locations. Principal Component Analysis suggested that Cd, As, Cr, Cu, and Ni likely originated from common sources, while Pb had a distinct source, all due to anthropogenic activities. Additionally, Cr concentrations in purslane leaves exceeded the normal range, with one location recording a value ( $5.41 \text{ mg kg}^{-1}$ ) which was within the maximum toxicity threshold for plants. These findings underline the need

---

for remedial measures to mitigate the adverse effects of heavy metal contamination in the Bassa Industrial Zone.

## Keywords

Ecological Risk Index, Heavy Metals, Pollution Load Index, *Portulaca oleracea*, Soil Contamination

---

## 1. Introduction

Heavy metal (HM) contamination of soil and plants poses a significant threat to both environmental health and ecosystem sustainability, particularly in industrial areas where anthropogenic activities can lead to elevated concentrations of toxic metals (Angon et al., 2024; Sharafi & Salehi, 2025). In fact, among the many environmental issues faced by urban centres in developing countries, waste management and its impact on soil quality has become particularly obvious in recent years (Rouhani & Hejzman, 2024). It is common to observe the disposal of various substances into the environment without any treatment. Heavy metals tend to persist in the environment for long periods, often accumulating in soils, making it difficult to remediate contaminated sites (Briffa et al., 2020). Over time, heavy metals can leach into nearby water sources, impacting aquatic ecosystems and biodiversity (Khushbu et al., 2022). The toxicity of these metals is reflected by their characteristics, such as their solubility and bioavailability in the soil, which may differ among metals, depending on their molecular structures (Siebielec et al., 2006).

The Bassa industrial zone in Douala, Cameroon, (managed by Industrial Zones Development and Management Authority (MAGZI)) characterized by high industrial activity and urbanization, represents a hotspot for potential environmental pollution. This city, with its unplanned urban infrastructure, inadequate water supply, and poor sanitation system, has created a situation where most industries and households discharge their waste and effluents directly into the environment without any prior treatment (Boum-Nkot et al., 2023). Eventually, heavy metals are released into the environment and build up in the soil (Balkhaira & Ashraf, 2016). The soils may also become contaminated by the accumulation of heavy metals through emissions from the industries.

Plants are primary producers in terrestrial ecosystems and, as such, they can continuously absorb and accumulate metals, either deposited from the atmosphere through stomata and stem wounds or dissolved in the soil through their roots. (Subpiramanyam, 2021). Various edible plants have been reported to accumulate these metals at high levels, either with or without exhibiting toxic symptoms. One of such plants is Purslane (*Portulaca oleracea*) (Yousefi et al., 2023). Purslane, a widely distributed and hardy plant species, has been recognized for its ability to accumulate heavy metals from the soil, making it an effective bio-indicator of contamination levels (Subpiramanyam, 2021). Purslane is a succulent,

edible plant that is commonly found growing as a weed in many parts of the world. It has thick, fleshy leaves and stems, and its small, yellow flowers bloom typically in the summer. Purslane is known for its slightly sour, lemony flavour and is often used in salads, soups, or as a garnish in various cuisines. It is highly nutritious, being rich in omega-3 fatty acids, vitamins A, C, and several B vitamins, as well as minerals like magnesium, calcium, and iron. Due to its high nutritional value, purslane is often considered a super food. Purslane grows well in poor soil and is drought-tolerant, making it a hardy plant that thrives in a variety of environments, from gardens to roadsides. In addition to its culinary uses, purslane has also been used in traditional medicine for its purported anti-inflammatory and antioxidant properties. It is ranked eighth as “most common plant in the world” (Liu et al., 2000) and ranked twelfth as “non-cultivating species well colonized in new areas” (Kale et al., 2015).

Understanding the extent of heavy metal pollution in both soil and plants is critical for assessing potential risks to public health and the surrounding ecosystem (Das et al., 2023). Metals such as lead (Pb), cadmium (Cd), chromium (Cr), Copper (Cu), Nickel (Ni), and arsenic (As) are particularly concerning due to their toxicity and persistence in the environment. These contaminants can enter the food chain, resulting in adverse health effects for both humans and wildlife (Mitra et al., 2022). Therefore, it is essential to monitor the concentrations of these metals in urban and industrial zones to ensure public safety and to guide sustainable land management practices.

This study aimed to assess the levels of heavy metal contamination in both soil and Purslane (*Portulaca oleracea*) in the Bassa industrial zone, Douala, and to explore the potential implications for environmental health and ecosystem sustainability. The findings of this research will contribute to a better understanding of pollution dynamics in the zone and inform strategies for mitigating the risks posed by industrial contaminants in urban environments.

## 2. Materials and Methods

### 2.1. Description of the Study Area

The Bassa Industrial Zone is located in Douala 3 in the Wouri Division of the Littoral Region of Cameroon. It hosts a variety of industrial activities, including manufacturing, chemical production, and transportation and has the highest level of industrial activities in Cameroon (Asaah et al., 2006). The area (coordinates at the outlet are 4°01'40.64"N and 9°44'10.13"E, altitudes < 100 m) is in the low coastal areas of Cameroon. The climate is of the tropical monsoon type, hot and humid, with two distinct seasons: a rainy season from mid-March to mid-November and a dry season from mid-November to mid-March. Temperatures range from 18°C to 34°C, with annual average rainfall of about 4000 mm (Charleine et al., 2024).

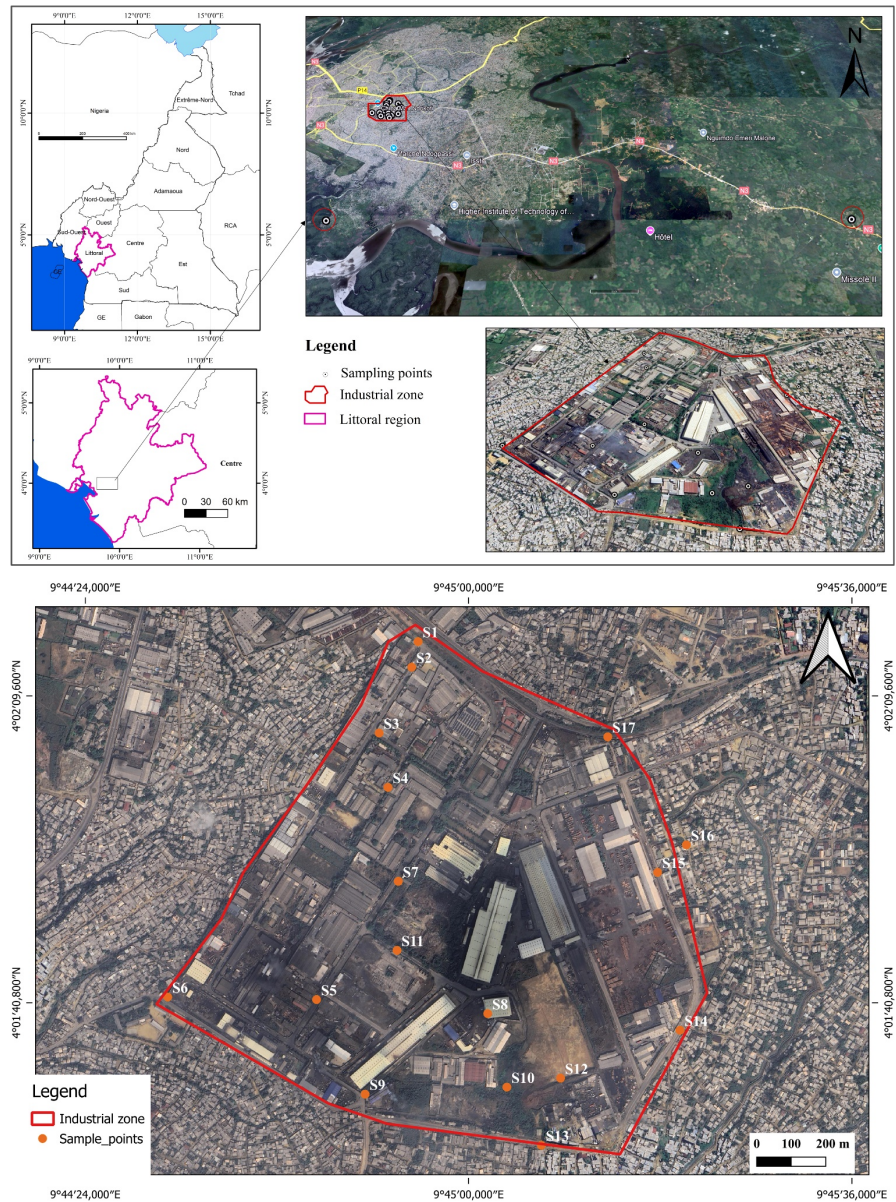
The geology of the site is characterized by sedimentary rock from the tertiary to quaternary sediments (Asaah et al., 2006) and area consists dominantly of sand stones with a few intercalations of limestone and shale.

## 2.2. Soil and Plant Samples Collection and Analysis

Soil samples were collected from 17 sampling locations within the month of April. At each location, 10 sub-samples were randomly collected using a Manual stainless steel auger to a depth of 0 - 15 cm. The 10 sub-samples were thoroughly mixed and bulked to form a composite sample representing that sampling location. Three control composite soil samples (Mean value reported) were collected from uncontaminated sites few kilometres from the industrial zone to provide a baseline against which the experimental samples were compared. This allowed for the identification of any variations in heavy metal concentrations that may be attributed to contamination rather than natural variability. In addition, all control sites were confirmed to have sandy clay loam soils, similar in texture, drainage properties, and parent material to the soils within the industrial zone. This similarity minimizes variability due to natural soil characteristics and strengthens confidence in the background metal concentrations used for pollution assessment. Purslane (*Portulaca oleracea*) plant samples were also collected around the soil sampling points. Plant samples of locations with similar environment were bulk giving a total of 4 composite plant samples. These samples were further separated to collect the leaves. All sampling sites were geo-located with a global positioning system receiver. **Figure 1** shows the distribution of sampling points. The soil and leaf samples were sent to the laboratory for analysis. Soil samples were air-dried and ground to pass through a 2 mm sieve and were further fine ground to pass through a 0.5 mm sieve for organic carbon analysis. Plant samples were cleaned and oven dried at 60°C for 48 hours and ground to a fine powder. Soil samples were extracted using aqua regia (a mixture of hydrochloric and nitric acids) solution (ISO 11466, 1995) and the plant samples with concentrated nitric acid (Jones & Case, 1990). Heavy metals in the soil digest (Cd, Pb, As, Cu, Cr, Ni) and plant digest (Cd, Pb, As, Cu, Cr) were measured by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP - OES). Soil pH in water was determined in a 1:2.5 (w/v) soil:water suspension, organic carbon by chromic acid digestion and spectrophotometric method (Heanes, 1984) and the particle size distribution by the hydrometer method (Bouyoucos, 1951). Soil organic matter (SOM) was calculated by multiplying organic carbon (OC) by 1.724 ( $SOM(\%) = OC(\%) \times 1.724$ ) as described by Allison (1965).

## 2.3. Quality control (QC)

The present study adopted a strict QC program. Four external reference soil and plant samples, one certified soil sample from international soil exchange program and one standard plant reference sample from National Institute of Standards and Technology (NIST) were also included in every batch. The Instrument was calibrated with certified standards. All chemicals used were of analytical reagent grade with high purity, and all solutions were prepared using deionised water.



**Figure 1.** Location of Douala-Bassa industrial zone and distribution of sampling points.

## 2.4. Assessment of Soil Contamination

The assessment of HMs in soil was evaluated by the following quantitative indices: contamination factor (CF), pollution load index (PLI), ecological risk factor (Er), potential ecological risk index (PERI) and geoaccumulation index ( $I_{geo}$ ) (Mugoša et al., 2016).

*Contamination factor (CF):* This represents the ratio of an individual metal value to the background values in soil. It is calculated as:  $CF = C_{metal} / C_{background}$ . The CF value monitors the HM enrichment in soil over a period of time. A CF value  $\geq 6$  represents high contamination,  $3 \leq CF < 6$ , is considerable,  $1 \leq CF < 3$  is moderate, and  $CF < 1$  shows low contamination of a given metal (Ferreira et al., 2022).

*Geoaccumulation index ( $I_{geo}$ ):* The geoaccumulation index ( $I_{geo}$ ) matrix could be applied to assess soil pollution.  $I_{geo}$  values for soils are calculated as:  $I_{geo} = \text{Log}_2(C_n/1.5B_n)$ , where  $C_n$  is the soil concentration of metal  $n$ ; and  $B_n$  is the background geochemical value of element  $n$ . In this case,  $B_n$  is the control value. The classification used to estimate the pollution level of the calculated Geoaccumulation index ( $I_{geo}$ ) is:  $I_{geo}$  value  $\leq 0$  (unpolluted),  $I_{geo}$  values between 0 and 1 (unpolluted-moderately polluted),  $I_{geo}$  values between 1 and 2 (moderately polluted),  $I_{geo}$  values between 2 and 3 (moderately-strongly polluted),  $I_{geo}$  value between 3 and 4 (strongly polluted),  $I_{geo}$  value between 4 and 5 (strongly-extremely polluted),  $I_{geo}$  value  $> 5$  (extremely pollution) (Okoro et al., 2020).

*Pollution load index (PLI):* Quality of soil is evaluated via the pollution load index. It is defined as the  $n^{\text{th}}$  root of the metal multiplications of the contamination factor ( $\text{PLI} = \left[ (\text{CF}_1 \times \text{CF}_2 \times \text{CF}_3 \times \dots \times \text{CF}_n)^{\frac{1}{n}} \right]$ ). This index classifies the soil into three categories, which are: Polluted ( $\text{PLI} > 1$ ), Baseline levels of pollution ( $\text{PLI} = 1$ ) and, Not polluted ( $\text{PLI} < 1$ ) (Ferreira et al., 2022).

*Ecological risk factor (Er):* It presents the ecological risk of a chemical element on soil studied. The equation was suggested by Hakanson (1980). It is expressed as:  $E_r = \text{CF}_i \times T_i$ , where  $T_i$  is the toxic-response factor for a given substance, and  $\text{CF}$  is the contamination factor. The  $T_i$  values of these HMs by Håkanson are such that: Cd is 30; As is 10; Cu, Pb and Ni is 5; and Cr is 2. This index classifies the chemical element in five categories:  $E_r < 40$ , low;  $40 E_r < 80$ , moderate;  $80 E_r < 160$ , considerable;  $160 E_r < 320$ , high; and  $E_r > 320$ , very high (Ferreira et al., 2022).

*The potential ecological risk index (PERI):* It is determined by the sum of the risk factors ( $\text{PERI} = \sum E_r$ ). To describe the PERI, the following terminology were used:  $\text{PERI} < 150$ , low risk;  $150 < \text{PERI} < 300$ , moderate;  $300 < \text{PERI} < 600$ , considerable;  $\text{PERI} \geq 600$ , very high (Ferreira et al., 2022).

## 2.5. Data Analysis

The soil and plant data were analysed statistically using Microsoft Excel 2016 and JMP 16 Statistical Software (SAS Institute). Heavy metal levels in the soil samples were examined through descriptive statistics (mean, median, standard deviation, minimum, and maximum values), and their variability was assessed using the coefficient of variation (CV). Less than 20% CV is regarded as low variability, between 20 and 50% CV is regarded as moderate variability, and between 50 and 100% CV is regarded as high variability. Any CV above 100% is regarded as very high variability (Phil-Eze, 2010; Nanganoo et al., 2020). Pearson's correlation was conducted to determine the key parameters influencing soil chemistry, with statistical significance set at a p-value less than 0.05. Factor analysis was carried out to describe the degree of association and identify possible sources of metals in the soil samples. The principal components were extracted with eigenvalues  $>1$  through a varimax rotation.

### 3. Results and Discussion

#### 3.1. Summary Statistics of Soil Properties

In the Douala-Bassa industrial zone, the SOM contents ranged from 1.22 to 2.99%, with a mean value of 1.86%. The soil pH ranged from 5.43 to 7.87, with an average value of 7.07, indicating that the soil in this area is neutral (Table 1). These soils have higher pH values as compared to the control site which was strongly acidic (4.76). This increase in soil pH might be due to HM such as Ni and Cr in the soil, making them more alkaline (Angon et al., 2024). The average EC of the soils was 148.16  $\mu\text{s}/\text{cm}$ , ranging from 57.8 to 295  $\mu\text{s}/\text{cm}$  and was also higher than that of the control (28.20  $\mu\text{s}/\text{cm}$ ). Electrical conductivity (EC) in heavy metal contaminated soils is generally higher compared to clean soil due to the increased presence of charged ions from the heavy metals, which readily conduct electricity when dissolved in soil moisture (Gomaa et al., 2020; Mboga et al., 2025). According to the USDA textural diagram, the studied soils had sandy clay loam texture with the exception of sample points S10 and S13 that were sandy loam (Figure 2). The predominant fraction is sand with an average value of 70.97%. The silt fraction is low with an average of 5.66%, while the clay fraction has an average of 23.37%. No variation in the content of sand, silt, and clay was observed with control site as compared to the study site, and so, the textures of the soils were similar and fall within the sandy clay loam textural class. Soils of this textural class are typically characterized by high porosity and permeability, which can promote the migration of heavy metals into the surrounding environment (Makuleke & Ngole-Jeme, 2020).

**Table 1.** Summary statistics for soils characteristics and concentrations of heavy metals in surfaces soils in the study area.

Sampling sites	Parameters									
	pH	EC	Org C	SOM	Cd	Pb	As	Cr	Cu	Ni
	-	$\mu\text{s}/\text{cm}$	%	%	$\text{mg kg}^{-1}$					
S1	6.97	104.10	0.80	1.37	2.00	101.05	13.78	57.49	23.42	20.958
S2	7.22	168.40	0.91	1.57	2.42	57.80	20.43	58.81	47.54	18.449
S3	7.75	129.70	1.01	1.74	1.00	45.40	20.13	61.67	49.63	16.874
S4	7.24	189.70	0.89	1.52	0.07	612.48	17.72	46.60	20.82	13.959
S5	7.18	90.60	0.77	1.32	0.09	644.36	15.92	45.38	21.51	10.792
S6	7.43	158.70	0.91	1.56	0.05	406.30	14.14	42.99	16.96	19.42
S7	7.38	151.70	1.14	1.96	0.03	128.19	19.72	57.00	26.69	19.051
S8	7.79	295.00	0.98	1.69	5.48	826.88	28.41	113.15	93.34	35.888
S9	7.54	139.70	1.25	2.15	0.02	133.08	19.64	55.39	19.04	14.062
S10	7.87	171.00	1.74	2.99	0.14	343.49	7.99	38.98	16.37	9.045
S11	6.71	157.00	1.30	2.32	0.03	1491.28	20.51	61.12	24.76	15.574

Continued

S12	6.24	94.70	1.48	2.55	0.01	19.14	12.81	35.28	8.92	5.124
S13	6.97	138.20	1.33	2.28	0.09	20.25	10.24	29.96	7.70	5.084
S14	7.00	187.40	0.96	1.66	0.03	11.05	13.70	36.61	11.86	6
S15	7.58	140.60	1.33	2.28	0.02	243.76	21.23	58.52	30.10	19.185
S16	5.87	117.70	0.71	1.22	0.02	28.67	14.21	49.77	10.18	11.537
S17	5.43	57.80	0.95	1.63	0.09	35.08	18.87	51.36	11.32	11.372
Control site	4.76	28.20	0.80	1.38	0.09	0.59	9.08	26.12	2.80	3.05
Total	120.17	2492	18.46	31.81	11.59	5148.26	289.45	900.08	440.16	252.37
Minimum	5.43	57.8	0.71	1.22	0.01	11.05	7.99	29.96	7.7	5.08
Maximum	7.87	295	1.74	2.99	5.48	1491.28	28.41	113.15	93.34	35.89
Mean	7.07	146.59	1.09	1.87	0.68	302.84	17.03	52.95	25.89	14.85
Median	7.22	140.6	0.98	1.69	0.07	128.19	17.72	51.36	20.82	14.06
SD	0.68	52.26	0.28	0.49	1.44	397.97	4.89	18.35	21.13	7.49
CV (%)	9.62	35.65	25.69	26.20	163.24	131.41	28.27	34.66	82.27	50.44

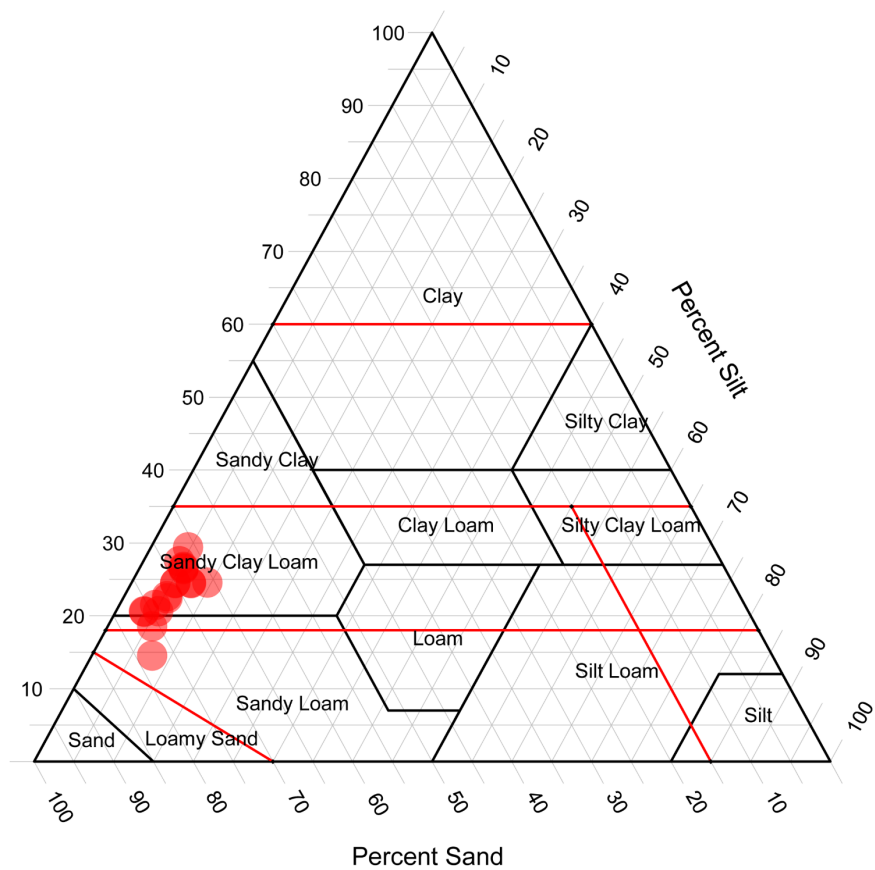


Figure 2. Soil textural class for the study site.

As shown in **Table 1**, the average concentrations of the HMs (in mg kg<sup>-1</sup>: Cd 0.65; Pb 292.65; As 16.87; Cr 52.48, Cu 25.37, and Ni 14.74) were higher than their control values with accumulations of 622.22%; 49501.69%; 85.79%; 100.92%; 806.07%; and 383.28% respectively. Pb is the largest accumulated element in this soil, with maximum value of 1491.28 mg·kg<sup>-1</sup> and the metal order in the soil was Pb > Cr > Cu > As > Ni > Cd. **Tian et al. (2020)** also reported high accumulation of Pb in sediments from the coastal areas of the Bohai Sea. The CV value of Cd (215.38%) and Pb (132.75%) were very high. Cu had a high CV (81.28%), while As (28.39%), Cr (37.94%), and Ni (49.39%) had moderate CVs in the soils. The high coefficient of variation observed in the spatial distribution of heavy metals likely reflects the heterogeneity in industrial pollution sources, with different industries contributing pollutants in distinct ways. Such variability is commonly associated with localized or point-source pollution resulting from anthropogenic activities. However, this study is limited by its focus on a single sampling season and the surface soil, which may not capture seasonal or vertical variability in metal concentrations.

### 3.2. Assessment of Soil Contamination

An attempt was made to compare Cd, Pb, As, Cr, Cu, and Ni concentrations in the soils against Soil quality guidelines for Environmental Health for total metal concentrations for industrial land use (**CCME, 2007**). The highest concentrations of Cd and Ni in this study were within the maximum allowable Limits. However, the concentration of Pb, As, Cr, and Cu in sample location S8, including Pb and As for locations S4, S5, and S11; and As for the remaining locations (except for S10 and S13) were above the Soil Quality Guidelines for environmental health for industrial land use (**Table 2**) hence, soils were polluted and dangerous to human health and the environment (**CCME, 2007; Bermudez et al., 2010**).

**Table 2.** Soil quality guidelines for Environmental Health for total metal concentrations (mg kg<sup>-1</sup>).

Element	Cd	Pb	As	Cr	Cu	Ni
<b>Industrial Land use</b>	22	600	12	87	91	50

Thus, assessing HM pollution in these soils cannot be done solely based on the concentrations of HM. Other quantitative pollution and ecological risk indices are needed in assessing the contamination from these chemical elements in soils.

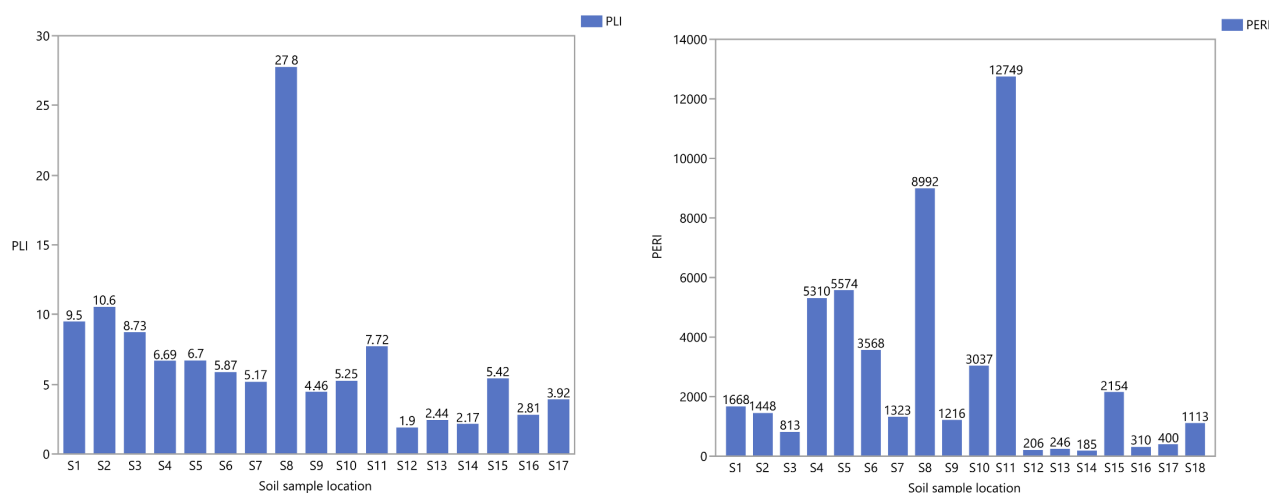
### 3.3. Contamination Factor (CF) and Pollution Load Index (PLI)

The CF results for each element is shown in **Table 3**. The highest CF values were obtained for Pb (very high contamination) with a mean CF of 497.27. Very high contamination for Cd and Cu (**Table 3**) were observed. However, for Cd, only location S1 (22.34), S2 (27.03), S3 (11.19), and S8 (61.15) were very highly con-

taminated, S10 (1.58), and S13 (1.03) were moderately contaminated and the other locations had low contamination ( $CF < 1$ ). Copper (Cu) showed considerable contamination in sample locations S12 (3.19), S14 (4.24), S16 (3.64), and S17 (4.05). The mean CF values suggested that there is moderate metal contamination ( $1 \leq CF < 3$ ) for As and Cr except for location S8 with considerable As (3.13) and Cr (4.33) contaminations. Ni recorded a considerable enrichment. However, very high contamination ( $CF \text{ value} \geq 6$ ) was obtained in S1, S2, S6-S8, and S15. The PLI values exceeded 1 in all the locations, indicating the presence of heavy metal pollution in the entire study area with location S8 recording the highest PLI value (**Figure 3**). The heavy metal enrichment particular Pb in the Douala Bassa industrial zone is primarily attributed to industrial activities that release heavy metals into the environment (Asaah et al., 2006).

**Table 3.** Contamination factor (CF) and ecological risk factor (Er), values of heavy metals in soil.

Descriptive statistics	Element					
	Cd	Pb	As	Cu	Cr	Ni
	CF					
Min	0.14	18.78	0.88	2.75	1.15	1.67
Max	61.15	2534.01	3.13	33.36	4.33	11.75
Mean	7.61	514.59	1.88	9.25	2.03	4.86
	Er					
Min	4.21	93.90	8.80	13.75	2.29	8.32
Max	1834.47	12670.03	31.30	166.78	8.66	58.77
Mean	228.41	2572.94	18.76	45.53	4.05	24.31



**Figure 3.** Pollution load index (PLI) and Ecological risk index (PERI) values of heavy metals in soil sample locations in Douala Bassa Industrial zone.

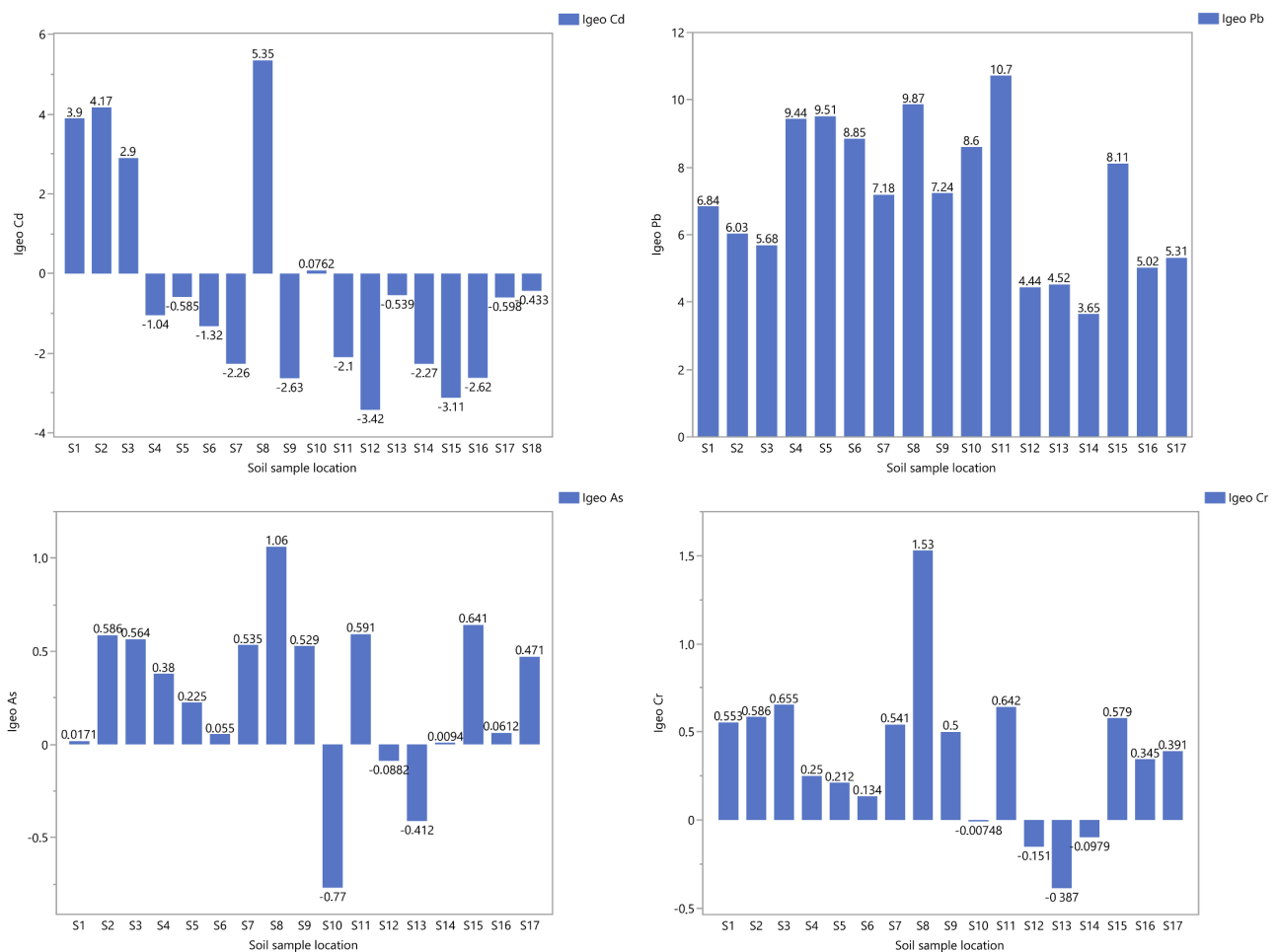
### 3.4. Ecological Risk Factor (Er) and Potential Ecological Risk Index (PERI)

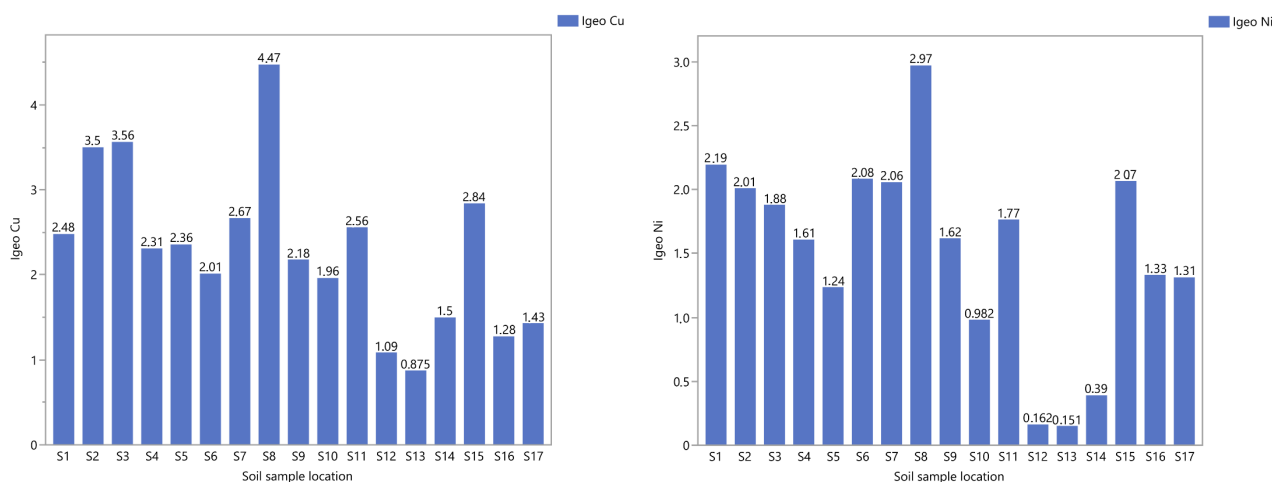
The ecological risk factor (Er) (**Table 3**) was compatible with the contamination factor. Similar observation was also made by do Nascimento Monte et al. (2021). For example, Cd, only the locations (S1, S2, S3, and S8) with very high CF values ( $CF \geq 6$ ) presented serious ecological risk ( $E_r \geq 320$ ). The Er values for As and Cr varied from 8.80 to 31.30 and 2.29 to 8.66 respectively, indicating low ecological risk from these metals (**Table 3**). Ni also presented low ecological risk except for location S8 ( $E_r = 58.77$ ) which showed moderate ecological risk. Lead (Pb) posed a very high ecological risk in comparison to any of the other elements (**Table 3**). However, Pb at S14 (93.9) had considerable ecological risk while S12 (162.64), S13 (172.06), S16 (243.6), and S17 (298) showed high ecological risk and was also consistent with the conclusions relative to the contamination factor. Results for PERI are presented in **Figure 3**. Locations S12, S13, and S14 had moderate ecological risk ( $150 < PERI < 300$ ), S16 and S17 presented high potential ecological risk ( $300 < PERI < 600$ ), and the rest of the sites showed significantly high ecological risk ( $PERI \geq 600$ ). The primary contributors to the PERI are the most toxic elements: Pb, followed by Cd and then Cu. These elevated concentrations of heavy metals, particularly Pb, Cd, and Cu, detected in the industrial zone pose serious ecological and human health risks at both local and regional scales. Locally, the accumulation of these metals in soils can degrade soil quality, reduce microbial biodiversity, and impair plant health and productivity. This, in turn, affects terrestrial food chains and may lead to bioaccumulation in herbivores and higher trophic levels. Cd, for instance, is known for its high bioavailability and toxicity to plants and soil organisms, potentially disrupting local ecosystems and agricultural viability in adjacent areas. Regionally, the risk extends through runoff and atmospheric deposition, enabling the spread of contaminants to surrounding farmland, surface waters, and residential areas. This increases the likelihood of human exposure through contaminated food crops, water sources, and air, especially in communities located near the industrial operations. The accumulation of Pb for example in soil around industries poses serious health risks to humans, particularly through ingestion and inhalation, which leads to neurological and reproductive damage (Moya & Phillips, 2014). It also harms ecosystems by disrupting plant growth, contaminating the food chain, and negatively affecting soil organisms (Collin et al., 2022). Health risks posed by Cd include kidney and bone damage, cancer, and cardiovascular issues. It is especially dangerous to vulnerable populations such as children and pregnant women. Ecologically, Cd contaminates soil and disrupts plant growth, soil organisms, and the food chain, causing long-term harm to ecosystems (Mugoša et al., 2016). Cu is an essential trace element for both humans and plants, but in excess in soil, can pose serious health risks, including liver and kidney damage, gastrointestinal issues, and neurological effects, particularly in vulnerable populations. Ecologically, excessive copper in soil can harm plant growth, reduce biodiversity, and disrupt soil ecosystems, including soil microorganisms

and invertebrates. Copper can also bio-accumulate through the food chain, affecting animals and humans (Afzal & Mahreen, 2024). The observed correlation between high metal concentrations and elevated electrical conductivity (EC) also indicates increased ion loading, which may further stress aquatic and terrestrial ecosystems in the broader region.

### 3.5. Geoaccumulation Index ( $I_{geo}$ )

Based on  $I_{geo}$ , the greatest contribution to heavy metal contamination were Pb and Cd with respectively 15 and 1 out of the 17 samples being extremely contaminated ( $I_{geo} > 5$ ) (Figure 4). Heavily to extremely contamination level ( $4 \leq I_{geo} \leq 5$ ) were obtained from Pb (S12 and S13), Cd (S2) and Cu (S8) (Figure 4). Uncontaminated to moderately contaminated class resulted from As and Cr. The Douala Bassa industrial zone was also moderately contaminated by Ni though with low ecological risk.  $I_{geo}$  also showed that, the main contaminants were Pb, followed by Cd and Cu. Asaah et al. (2006), who studied heavy metal concentrations and distribution in surface soils of Bassa industrial zone 1 of Douala, Cameroon, indicated that, the area was highly polluted in metals like Pb, Zn, Cu, Co, Sb, and to a lesser extent in Ag, Cd, Fe, Mn, Mo, and Ni. Metals like Cr and As showed moderate pollution.





**Figure 4.** Geo-accumulation index (Igeo) values of heavy metals in soil samples in Bassa Industrial zone, Douala.

### 3.6. Correlation Analysis

The Pearson correlation coefficients between the six heavy metals and other soil properties are listed in **Table 4**. Inter element relationships can provide interesting information on heavy metal sources and pathways. Cadmium (Cd) showed a significant positive correlation with As, Cr, Cu, and Ni ( $r^2 = 0.5868 - 0.8951$ ), with correlations at the 0.01 significance level for As, Cu, and Ni, and at the 0.05 level for Cr (**Table 4**). This suggests that; these metals are likely influenced by common factors and may originate from similar or related sources. Such relationships point to a multi-metal contamination scenario, where a single pollution source contributes multiple heavy metals to the environment. Additionally, the strong correlations indicate that Cd, As, Cr, Cu, and Ni may exhibit similar environmental behaviour, particularly in terms of transport and mobility in soil. The concentration of Pb did not show a significant correlation with other heavy metals (**Table 4**), which may indicate that Pb originates from different sources or follows distinct environmental pathways. Unlike more mobile metals such as Cd and Ni, Pb tends to be less mobile and more strongly bound to soil particles, potentially leading to a different spatial distribution. Additionally, Pb contamination may reflect historical pollution, in contrast to the more recent industrial inputs associated with other metals (Modrzewska & Wyszowski, 2014). EC was also significantly correlated with Cd, Cr, Cu and Ni suggesting that these metal ions contributed to the elevated EC observed in the industrial zone compared to the control site. This relationship implies that industrial discharges not only increased heavy metal concentrations but also enhanced the ionic strength of soil solutions, resulting in higher electrical conductivity. Okonkhua & Orhue (2024) also reported a positive significant correlation between HMs and EC. Soil pH and EC were also significantly correlated (**Table 4**).

### 3.7. Factor Analysis

Factor analysis with Varimax rotation was applied to the experimental data to ef-

fectively identify the potential sources (lithogenic or anthropogenic) and gain a deeper understanding of the relationships between the metals in the soils and other soil properties (Akoto et al., 2023). The PCA revealed that only two components had eigenvalues greater than 1, accounting for 74.4% of the total variance (Table 5). The first component (F1), explaining 52.07% of the variance, had high loadings for Cd, As, Cr, Cu, and Ni, indicating a strong association and likely a common anthropogenic source such as industrial effluents. In contrast, Pb showed a weak association with this factor, suggesting it may originate from a different source or exhibit distinct environmental behaviour, consistent with its lack of significant correlation with other metals. The different industries present in MAGZI, BASSA industrial zone are metal transformation, Wood, Paint, Printing, Water and Energy industries coupled with transportation.

**Table 4.** Pearson correlation matrix for the soil physicochemical properties.

	pH	EC	Org. C	SOM	Cd	Pb	As	Cr	Cu	Ni
<b>pH</b>	1									
<b>EC</b>	0.6009**	1								
<b>Org. C</b>	0.2433	0.052	1							
<b>SOM</b>	0.2353	0.0567	0.9991**	1						
<b>Cd</b>	0.3065	0.6307**	-0.2478	-0.2467	1					
<b>Pb</b>	0.1866	0.3958	0.0577	0.0883	0.1793	1				
<b>As</b>	0.1994	0.4277	-0.276	-0.2631	0.5817**	0.369	1			
<b>Cr</b>	0.3005	0.5959*	-0.2252	-0.2154	0.8436*	0.3991	0.8607**	1		
<b>Cu</b>	0.5024*	0.6846**	-0.1702	-0.1654	0.8940**	0.3102	0.7817**	0.9174**	1	
<b>Ni</b>	0.4315	0.5825*	-0.2976	-0.2931	0.7889**	0.3545	0.7689**	0.9126**	0.8538**	1

\*Correlation is significant at the 0.05 level. \*\*at the 0.01 level.

**Table 5.** Varimax-rotated factor loadings of the soil properties.

	Factors	
	F1	F2
<b>pH</b>	0.441545	0.283374
<b>EC</b>	<b>0.674991</b>	0.112011
<b>Org. C</b>	-0.088296	<b>0.996095</b>
<b>SOM</b>	-0.080446	<b>0.995852</b>
<b>Cd</b>	<b>0.856013</b>	-0.172931
<b>Pb</b>	0.396977	0.09312

## Continued

<b>As</b>	<b>0.816214</b>	<b>-0.204718</b>
<b>Cr</b>	<b>0.964519</b>	-0.140541
<b>Cu</b>	<b>0.948537</b>	-0.086764
<b>Ni</b>	<b>0.90096</b>	-0.218902
<b>Total Variance Explained</b>		
<b>Total</b>	5.2391	2.2429
<b>% of Variance</b>	52.391	22.429
<b>Cumulative %</b>	52.391	74.819

NB: High positive factor loading is shown in bold.

### 3.8. Heavy Metal Accumulation in Purslane Leaves

The bioaccumulation tendency of purslane for heavy metals (Cd, Pb, As, Cr and Cu) in the Bassa industrial zone was investigated. Plant sample 1 (PS1) was composite leaf sample from location S1 to S4; Plant sample 2 (PS2) from S5 to S12; Plant sample 3 (PS3) from locations S13 and S14; and plant sample 4 (PS4) from locations S15 to S17. The average heavy metal content in the leaf samples and their corresponding mean soil values are shown in **Table 6**. These values are reported in dry weight.

**Table 6.** Average concentrations of heavy metals in leaves and their corresponding surface soils in the study area.

Sample sites	Parameters					
	Cd	Pb	As	Cr	Cu	
	mg kg <sup>-1</sup>					
PS1	Leaf	<b>2.08</b>	<b>3.07</b>	<b>0.46</b>	<b>1.59</b>	<b>41.67</b>
	Soil	1.373	204.180	18.012	56.140	35.353
PS2	Leaf	<b>1.74</b>	<b>7.12</b>	<b>0.29</b>	<b>2.48</b>	<b>19.52</b>
	Soil	0.732	499.091	17.391	56.159	28.447
PS3	Leaf	<b>0.82</b>	<b>5.94</b>	<b>0.26</b>	<b>1.28</b>	<b>13.65</b>
	Soil	0.060	15.652	11.969	33.283	9.779
PS4	Leaf	<b>1.00</b>	<b>8.74</b>	<b>0.07</b>	<b>5.41</b>	<b>19.74</b>
	Soil	0.042	102.501	18.101	53.218	17.201

In the purslane leaf samples, the concentrations of Cd ranged from 0.82 to 2.08 mg kg<sup>-1</sup>, Pb (3.07 to 8.74 mg kg<sup>-1</sup>), As (0.07 to 0.46 mg kg<sup>-1</sup>), Cr (1.28 to 5.41 mg kg<sup>-1</sup>), and Cu (13.65 to 41.67 mg kg<sup>-1</sup>). The HMs in plant samples were in the

order Cu > Pb > Cd > Cr > As for PS1 and in the order Cu > Pb > Cr > Cd > As in PS2, PS3, and PS4. While the highest Cd value was measured in PS1 (2.08 mg kg<sup>-1</sup>), the lowest values was measured in PS3 (0.82 mg kg<sup>-1</sup>). Based on available data, the typical range of HMs in plants is as follows: Cadmium (Cd) usually between 0.01 - 0.2 mg kg<sup>-1</sup>, Lead (Pb) ranges from 5 - 10 mg kg<sup>-1</sup>, Arsenic (As) falls between 1 - 1.5 mg kg<sup>-1</sup>, Copper (Cu) is around 5 - 30 mg kg<sup>-1</sup>, and Chromium (Cr) is typically between 0.1 - 0.5 mg kg<sup>-1</sup> (Shi et al., 2023). According to these values, the Cd concentrations in this study site were higher than the normal range in plants (Table 6) (Kacálková et al., 2014). Erkoç and Çolak-Esetlili (2024), in another study, obtained 1.12 mg kg<sup>-1</sup> as their highest value of Cd in purslane leaf samples when 5 mg Cd per kg of CdSO<sub>4</sub> treatment was applied in soil pot experiment in greenhouses, followed by the applications of 20 mg kg<sup>-1</sup> Cd (0.79 mg kg<sup>-1</sup>) and 10 mg kg<sup>-1</sup> Cd (0.60 mg kg<sup>-1</sup>). Their study indicated that Cd accumulation in purslane leaves occurs up to a certain value irrespective of Cd content in the soil medium. According to literature, Pb and As values were within the normal range of this metals in plants (Table 6) (Osma et al., 2014). Despite high Pb in soil, purslane did not absorb significant amounts of Pb. Other studies have indicated that this plant fails to remove Pb when it is exposed to Pb along other heavy metals (Wei et al., 2005; Javed et al., 2018). The Pb concentrations in purslane from various locations in Istanbul were also found to be under 10 mg kg<sup>-1</sup> (Osma et al., 2014). In comparison to the typical levels of heavy metals found in plants, Cr exceeded the normal range of Cr in plants and was within the maximum toxicity threshold (Cr: 5 - 0.5 mg kg<sup>-1</sup>) with PS4 (5,41 mg kg<sup>-1</sup>) slightly higher than the upper limit (Shi et al., 2023). Only PS1 had Cu value above the normal range. Except for Cu in PS1 (41.67 mg kg<sup>-1</sup>), the Cu levels were consistent with the findings of Osma et al. (2014), where Cu concentrations in both wild-type and cultivated purslane grown at various sites in Istanbul ranged from 2 to 20 µg Cu/g. Though purslane is known to be a hyper accumulator of Cr (VI), the amount of Cr accumulated by the plant was very low as compared to report by Alyazouri et al., 2020. This low uptake of Cr might be as a result of soil pH that has a major effect on the geochemical properties of chromium by affecting the chemical speciation of the metal and the adsorption ability of the soil. In neutral-alkaline soils, like in the case of our study area, Cr (VI) exists as sparingly soluble calcium chromate thus reduce uptake by the plant. Most studies have shown that, the highest HMs accumulation was in Purslane root (Yousefi et al., 2023). Therefore, soil Neutral to alkaline pH, may have slowed movement of heavy metals to the upper extremities of the plant (Yousefi et al., 2023). Nonetheless, the use of composite plant samples masked localized differences in uptake, and ecological and human health risk estimates.

#### 4. Conclusion

The results of this study highlight significant heavy metal contamination in both the soil and purslane (*Portulaca oleracea*) across various locations in the Bassa

industrial zone of Douala, Cameroon. The Pollution Load Index (PLI) values consistently exceeded 1 across all locations, confirming the widespread presence of heavy metal pollution in the area. The Potential Ecological Risk Index (PERI) results revealed varying levels of ecological risk, from moderate risk category to high potential ecological risk, underscoring the potential adverse effects of heavy metal pollution on local ecosystems. The primary contributors to the ecological risk were Pb, followed by Cd and Cu. Chromium levels in purslane leaves exceeded the normal range and approached the maximum toxicity threshold, with the highest recorded concentration in PS4 (5.41 µg/g), slightly surpassing the upper limit. Overall, the findings of this study underscore the pressing need for remediation efforts in the Bassa industrial zone to mitigate heavy metal contamination and protect both environmental health and ecosystem sustainability. Addressing the sources of pollution, particularly those related to Pb, Cd, and Cu, is critical for reducing the ecological and human health risks posed by the contamination in this industrial area. At the site level, regular monitoring of soil, water, and biota should be implemented to track contamination trends and identify hotspots. The use of phytoremediation (e.g., hyperaccumulator plants) and soil amendments such as biochar or lime can help immobilize metals and reduce bioavailability. Regionally, stricter regulations on industrial effluent discharge, improved waste management practices, and the establishment of buffer zones between industrial and agricultural/residential areas can help limit the spread of contaminants. Furthermore, raising public awareness and conducting health surveillance in potentially affected populations can support early intervention and reduce long-term exposure risks.

## Acknowledgements

The authors wish to express their gratitude to MAGZI Bassa Industrial Zone for permission to carry out this study.

## Conflicts of Interest

The authors declare no conflict of interest.

## References

- Afzal, A., & Mahreen, N. (2024). Emerging Insights into the Impacts of Heavy Metals Exposure on Health, Reproductive and Productive Performance of Livestock. *Frontiers in Pharmacology*, 15, Article 1375137. <https://doi.org/10.3389/fphar.2024.1375137>
- Akoto, O., Yakubu, S., Ofori, L. A., Bortey-sam, N., Boadi, N. O., Horgah, J. et al. (2023). Multivariate Studies and Heavy Metal Pollution in Soil from Gold Mining Area. *Heliyon*, 9, e12661. <https://doi.org/10.1016/j.heliyon.2022.e12661>
- Allison, L. E. (1965). Organic Carbon. In A. G. Norman (Ed.), *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties* (pp. 1367-1378). American Society of Agronomy, Soil Science Society of America. <https://doi.org/10.2134/agronmonogr9.2.c39>
- Alyazouri, A., Jewsbury, R., Tayim, H., Humphreys, P., & Al-Sayah, M. H. (2020). Uptake of Chromium by *Portulaca oleracea* from Soil: Effects of Organic Content, Ph, and Sul-

- phate Concentration. *Applied and Environmental Soil Science*, 2020, Article ID: 3620726. <https://doi.org/10.1155/2020/3620726>
- Angon, P. B., Islam, M. S., KC, S., Das, A., Anjum, N., Poudel, A. et al. (2024). Sources, Effects and Present Perspectives of Heavy Metals Contamination: Soil, Plants and Human Food Chain. *Heliyon*, 10, e28357. <https://doi.org/10.1016/j.heliyon.2024.e28357>
- Asaah, V. A., Abimbola, A. F., & Suh, C. E. (2006). Heavy Metal Concentrations and Distribution in Surface Soils of the Bassa Industrial Zone 1, Douala, Cameroon. *Arabian Journal for Science and Engineering Section B: Engineering*, 31, 147-158.
- Balkhair, K. S., & Ashraf, M. A. (2016). Field Accumulation Risks of Heavy Metals in Soil and Vegetable Crop Irrigated with Sewage Water in Western Region of Saudi Arabia. *Saudi Journal of Biological Sciences*, 23, S32-S44. <https://doi.org/10.1016/j.sjbs.2015.09.023>
- Bermudez, G. M. A., Moreno, M., Invernizzi, R., Plá, R., & Pignata, M. L. (2010). Evaluating Top Soil Trace Element Pollution in the Vicinity of a Cement Plant and a Former Open-Cast Uranium Mine in Central Argentina. *Journal of Soils and Sediments*, 10, 1308-1323. <https://doi.org/10.1007/s11368-010-0243-1>
- Boum-Nkot, S. N., Nlend, B., Komba, D., Ndong, G. R. N., Bello, M., Fongoh, E. J. et al. (2023). Hydrochemistry and Assessment of Heavy Metals Groundwater Contamination in an Industrialized City of Sub-Saharan Africa (Douala, Cameroon). Implication on Human Health. *HydroResearch*, 6, 52-64. <https://doi.org/10.1016/j.hydres.2023.01.003>
- Bouyoucos, G. J. (1951). A Recalibration of the Hydrometer Method for Making Mechanical Analysis of Soils. *Agronomy Journal*, 43, 434-438. <https://doi.org/10.2134/agronj1951.00021962004300090005x>
- Briffa, J., Sinagra, E., & Blundell, R. (2020). Heavy Metal Pollution in the Environment and Their Toxicological Effects on Humans. *Heliyon*, 6, e04691. <https://doi.org/10.1016/j.heliyon.2020.e04691>
- Canadian Council of Ministers of the Environment (CCME) (2007). *Canadian Sediment Quality Guidelines for the Protection of Aquatic Life: Summary Tables. Updated. In Canadian Environmental Quality Guidelines (1999) CCME.*
- Charleine, D. S., Neculina, A., Egbe, A. M., Tabot, P. T., Bernard, T., & Ambo, F. B. (2024). Nutrient and Heavy Metal Content of Three Leafy Vegetables (*Talinum fruticosum* (L.) Juss., *Vernonia amygdalina* Delile, *Solanum macrocarpon* L.) from an Effluent-Receiving Wetland in the Douala Bassa Industrial Development Zone, Cameroon: Implications For. *Asian Pacific Journal of Environment and Cancer*, 7, 21-31. <https://doi.org/10.31557/apjec.2024.7.1.21-31>
- Collin, S., Baskar, A., Geevarghese, D. M., Ali, M. N. V. S., Bahubali, P., Choudhary, R. et al. (2022). Bioaccumulation of Lead (Pb) and Its Effects in Plants: A Review. *Journal of Hazardous Materials Letters*, 3, Article ID: 100064. <https://doi.org/10.1016/j.hazl.2022.100064>
- Das, S., Sultana, K. W., Ndhala, A. R., Mondal, M., & Chandra, I. (2023). Heavy Metal Pollution in the Environment and Its Impact on Health: Exploring Green Technology for Remediation. *Environmental Health Insights*, 17, 1-10. <https://doi.org/10.1177/11786302231201259>
- do Nascimento Monte, C., de Castro Rodrigues, A. P., de Freitas, A. R., Braz, B. F., Freire, A. S., Cordeiro, R. C. et al. (2021). Ecological Risks Associated to Trace Metals of Contaminated Sediments from a Densely Urbanized Tropical Eutrophic Estuary. *Environmental Monitoring and Assessment*, 193, Article No. 767. <https://doi.org/10.1007/s10661-021-09552-7>

- Erkoç, H. A., & Çolak Esetlili, B. (2024). Potential of Purslane (*Portulaca oleracea* L.) in Phytoremediation: A Study on the Bioaccumulation and Bio-Transfer of Cadmium, Nickel, and Copper in Contaminated Soils. *Tarım Bilimleri Dergisi*, *30*, 284-292. <https://doi.org/10.15832/ankutbd.1346861>
- Ferreira, S. L. C., da Silva, J. B., dos Santos, I. F., de Oliveira, O. M. C., Cerda, V., & Queiroz, A. F. S. (2022). Use of Pollution Indices and Ecological Risk in the Assessment of Contamination from Chemical Elements in Soils and Sediments—Practical Aspects. *Trends in Environmental Analytical Chemistry*, *35*, e00169. <https://doi.org/10.1016/j.teac.2022.e00169>
- Gomaa, M. M., Melegy, A., Metwaly, H., & Hassan, S. (2020). Geochemical and Electrical Characterization of Heavy Metals in Contaminated Soils. *Heliyon*, *6*, e04954. <https://doi.org/10.1016/j.heliyon.2020.e04954>
- Hakanson, L. (1980). An Ecological Risk Index for Aquatic Pollution Control. A Sedimentological Approach. *Water Research*, *14*, 975-1001. [https://doi.org/10.1016/0043-1354\(80\)90143-8](https://doi.org/10.1016/0043-1354(80)90143-8)
- Heanes, D. L. (1984). Determination of Total Organic-C in Soils by an Improved Chromic Acid Digestion and Spectrophotometric Procedure. *Communications in Soil Science and Plant Analysis*, *15*, 1191-1213. <https://doi.org/10.1080/00103628409367551>
- ISO 11466 (1995). *International Standard: Soil Quality-Extraction of Trace Elements Soluble in Aqua Regia*. International Organization for Standardization.
- Javed, M. T., Akram, M. S., Habib, N., Tanwir, K., Ali, Q., Niazi, N. K. et al. (2018). Deciphering the Growth, Organic Acid Exudations, and Ionic Homeostasis of *Amaranthus viridis* L. and *Portulaca oleracea* L. under Lead Chloride Stress. *Environmental Science and Pollution Research*, *25*, 2958-2971. <https://doi.org/10.1007/s11356-017-0735-2>
- Jones, B. J. J., & Case, W. V. (1990). Sampling, Handling and Analyzing Plant Tissue Samples. In R. L. Westerman (Ed.), *Soil Testing and Plant Analysis* (3rd ed., pp. 389-427). SSSA Book.
- Kacálková, L., Tlustoš, P., & Száková, J. (2014). Chromium, Nickel, Cadmium, and Lead Accumulation in Maize, Sunflower, Willow, and Poplar. *Polish Journal of Environmental Studies*, *23*, 753-761.
- Kale, R. A., Lokhande, V. H., & Ade, A. B. (2015). Investigation of Chromium Phytoremediation and Tolerance Capacity of a Weed, *Portulaca oleracea* L. in a Hydroponic System. *Water and Environment Journal*, *29*, 236-242. <https://doi.org/10.1111/wej.12106>
- Khushbu, Gulati, R., Sushma, Kour, A., & Sharma, P. (2022). Ecological Impact of Heavy Metals on Aquatic Environment with Reference to Fish and Human Health. *Journal of Applied and Natural Science*, *14*, 1471-1484. <https://doi.org/10.31018/jans.v14i4.3900>
- Liu, L., Howe, P., Zhou, Y., Xu, Z., Hocart, C., & Zhang, R. (2000). Fatty Acids and  $\beta$ -Carotene in Australian Purslane (*Portulaca oleracea*) Varieties. *Journal of Chromatography A*, *893*, 207-213. [https://doi.org/10.1016/S0021-9673\(00\)00747-0](https://doi.org/10.1016/S0021-9673(00)00747-0)
- Makuleke, P., & Ngole-Jeme, V. M. (2020). Soil Heavy Metal Distribution with Depth around a Closed Landfill and Their Uptake by *Datura stramonium*. *Applied and Environmental Soil Science*, *2020*, Article ID: 8872475. <https://doi.org/10.1155/2020/8872475>
- Mboga, V. O., Maingi, S., Gathuru, G., Waswa, A. K., & Fred, O. (2025). Environmental Safety and Management of Heavy Metals along Machakos Road, Nairobi County, Kenya. *Journal of Geoscience and Environment Protection*, *13*, 147-169. <https://doi.org/10.4236/gep.2025.136011>
- Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A. et al. (2022). Impact of Heavy Metals on the Environment and Human Health: Novel Therapeutic

- Insights to Counter the Toxicity. *Journal of King Saud University—Science*, 34, Article ID: 101865. <https://doi.org/10.1016/j.jksus.2022.101865>
- Modrzewska, B., & Wyszowski, M. (2014). Trace Metals Content in Soils along the State Road 51 (Northeastern Poland). *Environmental Monitoring and Assessment*, 186, 2589-2597. <https://doi.org/10.1007/s10661-013-3562-z>
- Moya, J., & Phillips, L. (2014). A Review of Soil and Dust Ingestion Studies for Children. *Journal of Exposure Science & Environmental Epidemiology*, 24, 545-554. <https://doi.org/10.1038/jes.2014.17>
- Mugoša, B., Đurović, D., Nedović-Vuković, M., Barjaktarović-Labović, S., & Vrvic, M. (2016). Assessment of Ecological Risk of Heavy Metal Contamination in Coastal Municipalities of Montenegro. *International Journal of Environmental Research and Public Health*, 13, Article 393. <https://doi.org/10.3390/ijerph13040393>
- Nanganoa, L. T., Ngome, F. A., Suh, C., & Basga, S. D. (2020). Assessing Soil Nutrients Variability and Adequacy for the Cultivation of Maize, Cassava, and Sorghum in Selected Agroecological Zones of Cameroon. *International Journal of Agronomy*, 2020, Article ID: 8887318. <https://doi.org/10.1155/2020/8887318>
- Okonokhua, B. O., & Orhue, E. R. (2024). Status of Heavy Metals and Remediation Potential of Indigenous Plants at Contaminated Benin City and Abudu Sites of Edo, Nigeria. *International Journal of Environment*, 13, 102-120. <https://doi.org/10.3126/ije.v13i1.70857>
- Okoro, E. E., Ochonma, C., Omeje, M., Sanni, S. E., Emetere, M. E., Orodu, K. B. et al. (2020). Radiological and Toxicity Risk Exposures of Oil Based Mud: Health Implication on Drilling Crew in Niger Delta. *Environmental Science and Pollution Research*, 27, 5387-5397. <https://doi.org/10.1007/s11356-019-07222-3>
- Osma, E., Ozyigit, I. I., Demir, G., & Yasar, U. (2014). Assessment of Some Heavy Metals in Wild Type and Cultivated Purslane (*Portulaca oleracea* L.) and Soils in Istanbul, Turkey. *Fresenius Environmental Bulletin*, 23, 2181-2189.
- Phil-Eze, P. O. (2010). Variability of Soil Properties Related to Vegetation Cover in a Tropical Rainforest Landscape. *Journal of Geography and Regional Planning*, 3, 177-184.
- Rouhani, A., & Hejman, M. (2024). A Review of Soil Pollution around Municipal Solid Waste Landfills in Iran and Comparable Instances from Other Parts of the World. *International Journal of Environmental Science and Technology*, 22, 9711-9728. <https://doi.org/10.1007/s13762-024-05728-z>
- Sharafi, S., & Salehi, F. (2025). Comprehensive Assessment of Heavy Metal (HMs) Contamination and Associated Health Risks in Agricultural Soils and Groundwater Proximal to Industrial Sites. *Scientific Reports*, 15, Article No. 7518. <https://doi.org/10.1038/s41598-025-91453-7>
- Shi, J., Qian, W., Jin, Z., Zhou, Z., Wang, X., & Yang, X. (2023). Evaluation of Soil Heavy Metals Pollution and the Phytoremediation Potential of Copper-Nickel Mine Tailings Ponds. *PLOS ONE*, 18, e0277159. <https://doi.org/10.1371/journal.pone.0277159>
- Siebielec, G., Stuczyński, T., & Korzeniowska-Puculek, R. (2006). Metal Bioavailability in Long-Term Contaminated Tarnowskie Gory Soils. *Polish Journal of Environmental Studies*, 15, 121-129.
- Subpiramanyam, S. (2021). *Portulaca oleracea* L. for Phytoremediation and Biomonitoring in Metal-Contaminated Environments. *Chemosphere*, 280, Article ID: 130784. <https://doi.org/10.1016/j.chemosphere.2021.130784>
- Tian, K., Wu, Q., Liu, P., Hu, W., Huang, B., Shi, B. et al. (2020). Ecological Risk Assessment of Heavy Metals in Sediments and Water from the Coastal Areas of the Bohai Sea

and the Yellow Sea. *Environment International*, 136, Article ID: 105512.

<https://doi.org/10.1016/j.envint.2020.105512>

Wei, S., Zhou, Q., & Wang, X. (2005). Identification of Weed Plants Excluding the Uptake of Heavy Metals. *Environment International*, 31, 829-834.

<https://doi.org/10.1016/j.envint.2005.05.045>

Yousefi, Z., Babanejad, E., Mohammadpour, R., & Noori Esbokolae, H. (2023). Evaluation of Cd Phytoremediation by *Portulaca oleracea* Irrigated by Contaminated Water. *Environmental Health Engineering and Management*, 10, 67-73.

<https://doi.org/10.34172/ehem.2023.08>