

Article

Soil Heavy Metal Contamination in the Targuist Dumpsite, North Morocco: Ecological and Health Risk Assessments

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Abstract

This study aims to assess the ecological and human health risks associated with four heavy metals (Cd, Cr, Cu, and Zn) in the soil of a dumpsite in Targuist city, Morocco. In total, 16 surface soil samples were collected from the dumpsite and its nearby areas following leaching drain flows. The pollution load index (PLI), geo-accumulation index (Igeo), and potential ecological risk index (RI) were subsequently determined. In addition, hazard quotient (HQ) and health index (HI) were used to assess the non-carcinogenic and carcinogenic risks associated with the soil heavy metal contents. The PLI indicated significant contamination by the studied heavy metals. On the other hand, the Igeo values suggested no Cr contamination, moderate contamination by Cu and Zn, and severe contamination by Cd. The RI indicated a dominant contribution from Cd, with minor contributions from Cu, Zn, and Cr accounting for 92.47, 5.44, 1.11, and 0.96%, respectively, to the potential ecological risk in the study area. The non-carcinogenic health risks associated with exposure of the nearby population to the soil heavy metals at the dumpsite and burned solid waste-derived air pollution were below the threshold value of 1 for both children and adults. Although carcinogenic risks were observed in the study area, they were acceptable for both children and adults according to the United States Environmental Protection Agency (USEPA). However, carcinogenic risks associated with Cr were unacceptable according to the Italian Legislation. Finally, strategies to mitigate the risks posed by the dumpsite were also discussed in this study.

Keywords: dumpsite; heavy metals; ecological risks; health risks; solid waste



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1. Introduction

The unregulated disposal of urban solid waste landfills in densely populated areas is increasingly becoming a significant source of environmental pollution, directly affecting the well-being of the human population in numerous low- and middle-income countries (LMICs) [1]. The rapid expansion of urban populations within these countries has led to a substantial increase in solid waste production in recent years [2]. This situation presents substantial challenges for municipalities, particularly those with small sizes or newly established, which are often faced with limited budgets and insufficient capacity to manage solid waste effectively and sustainably. This situation has been exemplified in Targuist city in the Rif Mountains of North Morocco.

The indiscriminate disposal of solid waste in uncontrolled landfills or dumpsites leads to serious pollution by toxic and carcinogenic materials, including heavy metals [3–5]. The accumulation of heavy metals in soils and pollutant emissions during waste burning constitute a major concern for public health. Heavy metals can enter the human body primarily through three exposure pathways: inhalation, ingestion, and dermal contact [6]. For instance, soils in the vicinity of waste disposal sites and surrounding areas may become heavily contaminated with toxic elements, leading to adverse health effects on nearby populations primarily through the food chain [6].

Soils are complex and multifunctional systems, where energy and matter exchanges are influenced by the lithosphere, hydrosphere, atmosphere, and biosphere [7]. Inappropriate selection of potential disposal sites in areas with relatively high soil permeability can lead to leaching of pollutants into groundwater systems [8]. For instance, heavy metals from contaminated soils can contaminate both surface water and groundwater through runoff and leaching, as well as crops, thereby directly impacting human health [9–11]. Furthermore, unregulated waste burning is often a common practice employed by the local population to reduce waste volume in dumpsites or to recover valuable materials, such as gold, copper, and silver from electronic waste (E-waste), particularly in resource-limited settings [12,13]. Nevertheless, the burning of waste materials can lead to the emissions of numerous toxic or carcinogenic pollutants [14], including dioxins [15] and brominated flame retardants [16].

In this context, the ecological risks posed by heavy metals have been extensively investigated in recent years by numerous researchers, providing further insights into the potential toxic effects associated with soil contamination in landfills and dumpsites [4,5,17]. Moreover, numerous studies have assessed the human health risks associated with long-term exposures to soil heavy metals in dumpsites or through the direct consumption of crops cultivated in the vicinity of dumpsites [18–20].

In Morocco, the estimated total amount of solid waste in 2015 was 26.8 million tons (Mt), excluding agri-waste. Moreover, this amount is expected to reach 39.0 Mt by 2030 [21]. In fact, the solid wastes in Morocco can be classified into household, industrial, and construction wastes, amounting to about 7.4, 5.4, and 14.0 Mt, respectively [21].

Waste management-related legislation has been proposed in Morocco since 2006. These legislative efforts include Law 28.00 [22], related to waste management and elimination, framework Law 99.12 [23], related to the national chart of environment and sustainable development, and Law 77.15 [24], concerning the plastic bag ban. In addition to these legal frameworks, numerous strategies, programs, and action plans have been formulated, including the National Plan for Domestic Waste Management (NPDWM) in 2008, the National Action Plan on Sustainable Consumption and Production Modes (PAN-MCPD) in 2015, and the National Sustainable Development Strategy (NSDS) in 2017. The concept of a circular economy plays a pivotal role in achieving appropriate waste management and sustainability. Furthermore, recycling, composting, and methane recovery for energy pro-

duction are integral components of Morocco's approach to addressing this environmental issue and promoting sustainable waste management practices.

As a consequence, Morocco formulated a national strategy in 2019 to reduce and promote the effective reuse of solid waste. However, despite the significant efforts invested in Morocco to promote sustainable urban solid waste management, uncontrolled landfill sites still exist in several fast-growing areas throughout the country, including Targuist city. Evaluating the ecological and health risks associated with inadequate solid waste disposal is essential for developing appropriate control measures and site-specific waste management strategies [25].

Many authors have highlighted the need for sharing accurate and relevant data in the field of solid waste management in low- and middle-income countries (LMICs) [26]. Indeed, extensive related research has been carried out in Africa over the last few years to assess the ecological and human health risks associated with inadequate waste disposal. Afolagboye et al. [27] evaluated the soil contamination levels around a municipal waste dumpsite in Nigeria using different contamination indices, including the geo-accumulation index (Igeo), enrichment factor (EF), and contamination factor (CF), highlighting soil Cr and Pb contamination in the dumpsite area. Oruko et al. [28] explored the ecological risks associated with soil Cr and Cr(VI) contents in dumpsite areas in Kenya and South Africa using the Igeo, CF, pollution load index (PLI), and ecological risk index (PRI). Their findings revealed unacceptable Cr concentrations in the affected soils. On the other hand, only a few studies have been conducted on the ecological and health risks associated with dumpsites in Morocco. Benhamdoun et al. [4] evaluated the soil heavy metal contents in a dumpsite in Safi city, the Marrakech-Safi region, using the Igeo, CF, and PLI, and reported elevated levels of Zn, Cu, and Cd. El Fadili et al. [5] evaluated the spatial distributions and risks associated with heavy metals in surface soils near the dumpsite of Benguerir city, the Marrakech-Safi region, using pollution indicators, multivariate statistics, and health risk indices, showing higher average Zn, Cd, Fe, Cu, Ni, Pb, and Cr contents than the corresponding geochemical backgrounds. Ben Ali et al. [29] evaluated the ecotoxicological risks of heavy metals in soil at a dumpsite close to Khouribga city, Beni Mellal-Khenifra region, Morocco, where municipal solid wastes and sewage sludge are disposed of, outlining non-carcinogenic risks to children and adults. In addition, the associated carcinogenic risk values were above the threshold value (10^{-4}) for children. However, further research is needed to extend the understanding of human health and ecological risks associated with dumpsites at the national and continental levels. In this context, the present study is part of a large ongoing study on the physicochemical characterization of soils near dumpsites [30]. It aims to evaluate the ecological and health risks caused by dumpsites and the characteristics of disposed solid waste in Targuist city to further promote sustainable waste management in Morocco. Indeed, Andaloussi et al. [30] evaluated the soil physicochemical characteristics from 16 sampling sites near the Targuist dumpsite. The authors conducted a Pearson correlation analysis to investigate the correlations between the soil properties and four heavy metals (Cd, Cr, Cu, and Zn), showing significant correlations ($p < 0.01$) between the soil pH values and the contents of three heavy metals (Cd, Cu, and Zn). However, to the best of our knowledge, Morocco is still characterized by the lack of ecological and health risk assessments for mountain ecosystems and uncontrolled dumpsites like Targuist. It is worth emphasizing that many countries worldwide, in particular LMICs, are facing complex contamination scenarios linked to dumpsites [31]. This highlights the urgent need to develop and implement appropriate strategies for investigation, monitoring, and risk mitigation. Additionally, over the years, scholars have increasingly underscored the importance of site-specific data collection as a critical foundation for the development of

effective solid waste management strategies in LMICs, which are often characterized by a paucity of such information [26,32].

In this context, the main objective of the present work was to assess the ecological and human health risks associated with four heavy metals (Cd, Cr, Cu, and Zn) in the surface soil near the Targuist dumpsite. Moreover, given that the root systems of most edible plants typically remain confined to the surface soil, and that waste pickers often collect materials from this soil layer, prioritizing the risk assessment of pollutants in surface soil was a strategic and contextually justified choice.

2. Materials and Methods

2.1. Study Area

The study dumpsite was situated approximately 1.5 km to the Southeastern part of Targuist city (Tangier-Tetouan-Al Hoceima region, Morocco) in the Rif Mountains. It is located at distances of 1 km and 500 m from Maraha village and National Road 8, respectively, covering an area of approximately 1208 m² (Figure 1). The altitude of the dumpsite ranges approximately from 1007 to 1013 m (Table S1). A seasonal river, located 170 m to the south, intermittently flows through the area and receives solid waste-derived leachates, primarily during wet seasons. The study area is characterized by the absence of aquifer systems.

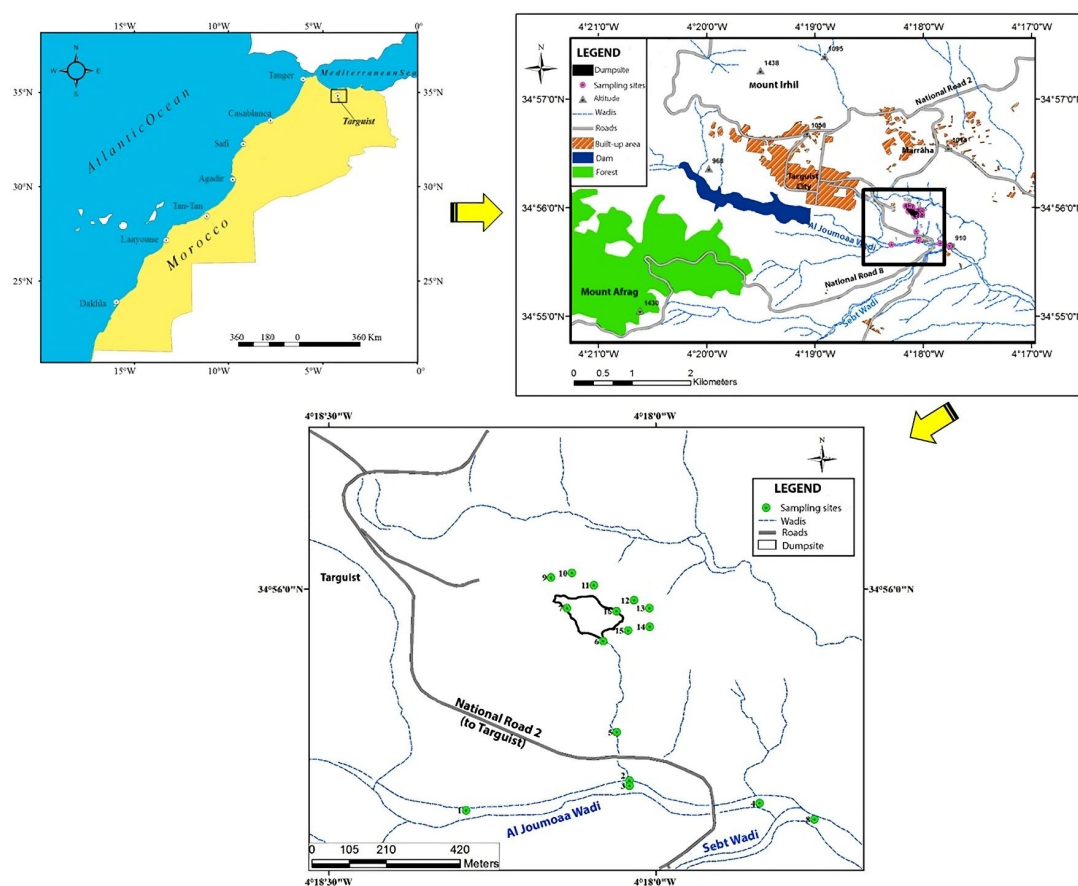


Figure 1. Geographic locations of the Targuist dumpsite (North Morocco) and sampling sites.

2.2. Sample Collection

The absence of drainage systems in the study area enhances the infiltration and runoff of solid waste-derived leachate into nearby areas, particularly in wet seasons. In this study, soil sampling was carried out in the winter season (January) of 2018 under dry conditions,

with no rainfall events occurring beforehand. The sampling points were selected based on the runoff directions. Specifically, there were 10 sampling points along the perimeter of the dumpsite or a few meters outside of it, as it was challenging to define the specific borders of the dumpsite accurately. Indeed, dumpsites are often characterized by the absence of fences and clear demarcation [33]. Six additional sampling points (S1, S2, S3, S4, S5, and S8) were situated at a distance greater than 200 m from the dumpsite, adjacent to the water stream flowing west to east (Table S1 and Figure 1); these six points will hereafter be referred to as “outside the dumpsite”.

The dumpsite receives an estimated daily solid waste of approximately 20 tons, including municipal solid, industrial, medical, and electronic wastes. The waste is deposited in layers and compacted. However, it is crucial to note that solid waste management practices (e.g., dumping and burning) at the dumpsite are unsafe, which may lead to serious environmental and human health concerns [34]. Prior to the sampling, stones, vegetation, and solid wastes were manually and systematically removed. A 1.5×1.5 m area was first demarcated, and then soil samples were collected from five specific locations within the square (the four corners and center of the area). At each of these designated sampling points, soil samples were collected from the top 0–20 cm soil layer. These samples were subsequently thoroughly mixed to obtain a composite soil sample of 1 kg from each sampling point. In total, 16 composite soil samples were collected, placed in polyethylene bags, and labeled with corresponding tags, including information on the sampling point. The collected soil samples were stored at 4 °C in coolers and sent to the laboratory for analyses. At the laboratory, composite soil samples were cleaned by removing wastes, and oven dried at 60 °C for 48 h until reaching constant weights. The dried soil samples were subsequently sieved through a 2 mm stainless steel sieve, homogenized, and crushed using an agate mortar for subsequent analyses.

2.3. Heavy Metals Concentration Analysis

The pseudo-total concentrations for four heavy metals, namely, copper (Cu), zinc (Zn), cadmium (Cd), and chromium (Cr), were determined following the protocols described by Kouali et al. [35] and Benhamdoun et al. [4]. For each sample, 0.5 g of soil was digested using aqua regia ($\text{HNO}_3\text{:HCl}$, 3:1), a mixture of concentrated nitric acid (65%, Sigma-Aldrich, Buchs, Switzerland) and hydrochloric acid (37%, Sigma-Aldrich, Buchs, Switzerland). The resulting digests were filtered, diluted to 50 mL with bi-distilled water, and centrifuged at 2000 rpm for 15 min to obtain a clear supernatant for analysis.

The quantification of these elements was performed using an atomic absorption spectrophotometer (AAS) equipped with a flame (AI 1200, Aurora Instruments Limited, Vancouver, BC, Canada), according to the protocol described by Kouali et al. [35]. The detection limits of the AAS instrument were $0.03 \mu\text{g g}^{-1}$ for Cd and $0.05 \mu\text{g g}^{-1}$ for Cu, Zn, and Cr. We used the soil ISE-871 certified reference material from Wageningen Evaluating Programs for Analytical Laboratories (WEPAL) for Quality Assurance/Quality Control (QA/QC) purposes. The relative standard deviations were about 8%, indicating good analytical precisions. Chemical speciation of chromium could not be performed, although it would have been valuable for a more accurate assessment of the health risks associated with Cr(VI), the most toxic form. Consequently, we adopted a precautionary approach, following the methodology mentioned by the US EPA [36], which assumes that the total measured chromium is entirely in the hexavalent form (Cr(VI)). Indeed, chromium-6 and chromium-3 are covered under the total chromium drinking water standard because they can convert back and forth in water and in the human body, depending on environmental conditions. While this assumption likely overestimates the actual risk, it ensures a conservative evaluation. Future studies should incorporate chromium speciation to enable a more

precise risk assessment. The four heavy metals were selected in this study due to their typical bioaccumulation behaviors in the edible parts of many plants [37]. They can, in fact, enter the food chain and biomagnify through food and vegetable consumption, posing potential human health threats [37,38].

2.4. Heavy Metal Pollution Assessment

The quantified heavy metal contents were used to evaluate the pollution and contamination levels in the study area using different indices, including the contamination factor (CF), contamination degree (CD), modified contamination degree (mCD), pollution load index (PLI), geo-accumulation index (I_{geo}), and potential ecological risk index (RI) [39]. These indices are valuable tools in conveying environmental concerns to decision-makers, providing a useful reference for decision-making processes.

2.4.1. Contamination Factor (CF)

The CF was proposed for the first time by Hakanson [40] to qualitatively assess the accumulation of heavy metals in soils. In this study, we used the CF to determine the accumulation of each heavy metal element (*i*) at the sampling points, according to the following formula (Equation (1)):

$$CF = \frac{\text{Heavy metal contents}}{\text{Background value}} \quad (1)$$

Soil background values have been commonly used to distinguish between heavy metal contents from natural and anthropogenic sources. However, when information about background values in the reference area is not available or misleading, other values can be considered. For instance, Afolagboye et al. [27] evaluated the soil contamination status around a dumpsite in Nigeria. However, due to the uncontrolled land use in many areas, it was inappropriate to take the soil concentration of the region as a background value. Additionally, there was a lack of accurate national background values for soil trace metals in Nigeria. As a consequence, the authors used the average soil metal contents in other countries with similar geological features. Sakan et al. [41] used also the average soil heavy metal contents to assess the CF of the Tisza river sediments in Serbia due to the lack of local background values. However, other methods mentioned concern using the average shale values and the average concentration in the continental crust as background values [27,41].

The geochemical reference values are equivalent to the heavy metal contents in uncontaminated soils worldwide [42]. In this study, the Cd, Cr, Cu, and Zn reference values were set at 0.35, 70, 30, and 90 mg/kg, respectively. Geologically, the Targuist dumpsite is situated in a flysch zone characterized by high chemical variability, due to the presence of numerous clay minerals with differing adsorption capacities. However, there is still a lack of local background value for the study area. Therefore, we have used the global mean value as a reference background for total digestion analysis.

The calculated CF values were further classified into four classes according to Hakanson [40], namely, low ($CF < 1$), moderate ($1 \leq CF \leq 3$), considerable ($3 \leq CF \leq 6$), and very high ($CF \geq 6$) contamination degrees. Indeed, this classification was considered in several previous related studies [4,20,43].

2.4.2. Contamination Degree (CD)

The contamination degree is the sum of the CFs of all heavy metals at the sampling point, according to the following formula (Equation (2)) [44,45]:

$$CD = \sum_{i=1}^n CF_i \quad (2)$$

where n denotes the number of the trace metal (pollutant). The contamination rates were classified into low, moderate, high, and very high, corresponding to $CD < n$, $n \leq CD < 2n$, $2n \leq CD < 4n$, and $CD \geq 4n$, respectively.

2.4.3. Modified Contamination Degree (mCD)

The mCD is an empirical indicator used to assess the contamination degree of trace elements at a given sampling point. The mCD was calculated in this study using the following formula (Equation (3)):

$$mCD = \frac{\sum_{i=1}^n CF_i}{n} \quad (3)$$

where n denotes the number of heavy metals (pollutants). The mCD values were classified into seven classes, namely, nil to very low, moderate, high, very high, extremely high, and ultra-high degree of contamination corresponding to mCD ranges of <1.5 , $1.5 \leq mCD < 2$, $2 \leq mCD < 4$, $4 \leq mCD < 8$, $8 \leq mCD < 16$, $16 \leq mCD < 32$, and $mCD \geq 32$, respectively [46].

2.4.4. Pollution Load Index (PLI)

The pollution load index (PLI) was applied by numerous researchers [4,47,48] to quantitatively assess the contamination levels of heavy elements. This index was, in fact, developed by Tomlinson et al. [49] to assess the overall contamination levels of soils. PLI values above 1 indicate significant contamination levels. The PLI was applied in this study according to the following formula (Equation (4)):

$$PLI = \sqrt[n]{CF_i \times CF_j \times \dots \times CF_n} \quad (4)$$

where CF_i ; $CF_j \dots CF_n$ denote the CF values of heavy metal elements $i, j \dots n$, respectively.

Pollution load index (PLI) values lower and higher than 1 indicate soils unpolluted and polluted by the heavy metals, respectively.

2.4.5. Geo-Accumulation Index (I_{geo})

The geo-accumulation index (I_{geo}) is one of the most widely applied indices to assess soil heavy metal contamination levels. This empirical index was proposed for the first time by Müller [50] and applied in several related studies [45]. It can, in fact, be used to compare a given heavy metal content with a specific geological background according to the following formula (Equation (5)):

$$I_{geo} = \log_2 \frac{C_n}{1.5 B_n} \quad (5)$$

where n denotes the trace element in the study soil; C denotes average soil heavy metal content (mg/kg); B denotes the geochemical background value of the trace element (mg/kg); and 1.5 is a correction factor [50–52]. In this study, we referred to the global average Cd, Cr, Cu, and Zn metal contents in soils of 0.35, 70, 30, and 90 mg/kg, respectively [42,53]. Indeed, all previous related studies in Morocco have considered the global heavy metal concentrations in soils as geochemical background values. The I_{geo} values can be classified into seven classes according to Müller [50], namely, no pollution ($I_{geo} \leq 0$), no to moderate pollution ($0 \leq I_{geo} \leq 1$), moderate pollution ($1 < I_{geo} \leq 2$), moderate to heavy pollution ($2 < I_{geo} \leq 3$), heavy pollution ($3 < I_{geo} \leq 4$), heavy to extreme pollution ($4 < I_{geo} \leq 5$), and extreme pollution ($I_{geo} > 5$) [4,46,54].

2.4.6. Potential Ecological Risk Index (RI)

The RI reflects the potential biological risks caused by toxic pollutants, highlighting the potential ecological risk associated with environmental contamination or pollution [55]. In this study, we used the RI developed by Hakanson [40], according to the following formulas (Equations (6) and (7)):

$$Ei = Ti \frac{Ci}{Bi} \quad (6)$$

$$RI = \sum_{i=1}^n Ei \quad (7)$$

where Ei denotes the potential ecological risk index of a single element at a sampling site; Ti denotes the toxic response factor for element i (Zn = 1, Cr = 2, Cu = 5, and Cd = 30); Ci denotes the content of element i ; and Bi denotes the geochemical reference or background value of element i .

According to Hakanson [40], the Ei values can be classified into five classes, namely, low pollution ($Ei < 40$), moderate pollution ($40 \leq Ei < 80$), considerable pollution ($80 \leq Ei < 160$), high pollution ($160 \leq Ei < 320$), and very high pollution ($Ei \geq 320$). In this study, the RI was calculated as the sum of the potential ecological risk index (Ei) of the different studied heavy metal elements ($I = 1; I = 2 \dots I = n$) in the dumpsite soil. The calculated RI values were classified into four classes, namely, low risk ($RI \leq 150$), moderate risk ($150 \leq RI < 300$), high risk ($300 \leq RI < 600$), and very high risk ($RI \geq 600$) [56,57].

2.5. Human Health Risk Index

The studied dumpsite was near both Targuist city and Marraha village (Figure 1), posing potential health risks to the local population, which is estimated at 500,000 inhabitants. It is worth noting that we have observed frequent visits by men and children to the dumpsite to collect recyclable materials, including plastics, Cu, Fe, Zn, and others materials containing heavy metals. In addition, livestock is often raised in and around the dumpsite. Continuous solid waste burning emits dense smoke from smoldering combustion, darkening some nearby trees species (e.g., olive and almond trees) and, consequently, affecting their health. We hypothesize that children and adults in the dumpsite were at a high risk associated with direct exposure to the contaminated soil and combustion smoke from the dumpsite. In particular, following a conservative approach, we assumed that some soil could have been ingested by mistake by children and adults working in the zone as informal waste pickers. Indeed, waste pickers are common in many LMICs, and many exposure pathways and associated risk must be considered [13,58]. Such an approach, about health risk associated with soil ingestion near dumpsites, have been followed in previous research where chromium, among others pollutants, was considered [59,60]. Adults and children are potentially exposed to heavy metal-contaminated soils of the dumpsite through three different pathways, including ingestion, inhalation, and dermal contact. In this study, these three exposure pathways were considered in the assessments of carcinogenic and non-carcinogenic risks [61,62].

2.5.1. Non-Carcinogenic Hazards

The non-carcinogenic hazards were assessed in this study using the hazard quotient (HQ) (Equation (8)), representing the probability of an individual developing adverse effects from the pollutants. The HQ is defined as the ratio of the average daily intake (ADI) (Table S2) of an element to its chronic reference dose (RfD) under the same exposure pathway, according to the following formula [63]:

$$HQ = ADI/RfD \quad (8)$$

The USEPA provided the RfD values of the selected trace metals under the different exposure pathways [47,64,65]. However, the inhalation related RfD values of Cu and Zn, as well as the dermal contact-related RfQ value of Cr, were not provided by the USEPA. Therefore, their HQs were neglected in this study. The hazard index (HI) was developed to assess the overall potential non-carcinogenic effects of the heavy metal elements [66]. It is a result of the sum of all HQs of each trace metal, according to the following formula (Equation (9)):

$$HI = \sum HQ_i = HQ_{\text{Ingestion}} + HQ_{\text{Inhalation}} + HQ_{\text{Derma}} \quad (9)$$

HQ or HI ≤ 1 and HQ or HI >1 indicate lower and higher occurrence probabilities of non-carcinogenic risks to populations, respectively.

2.5.2. Carcinogenic Hazards

The carcinogenic risk is defined as the probability of an individual developing cancer over a lifetime as a result of exposure to potential carcinogens [11,67,68]. The potential carcinogenic risk was calculated in this study using the following formula (Equation (10)):

$$\text{Risk pathway} = \sum ADI_i \times CSF_i \quad (10)$$

where Risk denotes the probability of an individual developing cancer over a lifetime; ADI_i denotes the average daily uptake (mg/kg/day) ($AT = 365 \times 70$) (Table S2); and CSF denotes the cancer slope factor (mg/kg/day). The total excess lifetime cancer risk for an individual can finally be calculated using the average contribution of individual heavy metals to all exposure pathways, according to the following formula (Equation (11)):

$$\text{Risk total} = \text{Risk Ingestion} + \text{Risk Inhalation} + \text{Risk Dermal} \quad (11)$$

The total carcinogenic risk is equal to the sum of risks associated with all exposure pathways to individual heavy metals. The USEPA defined the CSF values of the selected heavy metals under the different exposure pathways [52,62,67]. The carcinogenic risk levels to human health associated with exposure to the trace metal-contaminated soil of the dumpsite were classified into three classes, namely, negligible (Risk $< 10^{-6}$), acceptable/tolerable ($10^{-6} < \text{Risk} < 10^{-4}$), and high risks (Risk $> 10^{-4}$) [52].

2.6. Statistical Analyses

In this study, descriptive statistics, including the mean, standard deviation, minimum, and maximum values, of the four soil heavy metal element contents were performed. Statistical analyses were performed using SPSS 20 software.

3. Results and Discussion

3.1. Heavy Metal Contents in the Dumpsite Soil

The observed heavy metal contents in the dumpsite soil in Targuist city are reported in Table 1. The concentrations of heavy metals in the dumpsite revealed notable degrees of variability. The mean values of the Cd, Cu, and Zn contents were 1.34 ± 0.57 , 43.77 ± 49.23 , and 134.70 ± 80.33 mg/kg, exceeding their established reference values of 0.35, 30, and 90 mg/kg, respectively. In contrast, the mean value of the Cr content was 46.35 ± 16.07 mg/kg, which is lower than the corresponding reference value of 70 mg/kg. Numerous studies have similarly reported elevated heavy metal concentrations in soils from open landfills and dumpsites compared to background values across various regions worldwide [4,43,69]. The average soil heavy metal contents along the dumpsite perimeter and near the water stream (Figure 1) were further explored. The results showed relatively

higher levels of Cr, Cu, and Zn contents in the vicinity of the dumpsite, as well as higher Cd contents close to the water stream. These findings may be attributed to the transport of leachate from the dumpsite into the water stream, particularly during wet seasons. The transported heavy metals from the leachate can be adsorbed by soils adjacent to the river. In addition, the elevated concentrations of heavy metals in the Targuist dumpsite soil may result from the dumping of plastics, metals, alloys, pigments, paints, and used batteries, along with household organic wastes [4,5].

Table 1. Descriptive statistics of the soil heavy metal contents in the entire area, along the perimeter (In), and outside the dumpsite (Out) of Targuist city (North Morocco).

Heavy Metals (mg/kg)	Cd		Cr		Cu		Zn	
	In	Out	In	Out	In	Out	In	Out
Mean	1.34	1.76	46.35	43.01	43.77	42.79	134.70	131.30
SD	0.57	0.56	16.07	18.40	49.23	5.22	80.33	14.79
Minimum	0.32	0.49	16.00	8.55	4.00	29.16	80.00	104.60
Maximum	2.10	2.35	71.00	78.90	234.55	49.70	430.70	154.10

SD: Standard deviation.

Additionally, practices of waste pickers in the dumpsite of Targuist city, including waste burning to recover valuable metals, might enhance the release and transport of heavy metals into the soil [4,16,70]. Considering the potential toxicity of Cd, Cr, Cu, and Zn to both the environment and human health, we calculated several contamination and pollution-related indices in this study (see Tables 2 and 3).

Table 2. Summary of the contamination factor (CF), contamination degree (CD), modified CD (mCD), and pollution load index (PLI) of Cu, Zn, Cd, and Cr in the dumpsite soil of Targuist city (North Morocco).

Sampling Sites	Cfi = Ci/Cref				CD = $\sum CFi$	mCD = $\sum CFi/n$	PLI = (CFi × CFj...CFn) ^(1/n)
	Cu	Zn	Cd	Cr			
S1	1.41	1.45	5.21	0.37	8.45	2.11	1.41
S2	1.61	1.61	6.64	0.57	10.45	2.61	1.77
S3	1.52	1.33	5.92	0.55	9.34	2.33	1.61
S4	1.46	1.49	5.14	0.80	8.90	2.22	1.73
S5	1.41	1.62	4.71	0.62	8.37	2.09	1.61
S8	1.18	1.22	2.52	0.75	5.68	1.42	1.28
Average (outside the dumpsite) (S.D.)	1.43 (0.15)	1.45 (0.16)	5.02 (1.40)	0.61 (0.15)	8.53 (1.59)	2.13 (0.40)	1.59 (0.19)
S6	5.79	3.80	5.78	0.30	15.68	3.92	2.48
S7	1.04	1.23	5.21	0.56	8.06	2.01	1.39
S9	0.90	0.97	1.02	0.88	3.79	0.94	0.94
S10	0.89	0.95	5.05	0.74	7.65	1.91	1.33
S11	1.04	1.13	3.62	0.62	6.43	1.60	1.28
S12	1.05	1.18	4.90	0.75	7.89	1.97	1.46
S13	1.16	1.11	1.78	0.49	4.56	1.14	1.03

Table 2. Cont.

Sampling Sites	Cfi = Ci/Cref				CD = ΣCFi	mCD = $\Sigma CFi/n$	PLI = (Cfi $\times$ CFj....CFn) ^(1/n)
	Cu	Zn	Cd	Cr			
S14	1.25	1.62	2.38	0.74	6.00	1.50	1.37
S15	0.89	1.53	2.82	0.96	6.22	1.55	1.39
S16	0.57	1.40	2.92	0.53	5.43	1.35	1.05
Average (along the perimeter of the dumpsite) (S.D.)	1.46 (1.53)	1.49 (0.84)	3.55 (1.62)	0.66 (0.20)	7.17 (3.30)	1.79 (0.83)	1.50 (0.43)

S.D.: Standard deviation.

Table 3. Igeo values of Cu, Zn, Cd, and Cr in the Targuist dumpsite.

Sampling Sites	Igeo = $\log_2 Cn/1.5 Bn$			
	Cu	Zn	Cd	Cr
S1	1.07	1.12	2.93	−0.85
S2	1.27	1.27	3.31	−0.20
S3	1.19	1.00	3.15	−0.26
S4	1.12	1.16	2.92	0.26
S5	1.08	1.28	2.78	−0.84
S8	0.80	0.87	1.76	0.17
Average (outside the dumpsite) (S.D.)	1.09 (0.16)	1.12 (0.16)	2.81 (0.55)	−0.28 (0.48)
S6	3.02	2.46	3.11	−1.15
S7	0.64	0.89	2.95	−0.24
S9	0.40	0.53	0.61	0.39
S10	0.41	0.52	2.87	0.15
S11	0.64	0.76	2.35	−0.11
S12	0.64	0.82	2.87	0.17
S13	0.80	0.73	1.42	−0.47
S14	0.90	1.24	1.75	0.14
S15	0.41	1.19	2.07	0.52
S16	−0.78	1.05	2.01	−0.59
Average (along the perimeter of the dumpsite) (S.D.)	0.71 (0.94)	1.02 (0.56)	2.20 (0.80)	−0.11 (0.51)

Igeo: Geo-accumulation index (Igeo). Cn: Mean concentration of the trace element in the study soil in mg/kg. Bn: Biochemical background value of the heavy element (mg/kg). S.D.: Standard deviation.

3.1.1. Contamination Factor (CF)

The CF values of the heavy metals in the study area are summarized in Table 2 and Figure 2. The CF values were classified in this study according to Hakanson [40]. The mean CF value of Cu was 1.46, indicating moderate contamination of the soil with Cu. The highest CF value was observed at the S6 sampling site (5.79), suggesting a high level of contamination along the dumpsite perimeter. Interestingly, the CF value of Cd was comparatively higher outside the dumpsite, particularly near the river. Indeed, Vinti et al. [71] showed elevated Cd concentrations in leachate from a dumpsite, likely due to the disposal of electrical and electronic waste and batteries. Consequently, it is plausible that leachate in

the present study may have reached the river or accumulated in surrounding soils. On the other hand, the higher CF values of Cr, Cu, and Zn along the perimeter of the dumpsite may be attributed to the informal activities of waste pickers, such as the recovery of gold, copper, and silver. Several studies have documented elevated concentrations of these heavy metals in soils impacted by informal E-waste recycling operations [12].

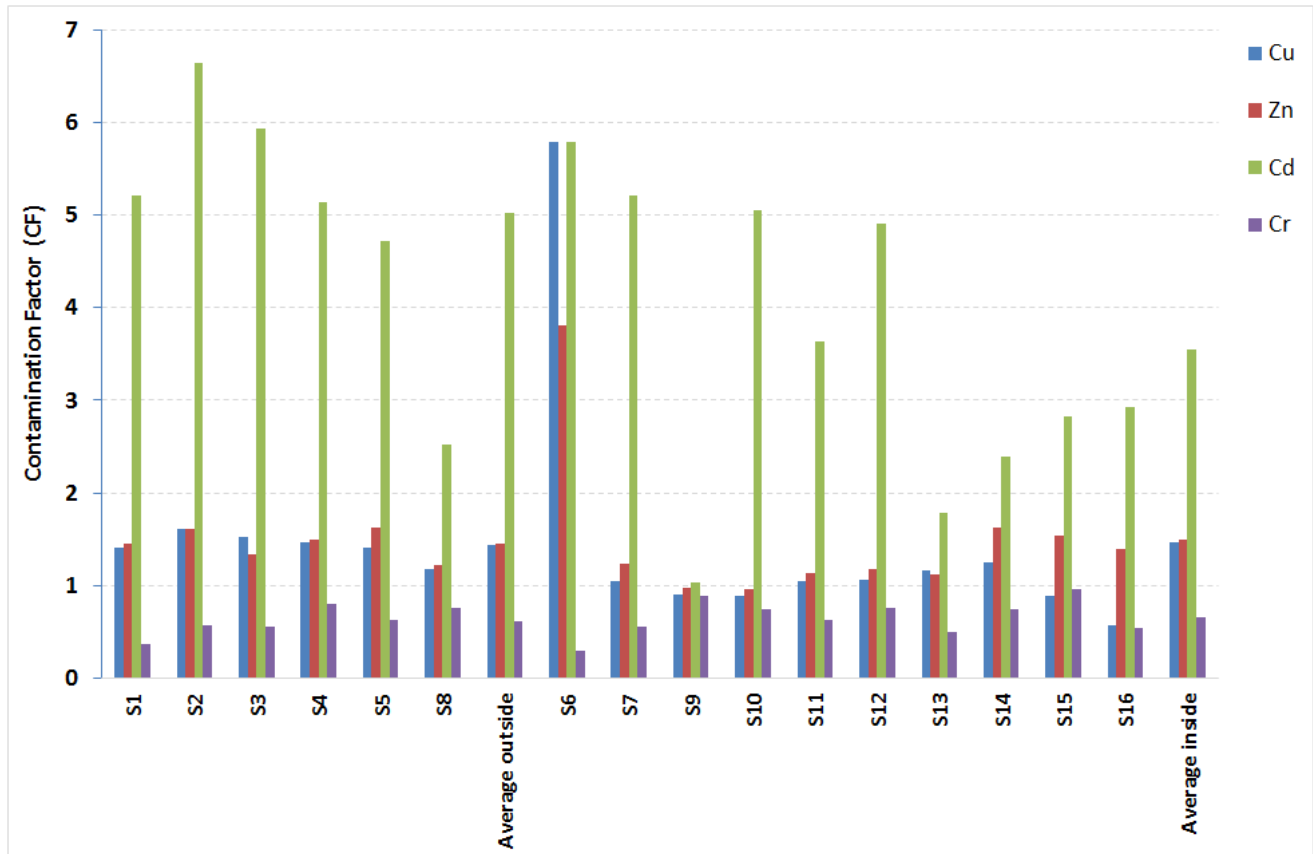


Figure 2. Contamination factor values of soil heavy metals in the dumpsite of Targuist city (North Morocco).

The lowest CF values were observed at only three sampling sites (S9, S10, and S16), suggesting low levels of soil contamination. Further investigations on the northern part of the study area appear necessary. Indeed, these three samples were situated in the dumpsite zone. However, the mean CF values for Cu, inside and outside the dumpsite, indicated moderate contamination. Similar patterns were observed for Zn, which exhibited moderate contamination levels. The highest CF value of Zn was 3.80 at S6, indicating a high level of contamination. The lowest CF values of Zn were below 1 at S9 and S10, suggesting low Zn contamination levels. These lower CF values for Zn may be influenced by prevailing seasonal wind patterns, as S9 and S10 are located in the northern part of the study area. Nevertheless, further research is required to confirm this hypothesis. The highest CF values of Cd were observed mainly at sampling sites outside the dumpsite. The average CF values of Cd were 5.02 and 3.55 outside and along the perimeter of the dumpsite, respectively, suggesting considerable Cd contamination levels. It is worth noting that a substantially high CF value (6.64) of Cd was observed at S2, highlighting a very high Cd contamination level. As mentioned above, the presence of high Cd concentrations in the leachate might affect the corresponding CF value. This sample was collected more than 200 m from the dumpsite, near the river, an area that may periodically receive leachate flow from the dumpsite.

On the other hand, the CF values of Cr were below 1, indicating low levels of Cr contamination in the study area. The findings underscore the dominant contribution of Cd to the overall contamination in the study area, as illustrated in Figure 2. Our CF results were different from those revealed by Afolagboye et al. [27] in an area near a Nigerian dumpsite. They showed comparatively lower CF values of Cu and Zn, as well as one order of magnitude higher CF values of Cr. The higher CF value of Cr might be related to the presence of particular waste categories, such as agricultural waste and E-waste. In addition, the obtained CF values in this study were comparatively lower than those outlined by Benhamdoun et al. [4] in a dumpsite soil in Morocco, except those of Cr, showing relatively similar values. However, it is crucial to investigate the Cr chemical speciation to evaluate the risk associated with Cr(VI). Saha et al. [72] highlighted soil contamination by Cr derived from leachate of waste disposal sites, faecal sludge, and wastes from mining and smelter sites. Therefore, further investigations are needed to examine the anthropogenic sources and waste types contributing to Cr levels in the study area.

3.1.2. Contamination Degree (CD)

The CD reflects the accumulation of heavy metal contents at each sampling site or point, which can be determined by summing all CF values of heavy metals. In this study, the average CD value was 7.17, indicating a moderate contamination level. Notably, except S8, all sampling sites outside and S6 along the perimeter of the dumpsite exhibited high CD values. The remaining sites indicate a moderate degree of contamination, as summarized in Table 2.

3.1.3. Modified Contamination Degree (mCD)

The average mCD value along the dumpsite perimeter was 1.79, indicating a low degree of heavy metal contamination. However, most sampling sites located outside the dumpsite exhibited moderate levels of metal contamination. In contrast, the majority of sampling sites along the perimeter of the dumpsite showed low levels of heavy metal contamination, with the exception of S6 (3.92) and S7 (2.01), which exhibited moderate contamination levels. It is noteworthy that the highest mCD values outside the dumpsite near the river water were due mainly to the strong contributions of Cd. However, as discussed above, the high Cd value might be the periodic discharge of leachate into the river water body, in particular during rainy seasons. The mCD values obtained in this study were relatively comparable to those reported by Afolagboye et al. [27], who investigated a site located a few meters from a dumpsite in Nigeria.

3.1.4. Pollution Load Index (PLI)

The PLI, also known as the integrated pollution index, is a conventional metric used to evaluate soil quality. Pollution load indices (PLI) higher than 1 indicate significant contamination levels. In this study, all sampling sites exhibited PLI values greater than 1 (Table 2). The highest PLI value of the dumpsite was observed at S6, followed, respectively, by those at S2 and S4, outside the dumpsite. The high PLI value at S6 was primarily due to the high soil Cu and Zn contents. The average PLI value outside the dumpsite was 1.59, which was higher than those observed along the perimeter (1.50) of the dumpsite. These results demonstrated deteriorated soil quality along the perimeter and outside the dumpsite of Targuist city, which is consistent with the results reported in previous related studies on heavy metal pollution in dumpsites of Morocco. Indeed, Benhamdoun et al. [4] and El Fadili et al. [5] highlighted severe soil heavy metal pollution in the dumpsites of Safi and Benguerir cities, respectively, posing serious potential ecological risks. However, the PLI values of the dumpsite of Safi city were four to five times higher than those obtained in this study, whereas those revealed in Benguerir city were almost similar to those found in

Targuist city. These findings suggest a high level of contamination in the Safi dumpsite. Interestingly, Benhamdoun et al. [4] collected most soil samples from the dumpsite area.

3.1.5. Geo-Accumulation Index (Igeo)

The geo-accumulation index (Igeo) is a valuable tool for assessing heavy metal contamination in soils, taking into consideration the actual soil heavy metal contents (C_n) and their geochemical background values (B_n). The Igeo can also provide insights into anthropogenic sources of heavy metals in soils. According to the classifications outlined by Müller [50] and Abraham and Parker [46], the overall average Igeo values indicated the absence of soil Cr pollution, both along the perimeter and outside the dumpsite (Table 3 and Figure 3).

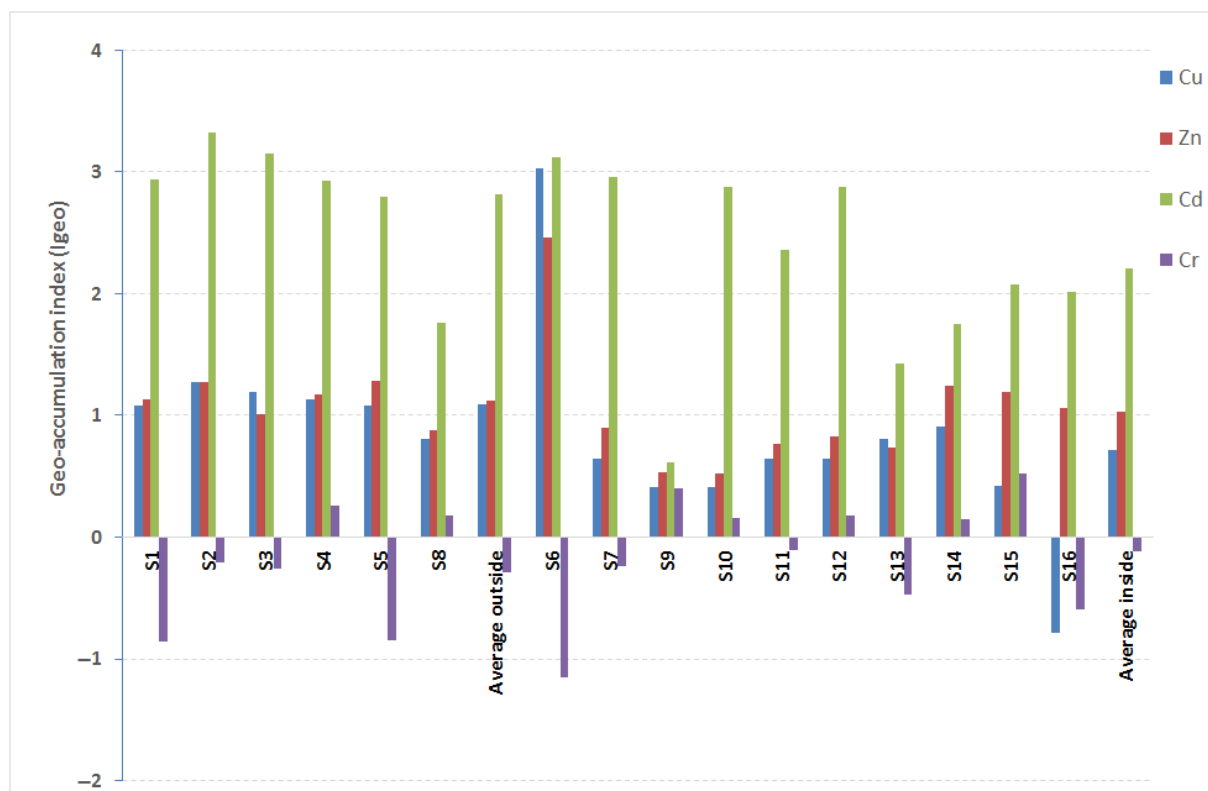


Figure 3. Bare chart of the Igeo values of Cu, Zn, Cd, and Cr in the Targuist dumpsite (North Morocco).

On the other hand, the observed average Igeo values of Zn suggested moderate pollution levels by this heavy metal, except S6, where the Igeo values of Zn and Cu were comparatively higher, suggesting serious soil pollution by these heavy metals. The high average Igeo values of Cd suggested moderate soil Cd pollution levels, particularly at S6, S3, and S2. The spatial distributions of the heavy metals in the study area are, indeed, in line with that of waste transported by trucks. It is evident that wastes were the main sources of the studied heavy metal elements in the dumpsite soil of Targuist city, which is consistent with the results of previous studies on dumpsites in North Africa [4,5], Asia [43,73], and Europe [74].

3.1.6. Potential Ecological Risk Index (RI)

The results of the E_i and RI values associated with the four heavy metal elements (Cd, Cr, Cu, and Zn) at each sampling site are reported in Table 4. The E_i values of Cu, Zn, and Cr were low across all sampling sites ($E_i < 40$), including those along the perimeter and outside the dumpsite (Table 4). In contrast, the E_i values of Cd were notably higher

than those of the other heavy metal elements, except S2 (high potential ecological risk), S8, S13, and S14 (moderate potential ecological risk), and S9 (low potential ecological risk). The results indicated a high contribution of Cd to the E_i values, accounting for approximately 92.47% of the total ecological risk. Indeed, the variability in soil Cd content had a marked influence on the RI distribution pattern, as shown in Table 4. This finding is consistent with previous related studies. Indeed, Ajah et al. [75] and Benhadmoun et al. [4] highlighted high contributions of Cd to the RI of over 90%. Interestingly, despite the elevated soil Cu concentration at S6, this metal did not significantly affect the RI values, which remained below 150, thus indicating a low potential ecological risk. The average RI values along the perimeter of the dumpsite was 116.73, suggesting low potential ecological risks. In contrast, the average RI outside the dumpsite was 160.71, indicating a moderate potential ecological risk (Table 4). Moreover, ecological risk assessments of soils should encompass all relevant toxic pollutants, including Pb, Hg, and As, as well as persistent organic pollutants such as non-biodegradable pesticides and hydrocarbons. El Fadili et al. [5] emphasized the importance of Cd and Pb in increasing the ecological risks associated with soil contamination in Benguerir city, Morocco, leading to high ecological risk levels.

Table 4. Individual potential ecological risk (E_i) and potential ecological risk index (RI) of the studied heavy metals in the dumpsite of Targuist city (North Morocco).

Sampling Sites	$E_i = T_i \times C_{Fi}$				RI = ΣE_i
	Cu	Zn	Cd	Cr	
S1	7.05	1.45	156.42	0.74	165.68
S2	8.07	1.61	199.28	1.15	210.12
S3	7.60	1.33	177.85	1.11	187.91
S4	7.30	1.49	154.28	1.60	164.69
S5	7.06	1.62	141.42	1.24	151.36
S8	5.92	1.22	75.85	1.50	84.50
Average outside (S.D.)	7.17 (0.72)	1.45 (0.16)	150.85 (42.03)	1.22 (0.31)	160.71 (42.70)
S6	28.97	3.80	173.57	0.60	206.94
S7	5.21	1.23	156.42	1.12	164.01
S9	4.53	0.97	30.85	1.77	38.13
S10	4.47	0.95	151.71	1.48	158.63
S11	5.24	1.13	108.85	1.25	116.48
S12	5.28	1.18	147.00	1.51	154.98
S13	5.82	1.11	53.57	0.99	61.50
S14	6.25	1.62	71.57	1.47	80.93
S15	4.46	1.53	84.85	1.92	92.78
S16	2.85	1.40	87.60	1.07	92.93
Average along the perimeter (S.D.)	7.31 (7.67)	1.49 (0.64)	106.60 (48.59)	1.32 (0.39)	116.73 (52.96)
Overall average (S.D.)	7.26 (5.95)	1.48 (0.66)	123.19 (49.95)	1.28 (0.35)	133.22 (52.67)

S.D.: Standard deviation.

3.2. Human Health Risk Index

3.2.1. Non-Carcinogenic Hazard Quotient (HQ) and Health Index (HI)

The HQ and HI values of the dumpsite of Targuist city are reported in Table 5. The ingestion route was identified as the primary exposure pathway for heavy metal risk to children along the perimeter of the dumpsite. According to the results, Cr and Zn showed the highest and lowest HQ values of 1.90×10^{-1} and 5.73×10^{-3} , respectively. A similar trend was observed for adults, confirming the predominant contribution of the ingestion pathway to the HQ for all heavy metals, except Zn. Indeed, the high HQ value of Zn (2.84×10^{-2}) was mainly associated with dermal exposure. The HI values of the studied heavy metal elements for children along the perimeter of the dumpsite followed the order of Cr (1.90×10^{-1}) > Cd (3.50×10^{-2}) > Cu (1.80×10^{-2}) > Zn (8.66×10^{-3}). On the other hand, the HI values of the heavy metal elements for adults along the perimeter of the dumpsite followed the order of Zn (2.90×10^{-2}) > Cr (2.10×10^{-2}) > Cd (4.24×10^{-3}) > Cu (2.23×10^{-3}).

Table 5. Hazard quotient (HQ) and health index (HI) values of the soil heavy metal elements for adults and children in the dumpsite and its surrounding areas in Targuist city (North Morocco).

		Pathways	Hazard Quotient (HQ)				Total
			Cd	Cr	Cu	Zn	
Along the perimeter of the dumpsite	Children	Ingestion	3.10×10^{-2}	1.90×10^{-1}	1.50×10^{-2}	5.73×10^{-3}	2.42×10^{-1}
		Inhalation	1.07×10^{-5}	7.56×10^{-4}	-	-	7.67×10^{-4}
		Dermal	4.06×10^{-3}	-	2.99×10^{-3}	2.93×10^{-3}	9.98×10^{-3}
		Hazard Index (HI)	3.50×10^{-2}	1.90×10^{-1}	1.80×10^{-2}	8.66×10^{-3}	2.52×10^{-1}
	Adults	Ingestion	3.40×10^{-3}	2.10×10^{-2}	1.62×10^{-3}	6.13×10^{-4}	2.66×10^{-2}
		Inhalation	4.60×10^{-6}	3.20×10^{-4}	-	-	3.25×10^{-4}
		Dermal	8.40×10^{-4}	-	6.16×10^{-4}	2.84×10^{-2}	2.99×10^{-2}
		Hazard Index (HI)	4.24×10^{-3}	2.10×10^{-2}	2.23×10^{-3}	2.90×10^{-2}	5.65×10^{-2}
Overall HI inside the dumpsite		3.92×10^{-2}	2.11×10^{-1}	2.02×10^{-2}	3.77×10^{-2}	3.08×10^{-1}	
Outside dumpsite	Children	Ingestion	4.50×10^{-2}	1.80×10^{-1}	1.40×10^{-2}	5.56×10^{-3}	2.45×10^{-1}
		Inhalation	1.52×10^{-5}	7.03×10^{-4}	-	-	7.18×10^{-4}
		Dermal	5.76×10^{-3}	-	2.91×10^{-3}	2.86×10^{-3}	1.15×10^{-2}
		Hazard Index (HI)	5.00×10^{-2}	1.80×10^{-1}	1.70×10^{-2}	8.42×10^{-3}	2.55×10^{-1}
	Adults	Ingestion	4.82×10^{-3}	1.90×10^{-2}	1.58×10^{-3}	6.00×10^{-4}	2.60×10^{-2}
		Inhalation	6.50×10^{-6}	3.02×10^{-4}	-	-	3.09×10^{-4}
		Dermal	1.18×10^{-3}	-	2.91×10^{-3}	5.93×10^{-4}	4.68×10^{-3}
		Hazard Index (HI)	6.00×10^{-3}	1.90×10^{-2}	4.49×10^{-3}	1.19×10^{-3}	3.07×10^{-2}
Overall HI outside the dumpsite		5.60×10^{-2}	1.99×10^{-1}	2.15×10^{-2}	9.61×10^{-3}	2.86×10^{-1}	

Ingestion remained the dominant exposure pathway contributing to health risks associated with heavy metals for children outside the dumpsite. The highest and lowest HQ values for children in this area were attributed to Cr (1.80×10^{-1}) and Zn (5.56×10^{-3}), respectively. Several studies have highlighted ingestion as the major pathway for heavy metal exposure [11,37,76].

The HI values for heavy metal in children followed the order: Cr (1.80×10^{-1}) > Cd (5.00×10^{-2}) > Cu (1.70×10^{-2}) > Zn (8.42×10^{-3}). In contrast, the HI values for

adults followed the order: Cr (1.90×10^{-2}) > Cd (6.00×10^{-3}) > Cu (4.49×10^{-3}) > Zn (1.19×10^{-3}). Khan et al. [32] reported non-carcinogenic risks associated with Cr exposure via the dermal pathway in agricultural soils. In addition, Rudzi et al. [77] revealed a lack of significant health risks of Cr to farmers in Malaysia. In all cases, the obtained HI values of the dumpsite in this study were below 1, indicating a low likelihood of non-carcinogenic adverse effects on the surrounding population. This result is in line with that revealed by Ben Ali et al. [29] in a dumpsite in Morocco, where Cd, Cr, Cu, and Zn were the most commonly found due to the effects of MSW and sewage sludge. However, it is important to recognize that children are more vulnerable to the potential adverse effects of heavy metal elements compared to adults. This is particularly relevant for children who spend extended periods outdoors, as they may experience elevated exposure to heavy metal-contaminated soils, dust, and smoke from waste burning while playing for several hours each day.

3.2.2. Carcinogenic Risks Associated with the Dumpsite Soil

It should be noted that Cu and Zn are not universally classified as carcinogenic [78]. Consequently, only carcinogenic risks associated with exposures to Cd and Cr were assessed in this study (Table 6). As mentioned above, values greater than 10^{-4} indicate high carcinogenic risks according to USEPA. According to the obtained carcinogenic risk values (Table 6), Cr had a higher probability of causing carcinogenic effects over the lifetime of adults than that of Cd. Noteworthy, the carcinogenic risk associated with the ingestion of Cr was above 10^{-5} both for children and adults along the perimeter of the dumpsite and adjacent to the river water stream. Although these values are considered acceptable according to the USEPA, they cannot be underestimated. Indeed, other legislations would consider these values high, posing serious associated risks. For example, in Italy, the acceptable carcinogenic risk levels for contaminants, including heavy metals, are set below 10^{-6} for individual substances and below 10^{-5} for multiple substances [79]. The risk values higher than 10^{-5} in the vicinity of the river suggest related investigations in different dry and wet seasons. Indeed, the potential occurrence of runoff in the wet season might reduce the soil Cr contents in the study area. In this study, the Cr-associated carcinogenic risk was relatively similar to that revealed by Ben Ali et al. [29] in a dumpsite in Morocco, which was also unacceptable according to the USEPA. However, the presence of Cr can be associated with multiple pollutants [72], suggesting further investigations to comprehensively assess the risks associated with heavy metals in the study area.

Table 6. Carcinogenic risk index of the soil heavy metals for adults and children in the dumpsite and its surrounding areas.

	Pathways	Carcinogenic Risk		Total Risk
		Cd	Cr	
Along the perimeter of the dumpsite	Children	Ingestion	-	2.53×10^{-5}
		Inhalation	3.28×10^{-10}	1.13×10^{-9}
		Dermal	-	-
		Total risk to children	3.28×10^{-10}	2.53×10^{-5}
	Adult	Ingestion	-	6.35×10^{-5}
		Inhalation	7.05×10^{-10}	2.42×10^{-9}
		Dermal	-	-
		Total risk to adults	7.05×10^{-10}	6.35×10^{-5}
	Total inside dumpsite		1.03×10^{-9}	8.88×10^{-5}

Table 6. Cont.

		Pathways	Carcinogenic Risk		Total Risk
			Cd	Cr	
Outside dumpsite	Children	Ingestion	-	2.35×10^{-5}	2.35×10^{-5}
		Inhalation	4.67×10^{-10}	7.42×10^{-10}	1.21×10^{-9}
		Dermal	-	-	-
		Total risk to children	4.67×10^{-10}	2.35×10^{-5}	2.35×10^{-5}
	Adult	Ingestion	-	5.90×10^{-5}	5.90×10^{-5}
		Inhalation	1.00×10^{-9}	1.59×10^{-9}	2.59×10^{-9}
		Dermal	-	-	-
		Total risk to adults	1.00×10^{-9}	5.90×10^{-5}	5.90×10^{-5}
	Total risk outside the dumpsite		1.47×10^{-9}	8.25×10^{-5}	8.25×10^{-5}

3.2.3. Identification of Site-Specific Interventions to Reduce Human Health Risks

Site-specific interventions should be implemented to reduce the heavy metal-associated ecological and human health risks. However, such interventions may be challenging, as they depend largely on political, social, technical, and economic factors. Safety works and the remediation of heavy metal-contaminated sites remain the most advisable approach to ensuring the availability of clean soil systems for the community. In some cases, such interventions have indeed been implemented in multiple LMICs [80]. However, over the next few years, wastes may probably continue to be disposed of at the investigated dumpsite. Therefore, targeted mitigation measures are necessary to reduce the associated human health risks. In particular, a leachate collection and storage system should be first installed to design an appropriate leachate treatment system. In addition, a suitable solution could consist of building a constructed wetland for landfill leachate treatment processes, as proposed by several authors [81,82]. It is also necessary to propose a strategy for capping the closed sections of the dumpsite [83]. These mitigation interventions would significantly mitigate the transport of pollutants to the surrounding environment, reducing associated human health risks. To further decrease the volume of waste requiring disposal, the 3Rs strategy (reduce, reuse, and recycle) should be reinforced. For example, local legislation can effectively reduce the amounts of some waste fractions, as demonstrated by plastic ban policies in some African countries [84].

Composting should also be promoted, as organic waste usually constitutes the main component of municipal solid waste. Indeed, the successful decentralized composting model proposed by Yeo et al. [85] in the Ivory Coast can be used as a reference. These authors demonstrated the effectiveness of waste composting compared to disposal in landfills or dumpsites in reducing GHG emissions.

4. Limitations

The present study has some limitations that should be addressed in future research. First, there was a lack of soil background values specific to heavy metals in the study area. However, as mentioned, other approaches can be considered when information about background values in the study area is unavailable or misleading. For example, the average heavy metal content in the continental crust or soils in other countries with similar geological features can be used as references [27,41]. However, further related investigations are required to accurately define the corresponding background values in future research. The obtained values can be substantially compared with the values

obtained in the current study. However, it must be highlighted that the background values did not affect the carcinogenic and non-carcinogenic risk assessment results. Many other studies have assessed human health risks associated with heavy metals without considering corresponding background values [29,59]. Second, it is suggested to increase the density of sampling sites in future related research to improve the accuracy of the assessment results. Furthermore, our study focused on surface soil. Indeed, the soil samples were collected in this study from the upper soil layers, as plant roots are mainly distributed on soil surfaces. In addition, waste pickers are usually in direct contact only with surface soils. However, in future research, soil samples from deeper soil layers should be collected to comprehensively assess human health risks associated with heavy metals. Finally, it is important to further evaluate human health risks associated with the heavy metals in water bodies in the study area. Such studies can also be useful for proposing site-specific fate and transport models for the heavy metals in the study area [86].

Despite the absence of local background values, we selected contamination assessment indicators that are widely recognized and applicable in such contexts. The geo-accumulation index (Igeo) was particularly suitable, as it accounts for both natural and anthropogenic contributions to metal levels and can be used with regional or global reference concentrations. However, particularly in hot areas, recrystallisation of Fe-oxides leads to fixation of Cr within non-aqua-regia-accessible fractions [87]. This may explain the negative Igeo. Likewise, the pollution load index (PLI) allowed for a simplified yet integrative assessment of overall contamination at each sampling site.

5. Conclusions and Perspectives

This study assessed the ecological and health risks associated with four soil heavy metals (Cu, Zn, Cr, and Cd) in the dumpsite of Targuist city (North Morocco). The results highlighted potential ecological and health risks associated with the soil heavy metals in the dumpsite and its surrounding river. In particular, the PLI indicated significant contamination by the studied heavy metals. On the other hand, the Igeo values suggested the absence of Cr contamination, moderate contamination by Cu and Zn, and severe contamination by Cd. The RI indicated a very high contribution of Cd to the potential ecological risk in the study area. The non-carcinogenic health risks associated with soil heavy metals were below 1 for both children and adults. Finally, the carcinogenic risks were within acceptable limits for both children and adults according to USEPA regulations. However, carcinogenic risks associated with Cr were unacceptable according to the Italian Legislation. Thus, further investigations are necessary. Informal waste pickers in the dumpsite represent the population most highly exposed to the associated health risks. In addition to more comprehensive environmental assessments of top soils, it will be crucial to further investigate heavy metal contamination in deeper soil layers and nearby water bodies. In addition, more detailed studies involving fate and transport modeling of heavy metals are needed to assess the health risks of people living in Targuist city, i.e., at greater distances from the dumpsite. The choice of contamination indices was guided by their relevance to the context of the study and their proven reliability in similar research settings. The PLI provided an integrative metric for evaluating the overall contamination status of each site. The Igeo was used to estimate contamination intensity while differentiating between natural and anthropogenic sources. Additionally, the potential ecological risk index (RI) offered insight into the toxicological significance of each metal, highlighting the particular risk posed by cadmium. These complementary indices ensured a comprehensive and robust evaluation of soil contamination and potential ecological risks.

In parallel, considering that the Targuist population is expected to increase over the future decades, it will be crucial to implement appropriate solid waste management

strategies. A circular economy approach, coupled with the sustainable landfill concept, must be adopted to reduce potential environmental and health risks associated with the dumpsite. Therefore, future research and interventions should also focus on an integrated solid waste management approach.

In our study area, further research on environmental and health risk assessments should also investigate additional carcinogenic or toxic compounds. As several authors have pointed out, other heavy metals (e.g., Co, Hg, Ni, and Pb) [88], as well as organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) [89], can be present in environmental matrices near dumpsites.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/soilsystems9030082/s1>, Table S1: Geographical coordinates, elevations and slope of soil sampling sites in Targuist dumpsite (North Morocco); Table S2: Equations of Average Daily Intake (ADI) (mg/kg day) calculations of potential trace element related to different exposure pathways.

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Abbreviations

The following abbreviations are used in this manuscript:

Igeo	Geo-accumulation index
EF	Enrichment factor
CF	Contamination factor
PLI	Pollution load index
PRI	Ecological risk index
THI	Total hazard index
AAS	Atomic absorption spectrophotometer
USEPA	United States Environmental Protection Agency
CD	Contamination degree
mCD	Modified contamination degree
RI	Potential ecological risk index
HQ	Hazard quotient
ADI	Average daily intake
RfD	Chronic reference dose
SD	Standard deviation
Ei	Individual potential ecological risk

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