Environ Monit Assess (2023) 195:941
https://doi.org/10.1007/s10661-023-11467-4

RESEARCH

Soil contamination by trace metals and assessment of the risks associated: the dumping site of Safi city (Northwest Morocco)

Abdellali Benhamdoun · Hafid Achtak · Giovanni Vinti · Abdallah Dahbi

Received: 12 March 2023 / Accepted: 5 June 2023 / Published online: 12 July 2023
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2023

Abstract The main objective of this work was to determine the soil contamination with trace metals within and around the dumpsite of Safi city (Morocco) and to evaluate the potential environmental risk associated. The results showed that the average soil concentrations of trace metals had the following order: Fe > Zn > Cu > Cr > Cd and exceeded the world and the upper continental background concentrations except for Fe. In addition, the concentrations of Zn, Cu, and Cd remained beyond the limit standards given by the WHO/FAO. Geoaccumulation index, enrichment factor, and pollution load index (PLI) indicated that the dumpsite soil is highly contaminated and deteriorated, presenting evidence of high ecological risk proved by the values of the potential ecological risk index (PERI). Correlation analyses revealed a strong relationship between the organic matter & [Fe, Zn, Cr, Cd], calcium carbonates & [Zn, Cr], and Cr & Cu inside the dumpsite soil. Principal component analysis confirmed the temporal and spatial classification of Zone A as the oldest and Zone C as the youngest and indicated that the regrouped trace metals could have the same behavior and or the same origin. The interpolation of trace metals concentrations and PERI revealed a plausible extension outside the landfill, confirmed by PLI values.

Keywords Dumpsites · Soil contamination · Trace metals · Pollution indices · Ecological risks

Introduction

The soil is increasingly contaminated by a wide range of pollutants as a direct consequence of anthropogenic activities such as using pesticides and fertilizers in agriculture, fossil fuel burning, and mining (Naidu et al., 2021). Additionally, the uncontrolled public dumps where municipal wastes are disposed of are among the major causes of large-scale soil contamination (Agbeshie et al., 2020; Alam et al., 2020). Actually, the world population produces more than 2 billion tons of municipal solid waste (MSW) of which 33% is dumped (Kaza et al., 2018). Landfilled wastes undergo a chemical and biological transformation or can be incinerated releasing important amounts of greenhouse gases such as CO2 and CH4, contributing to global warming (Abdel-Shafy & Mansour, 2018; Nanda & Berruti, 2021). Mainly for economic and managing reasons, non-engineered landfilling represents the waste

---

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10661-023-11467-4.

A. Benhamdoun (✉) · H. Achtak · A. Dahbi
Research Team “Environment and Health”, Department of Biology, Polydisciplinary Faculty, Cadi Ayyad University, Safi, Morocco
e-mail: abdellali.benhamdoun@gmail.com

G. Vinti
CISS (Cooperazione Internazionale Sud Sud) NGO, 90141 Palermo, Italy

management commonly used in developing countries, where no leachate or gas containment system is undertaken (Agamuthu, 2013; Idowu et al., 2019). Such inappropriate process in waste management by dumping and open burning generates harmful air emissions, including a significant amount of dust highly loaded with various pollutants such as trace metals, which induces harmful effects and considerable threats to the environment and human health (Siddiqua et al., 2022; Velis & Cook, 2021; Vinti et al., 2021). Phosphate fertilizers, liming materials, plant protection products, fertilizers used in agriculture, in addition to industrial activities, and atmospheric deposition can also contribute to soil contamination by trace metals (Taghavi et al., 2023; Wuana & Okieimen, 2011; Zwolak et al., 2019). Furthermore, heavy metals can generate from particular categories of household waste, such as batteries, mobile phones, and laptops, when they are not correctly managed (Chen et al., 2022). The soil contains natural levels of trace metals (Abdu et al., 2017; Chandrasekaran et al., 2015; Tóth et al., 2016). However, the soil becomes heavily contaminated by trace metals when waste disposal sites are located, with sometimes levels well above current standards (Cocârţă et al., 2016; El Fadili et al., 2022; Essien et al., 2019; Thongyuan et al., 2021; Vural et al., 2017). Trace metal contamination of soil is taking primary importance in ecotoxicological approaches worlwide. Several studies conducted in such waste concentration areas around the world confirmed and assessed the contamination of landfill (and dumpsite) soil by trace metals either in developing African countries (Agbeshie et al., 2020; El Daba & Abd El Wahab, 2020; Kennou et al., 2015), in Asia (Hussein et al., 2021; Thongyuan et al., 2021; Wang et al., 2020, 2022), and also in Europe (Nannoni et al., 2017; Vural et al., 2017).

Once in the soil, trace metals may follow vertical water transport by transferring in the deeper parts (Teta & Hikwa, 2017; Zeng et al., 2021). Moreover, the dumpsite soil may constitute an epicenter that gradually contaminates the surrounding areas through a horizontal transfer of such pollutants. The spread of soil contamination depends on numerous parameters such as the quantitative and qualitative characteristics of the landfill, the soil pedological characteristics, and its topography, as well as other physical and chemical parameters (Hooda, 2010; Naveen et al., 2018; Shaheen et al., 2013). In addition, the degree of metal bioavailability depends on several physicochemical parameters in the polluted soil as well as clay and organic matter content (Essien et al., 2019). Furthermore, the presence of a geomembrane or a layer with low hydraulic conductivity may strongly influence the spreading of leachate in the surrounding environment (Vaccari et al., 2018).

The soil is the primary matrix where almost all the biotic components of an ecosystem live (Bar-On et al., 2018). Once they reach the soil, trace metals persist and accumulate over time becoming toxic to living organisms when reaching high levels. Their accumulation in the soil directly impacts the food web (Agbeshie et al., 2020; Ebong et al., 2019; Foti et al., 2017) through several integration pathways, including root uptake at the plant level or dermal, respiratory, or ingestion for the animal biota potentially affecting human health (Vinti et al., 2023). Trace metals generate various cellular damage (Akanchise et al., 2020), when they accumulate in vegetable and animal tissues and exceed tolerable levels. Even the essential trace metals, such as zinc and copper, or non-essential trace metals like chromium and cadmium generate at high concentrations damage to cell division, water and nutrient imbalance, oxidative stress, and DNA damage (DesMarias & Costa, 2019; Ertani et al., 2017; Genchi et al., 2020; Kumar et al., 2021; Sarkar et al., 2013; Shanker et al., 2005; Wang et al., 2021). This leads to a wide range of negative impacts on the whole biocenosis, including a decrease in plant productivity combined with multiple disturbances at various scales: physiological, morphological, and behavioral. The persistence and harmful effects of trace metals on the biota living in the soil make such pollution a global concern. Indeed, to assess the ecological risks on the biological components of the local and nearby ecosystem of landfills, many studies around the world have used several indices such as geoaccumulation factor, contamination factor, pollution load index, enrichment factor, and potential ecological risk index, e.g., in Europe (Foti et al., 2017; Rinklebe et al., 2019; Doležalová Weissmannová et al., 2019), in Asia (Arya et al., 2021; Borah et al., 2020; Hussein et al., 2021; Thongyuan et al., 2021), and in Africa (Barakat et al., 2020; Essien et al., 2019; Kennou et al., 2015; Okonkwo et al., 2021; Yassine et al., 2021).

Despite several government strategies adopted, Morocco is a developing country suffering from waste management issues. The annual amount of waste generated reaches 7 million tons, of which 85% are collected.

Among the collected waste, only about 40% is deposited in controlled landfills, and almost 60% is disposed of in open dumps (Alikhan & Arib, 2019; Dahchour & Hajjaji, 2020). However, with the emerging concept of sustainable development, such a situation is becoming of national concern and presents a great challenge to the government to be solved. In this context, a strategy for rational management (National Domestic Waste Plan "NDWP") has been recently launched to reduce the number of uncontrolled landfills and their impact on the environment. Still, expected results have not been achieved. Indeed, the current trend indicates that the efforts could not prevent the persistence of uncontrolled waste disposal sites which still constitute more than 70% of total discharges in the country (Dahchour & Hajjaji, 2020). The situation worsens as scientific studies on the characterization of many aspects of landfills remain sporadic at the national scale. Indeed, few studies on four different landfills out of 220 in the country have been devoted to this subject in the last decade, linking soil contamination by trace metals and associated ecological risks. All the results indicated considerable soil contamination with a blend of trace metals. Kennou et al. (2015), Fait et al. (2018), and Andaloussi et al. (2021) recorded significant contamination of landfill soils by trace metals with concentrations exceeding the critical values. El Fadili et al. (2022) revealed more recently a remarkable risk presented by a mixture of trace metals in the soil of a landfill near Bengrir city and especially by toxic elements such as Cd and Pb which might pose a strong effect on public health and surrounding ecosystems.

Among uncontrolled dumps that continue to flourish out of control, the waste disposal site of Safi city is one of the most polluted hotspots in the Moroccan urban areas. It concentrates the urban waste from more than 600,000 inhabitants (https://www.hcp.ma/) and is an important industrial sector among the most prosperous nationwide, mainly the industries related to fishing activities. It daily receives about 300 tons of waste from various sources such as residential, commercial, construction, hospital, and industrial activities. Moreover, industrial activities include pottery, cement production, fish canneries, and phosphate production. Organic waste represents more than 80%, while plastic, metals, and textile leather represent 5.7%, 1.4%, and 3.7% of municipal waste, respectively. Wastes are managed by dumping and open incineration, while the generated leachate flows in all directions due to the lake of the landfill leachate collection system and a waterproof layer. Notwithstanding, to the best of our knowledge, no investigations have been carried out on the dumpsite of Safi city to describe its toxicological and ecotoxicological consequences despite its spatial extent and the socio-economic importance it plays at the regional scale.

Fore these reasons, this study aims to identify the trace metal contamination levels in the dumpsite soil, to assess the potential pollution caused by these pollutants, and to evaluate the ecological risk generated by these pollutants to the local and surrounding biota depending more or less on the soil. Indeed, during its functioning process, this dumpsite exhibited spatial dynamics with a spread of use that evolved from the area of dumpsite initiation or the epicenter and progressed to new areas of use. Such dynamics could be reflected in the pattern of soil contamination throughout the landfill. We hypothesize that the dumpsite is a mosaic that maps out a temporal sequence in the use of space, leading to older areas that are more contaminated than newer areas still in use and the expanse of this contamination.

Material and methods

Study area and sampling method

The study area is the dumpsite of the coastal city of Safi. The open landfill is located near the town on the edge of the provincial road N° 2307, about 3 km from the city center and a few hundred meters from the nearby dwellings. The dumpsite is located between latitude 32°16′36.2″N and longitude 9°12′27.4″W at 50 m above sea level. The climate is relatively moderated due to the influence of the sea; however, it is characterized as semi-arid with a hot and dry summer (May–November) and wet to temperate winter (December–April). The minimum rainfall occurred in 1980 (100 mm) and the maximum, for its part, occurred in 1995 (970 mm) with a surplus of 573 mm compared to the annual average rainfall which is 397 mm (Ayt Ougougdal et al., 2020). The average minimum temperature is 12.8° C in January, while the average maximum temperature is 32.1 °C in July. Geologically, the Safi open dump is located mainly on bioclastic limestones of the Plio-Quaternary and the silts of the recent Quaternary.

The disposal site has been active since 1983 and is considered one of the oldest dumps in Morocco, with an area of 25 hectares. The dumpsite of Safi is characterized by a considerable amount of leachate resulting from moistened wastes. This leachate flows in all directions due to the absence of a geomembrane or waterproof layer to isolate it from the soil and collect it for treatment. The waste disposal site is characterized by informal activities of recovery of some waste by garbage collectors, who burn specific waste such as tires and electrical cables to recover the metals. Ten sampling sites are located inside the dumpsite, and two stations are located outside it. A total of three replicates are taken at each station point. The selection of sites was based on accessibility to areas inside the dumpsite where there is no current dumping or open burning of waste. According to the age of the dump, the site was classified into three different inside zones (see Fig. 1). The youngest zone inside the dumpsite was named Zone C and covers 5.9 ha and includes four sample stations (S1, S2, S3, and S4). The intermediate zone, called Zone B, covers 4.5 ha and incorporates three sample stations (S5, S6, and S7). Wastes are managed by landfilling in the two first zones. Finally, the old dump named Zone A with 14.6 ha includes three sample stations (S8, S9, and S10) where wastes were managed by uncontrolled open burning and by landfilling. In addition to the three inside zones, the study included soil samples taken out of the dumpsite body, but belonging to soil located at the vicinity of the landfill, situated 100 m away approximately from the external border of the dumpsite. For the control measurements, the soil was sampled from a distant area of 7 km away and was known to be free of any source of metallic contamination. A total of 45 soil samples were randomly collected from the inside and the outside of the dumpsite as well as from the control area at 0–30 cm depth after removing surficial waste and humus. Samples were performed in March 2020 with three replicates at each sampling station. Figure 1 illustrates all sample stations including 10 from inside and 2 from outside the dumpsite body located in the southwest 100 m away from the dumpsite. The first station (S11) is from agricultural land, while the second station (S12) is from unused land. Each sample was labeled and placed separately in a clean polyethylene bag before the treatment and analyses in the laboratory.

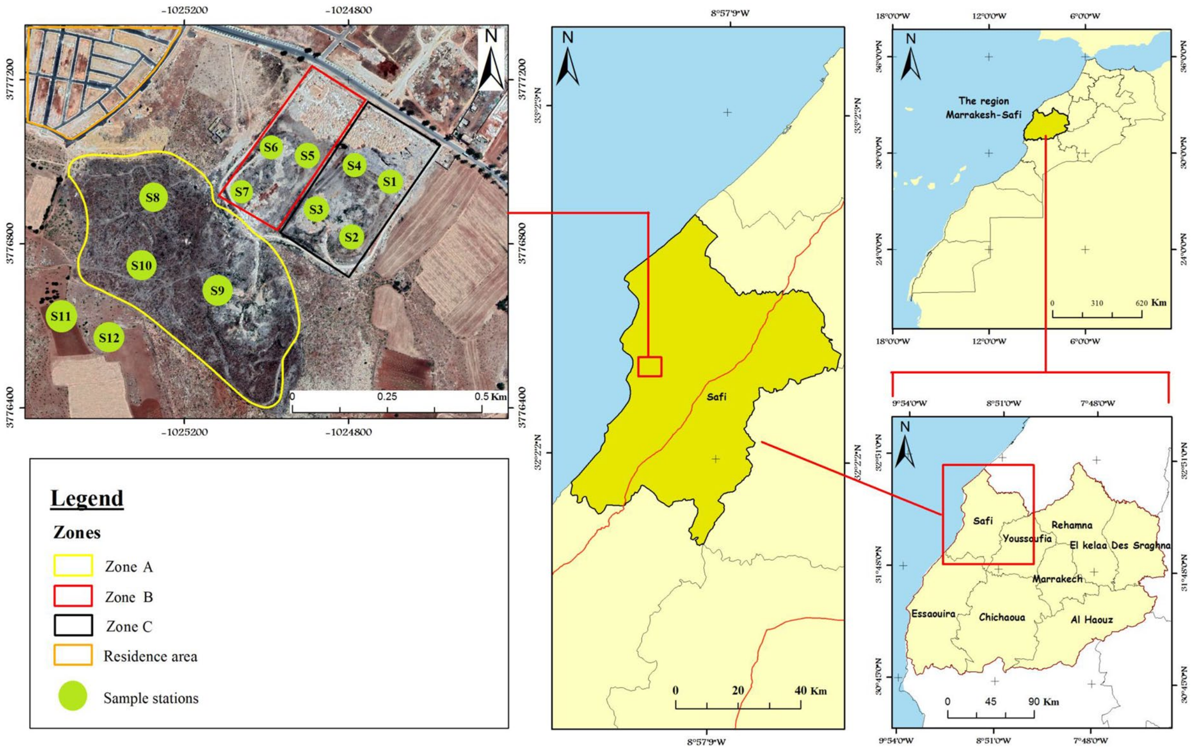


Fig. 1 Localization of study area and sample points in the Safi landfill body and the nearby area

Soil treatment and analyses

The treatment of samples was conducted within a few hours following the sampling process. Before analyzing physical and chemical parameters as well as the total concentrations of trace metals, each sample was cleaned by removal of wastes, dried in an oven to constant weight, and then sieved through a sieve of 3 mm stainless steel mesh.

For physical and chemical parameters of soil, pH, and EC were measured by electrometry in 1:2.5 and 1:5 soil–water suspension, respectively (NF-ISO 10390, NF-ISO 11265). Soil samples underwent a three-step heating process in a muffle furnace. Firstly, the samples were heated to 105 °C to remove water. Then, they were heated to 550 °C for 4 h to eliminate organic matter. Lastly, the samples were heated to 930 °C for 2 h to remove calcium carbonate (CaCO3). The amount of OM and CaCO3 present in the sample was determined by calculating the difference in weight between the sample after heating to 105 °C and 550 °C and between the sample after heating to 550 °C (soil without water and OM) and 930 °C (without CaCO3), respectively (Ennaji et al., 2020; Kouchou et al., 2020).

The concentration of five trace metals (Cd, Cr, Cu, Fe, and Zn) was determined after digestion of 0.5 g of each sample in an aqua regia (3:1): a mixture of concentrated nitric HNO3 65% (Sigma-Aldrich) and chlorhydric HCl 37% (Sigma-Aldrich) acids (Kouali et al., 2020). Then, the digested solutions were filtered and filled up with 50 ml of bi-distilled water and centrifuged (2000 rpm for 15 min) to obtain a transparent supernatant. The determination was conducted in triplicate for each sample station by using flame atomic absorption spectrometry (AI 1200, Aurora Instruments Limited, Canada). The selection of these trace metals was under previous local and national works on coastal and terrestrial areas (El Fadili et al., 2022; Kennou et al., 2015; Kouali et al., 2020, 2022a, b; Rafiq et al., 2022) that have focused on the assessment of trace metal concentrations such as Cd, Cr, Cu, and Zn and the risk arising from pollution. The soil ISE-871 certified reference material supplied by Wageningen Evaluating Programs for Analytical Laboratories (WEPAL) was used for Quality Assurance/Quality Control (QC/QA) purposes. The analytical precision, measured as the relative standard deviation, was below 8% in this study (Table 1S).

Assessment of contamination degree by pollution indices

The quantification of the soil contamination by trace metals and their toxicity was carried out using various single and total complex pollution indices such as the geoaccumulation index (Igeo), the contamination factor (CF), the enrichment factor (EF), and the pollution load index (PLI) (Barakat et al., 2020; El Hamzaoui et al., 2020; Hilali et al., 2020, 2022; Oumenskou et al., 2018). According to Kumar et al. (2019), these indices provide the most effective tools for assessing trace metal pollution regarding their total concentrations in the soil.

Geoaccumulation index

Many studies, especially in Europe, use the geoaccumulation index introduced by Müller (1969) to evaluate environmental contamination by trace metals (Barbieri et al., 2014; Brtnický et al., 2020; Charzyński et al., 2017; Korzeniowska & Krąż, 2020). It is calculated according to the equation mentioned in Table 1 by dividing the concentration of the metal in the sample by its background concentration for the upper continental crust given by Hans Wedepohl (1995), with a coefficient of 1.5 introduced to minimize the effect of possible variations in the background values attributed to the lithological changes in the sediments or the influence of anthropogenic sources.

Seven classes were defined based on Igeo and are as follows (Pecina et al., 2021):

- Uncontaminated if the values of the Igeo < 0
- Uncontaminated to moderately contaminated if $0 < \text{Igeo} < 1$
- Moderately contaminated if $1 < \text{Igeo} < 2$
- Moderately to heavily contaminated if $2 < \text{Igeo} < 3$
- Heavily contaminated if $3 < \text{Igeo} < 4$
- Heavily to extremely contaminated if $4 < \text{Igeo} < 5$
- Extremely contaminated if $\text{Igeo} > 5$

Contamination factor

The CF is defined as the ratio between the concentration of elements of interest in a soil sample and its background concentration. It can be computed using the equation mentioned in Table 1. The CF is classified as (Hakanson, 1980):

Table 1 Equations of the soil pollution indices

Indices	Formulas	Variables	Reference
Geoaccumulation index	$Igeo = \log2(C_m/1.5B_n)$	C_m: The measured concentration of trace metal in the soil sample B_n: The geochemical background value of trace metal in reference average shale (Hans Wedepohl, 1995)	(Muller, 1969)
Contamination factor	$CF = C_m/C_{bkg}$	C_m: The measured concentration of trace metal in the soil sample C_{bkg}: The background concentration of trace metal(Hans Wedepohl, 1995)	(Hakanson, 1980)
Pollution load index	$PLI = (CF1 \times CF2 \times CF3 \times \ldots \times CFn)^{1/n}$	where CF is contamination factor of single metal and n is the number of metals	(Rai et al., 2019)
Enrichment factor	$EF = (C_m/C_{Fe})sample/(C_m/C_{Fe})background$	C_m: Concentration of trace metal in the soil C_{Fe}: Concentration of Iron in the soil	(Barakat et al., 2020)
Ecological risk index	$E^i_r = T^i_r \times CF^i$	T^i_r: the toxicological response factor of each trace metal(Hakanson, 1980) CF^i: the contamination factor of each trace metal	(Kumar et al., 2021)
The potential ecological risk index	$PERI = \sum E^i_r$	E^i_r: ecological risk index of a single metal	

- $CF < 1$: Low contamination
- $1 \leq CF < 3$: Moderate contamination
- $3 \leq CF < 6$: Considerable contamination
- $CF > 6$: Very high contamination

Pollution load index

The determination of the pollution status of the soil caused by the contamination with a mixture of trace metals can be assessed by the PLI, which can be computed using the equation cited in Table 1. According to Yassine et al. (2021), this index classifies the soil as:

- Unpolluted soil when $PLI < 1$
- Pollutant levels are present when $PLI = 1$
- A deterioration of the site quality when $PLI > 1$

Enrichment factor

The enrichment factor is an index providing information about the sources of trace metals, anthropogenic or natural, by comparing the concentration of the elements of interest against a reference metal. The main reference elements used in a wide range of studies are Al, Ca, Fe, Mg, and Mn. In this study, EFs were calculated according to the equation cited in Table 1 with Fe as a reference element. There are five classes of EF identified according to Oumenskou et al. (2018) which are:

- $EF < 2$ (minimal enrichment)
- $2 \leq EF < 5$ (moderate enrichment)
- $5 \leq EF < 20$ (significant enrichment)
- $20 \leq EF < 40$ (very high enrichment)
- $EF \geq 40$ (extremely high enrichment)

Ecological risk assessment

Ecological risk assessment of trace metals allows the assessment of the risks posed by the presence of trace metals in the environment resulting from anthropogenic activities, on all living beings in the studied ecosystem. The calculation of E^i_r takes into account the concentration of the element in question and its toxic response factor (T^i_r). The toxic response factor of every single trace metal is Zn = 1, Cr = 2, Cu = 5, and Cd = 30. The toxic-response factors used in this study are taken from Hakanson (1980), who determined them following the toxicity level of each trace metal and the response of biocenosis to this toxicity level. The potential ecological risk index (PERI) is expressed as the sum of the potential risks of individual trace metals and can be calculated according to the equation cited in Table 1 (Thongyuan et al., 2021; Doležalová Weissmannová et al., 2019). The classification of E^i_r and PERI is listed in Table 2 (Pecina et al., 2021).

Data analysis

The descriptive statistics of physicochemical and trace metals metals of soil samples were performed using basic statistics such as mean, standard deviation (SD), and coefficient of variation (CV).

All data were checked for normality using the Shapiro–Wilk test and for homogeneity of variance by Levene's test. On this basis, a non-parametric Kruskal–Wallis test was adopted to evaluate the difference between the various parameters of soil stations. Furthermore, Pearson's correlation coefficient was used to check the level of correlation between soil parameters considered in this study. p value < 0.05 was considered to indicate statistical significance. In addition, principal component analysis was employed to identify potential sources of trace metals in different soils of the open landfill of Safi city (Kumar et al., 2021). All data were analyzed using Statistics Package for Social Science (SPSS) version 18.0 (IBM, Chicago, IL, USA).

Spatial analysis method

The spatial distribution of trace metal concentration in soil throughout the dumpsite body and the ecological risk parameters was visualized using the ordinary kriging method. This method estimates a value at a point in a region for which a variogram is known, using data from the vicinity of the estimation location. To do this, a kriging estimate of the local mean is first determined, and then a simple kriging estimator using this kriging mean is examined (Wackernagel, 1995). It was implemented in ArcGIS software version 10.2 (ESRI, Redlands, California, USA).

Results

Soil physical and chemical characterization

Results of the physical and chemical characteristics of soil from different sampling stations (control area, inside, and outside the dumpsite of Safi) are presented in Table 3. The soil in the control area is alkaline and has higher pH values than all soils from the three areas of the waste disposal site of Safi and outside it which are slightly alkaline. The mean values of pH are significantly different ($p < 0.05$) between all studied soils and are as follows: 8.19, 7.61, 7.47, 7.43, and 7.27 for the control area, Zone C, Zone B, Zone A, and outside the dumpsite body, respectively. Furthermore, the highest pH mean value is recorded at station 2 (pH = 7.80) and the lowest is recorded at station 8 (pH = 7.11) concerning the dumpsite soils. In contrast, values of organic matter (OM) show a reverse trend, being greater inside the dumpsite body compared to the values recorded outside the dumpsite body and in the control area. The mean values of the organic matter present the following decreasing order: Zone A (9.85%) > Zone B (8.35%) > Zone C (5.83%) > outside dumpsite (3.69%) > control area (3.06%) with significant difference between all studied stations also including among the three dumpsite stations (Kruskal–Wallis test, $p < 0.05$). Moreover, soil inside the dumpsite body shows the

Table 2 Classification of ecological risk index (E^i_r) and potential ecological risk index (PERI)

E^i_r	Risk classification	PERI	Risk classification
$E^i_r < 40$	Low risk	$RI < 150$	Low risk
$40 \leq E^i_r < 80$	Moderate risk	$150 \leq RI < 300$	Moderate risk
$80 \leq E^i_r < 160$	Considerable risk	$300 \leq RI < 600$	High risk
$160 \leq E^i_r < 320$	High risk	$RI \geq 600$	Very high risk
$E^i_r \geq 320$	Very high risk		

Table 3 Physical and chemical properties of the soils at different sites

Site			pH	E.C (ms/cm)	OM(%)	$CaCO_3$ (%)
Inside dumpsite	Zone A	$n=9$	7.43 ± 0.39^{a} (5.25%)	$2.97 \pm 4.57^{a,b}$ (153.30%)	$9.85 \pm 2.35^{a,b}$ (23.85%)	$19.58 \pm 3.40^{a,b}$ (58.30%)
	Zone B	$n=9$	7.47 ± 0.32^{a} (4.13%)	$4.54 \pm 1.02^{a,b}$ (22.46%)	$8.35 \pm 2.36^{a,b}$ (28.26%)	$17.93 \pm 3.08^{a,b}$ (17.18%)
	Zone C	$n=12$	7.61 ± 0.27^{a} (3.55%)	$2.95 \pm 1.72^{a,b}$ (58.30%)	$5.83 \pm 1.03^{a,b}$ (17.67%)	$11.97 \pm 3.97^{a,b}$ (33.16%)
Outside dumpsite		$n=6$	7.27 ± 0.12^{a} (1.65%)	$0.32 \pm 0.04^{a,b}$ (12.50%)	$3.69 \pm 0.36^{a,b}$ (9.75%)	$0.78 \pm 0.31^{a,b}$ (39.74%)
Control area		$n=9$	8.19 ± 0.12^{a} (1.46%)	$0.18 \pm 0.02^{a,b}$ (11.11%)	$3.06 \pm 0.80^{a,b}$ (26.14%)	$18.70 \pm 1.24^{a,b}$ (6.63%)

The value in brackets corresponds to the coefficient of variation. Means sharing a letter are significantly different according to the Kruskal–Wallis test at a significant level of $p < 0.05$. The letter "a" is for the comparison between all sites, and the letter "b" is for the comparison between sites inside the landfill

highest OM mean value at station 8 (12.02%), while the lowest is recorded at station 1 (5.35%). The same pattern is observed for the electrical conductivity (EC) throughout all the studied stations. Zone B presents the highest mean values (EC = 4.54 ms/cm) compared to the remaining areas namely Zone A (EC = 2.97 ms/cm), Zone C (EC = 2.95 ms/cm), outside dumpsite (EC = 0.32 ms/cm), and the control area (EC = 0.18 ms/cm). Statistical analysis revealed a significant difference in meanvalues of EC between all studied areas (Kruskal–Wallis test, $p < 0.05$). In addition, this difference is more obvious between soils inside the dumpsite body. The most elevated EC value registered inside the dumpsite body is recorded at station 6 (EC = 5.11 ms/cm). However, the lowest value is recorded at station 8 (EC = 0.56 ms/cm). Calcium carbonates (CaCO3), as shown in Table 3, conserve approximately the same distribution as that observed for the organic matter, but a higher variability is recorded between the soil sampled inside and outside the dumpsite body. Indeed, the soil in Zone A has the highest calcium carbonate content with a mean value of 19.58%, whereas the lowest carbonate calcium content is recorded outside the dumpsite body with a mean value of 0.78%. Additionally, calcium carbonate values vary significantly inside the dumpsite body and show a maximum average value recorded at station 10 (21.52%) and a minimum average value obtained at station 2 (8.85%). The soil outside the dumpsite exhibits a low level of calcium carbonates (0.78%), whereas the control area exhibits surprisingly a comparable level of calcium carbonates with that recorded inside the dumpsite body with a mean soil content reaching 18.70%.

Trace metal contents

Table 4 summarizes mean concentrations of trace metals in studied soil, the descriptive statistics, and the data recorded in other dumpsites and in two landfills (referring to the Malaysia case study) around the world, in addition to other background and limit values. The mean concentrations of the five trace metals named Fe, Zn, Cu, Cr, and Cd in soil sampled in the control area are 9614.41 ± 379.08, 37.37 ± 19.02, 6.09 ± 3.03, 3.44 ± 0.71, and 0.40 ± 0.27 mg/kg, respectively, and present a decreasing order as follow Fe > Zn > Cu > Cr > Cd. The mean concentrations of trace metals in soil sampled inside the dumpsite body follow the decreasing order: Fe (21,487 ± 10,017.3) > Zn (501.22 ± 211.48) > Cu (174.25 ± 85.79) > Cr (46.16 ± 28.12) > Cd (7.12 ± 2.60 mg/kg). These concentrations are 2.23, 13.41, 28.61, 13.42, and 17.80 times higher than those recorded in the control area for Fe, Zn, Cu, Cr, and Cd, respectively. The result indicates that soil in dumpsite bodies is highly enriched by these trace metals. In addition, the distribution pattern of trace metals is not similar throughout all study areas (Kruskal–Wallis test, $p < 0.05$). However, only several trace metals differed between stations inside the dumpsite body (Kruskal–Wallis test, $p < 0.05$). Indeed, we noticed a significant difference between Cr and Zn soil concentrations inside the dumpsite body, while the concentrations of Cu, Cd, and Fe remain similar. Details of concentrations of trace metals in every single station are shown in Fig. 2. For example, station 4 inside Zone C shows the highest mean concentration of Cu (276.80 ± 1.1 mg/kg) but the lowest mean concentration of Zn (242.43 ± 3.07 mg/kg). Moreover, Zn records

Table 4 Trace metals concentration in Safi landfill, similar studies in the world and relevant standards (mg/kg dry weight)

			Zn	Cu	Cr	Cd	Fe	
Inside dumpsite	Zone A	$n=9$	725.30 ± 195.21^{a,b}	226.78 ± 69.44^{a}	53.88 ± 15.17^{a,b}	6.37 ± 2.59^{a}	21,518.61 ± 7586.90^{a}	Current study
	Zone B	$n=9$	505.64 ± 137.30^{a,b}	140.23 ± 101.62^{a}	66.50 ± 31.04^{a,b}	6.20 ± 1.42^{a}	24,148.06 ± 16,751.58^{a}	
	Zone C	$n=12$	329.85 ± 57.92^{a,b}	160.36 ± 70.50^{a}	25.12 ± 18.58^{a,b}	8.37 ± 2.94^{a}	19,467.50 ± 2891.01^{a}	
Outside dumpsite		$n=6$	55.92 ± 12.40^{a}	25.75 ± 10.45^{a}	29.18 ± 4.19^{a}	0.22 ± 0.15^{a}	13,801.67 ± 2580.41^{a}	
Control area		$n=9$	37.37 ± 19.02^{a}	6.09 ± 3.03^{a}	3.44 ± 0.71^{a}	0.40 ± 0,27^{a}	9614.41 ± 379.08^{a}	
Morocco (Benguerir)			42.51	13.32	21.16	1.77	406.27	(El Fadili et al., 2022)
Morocco (Marrakech)			574–1134	425–526	99.69–576	0.72–4	NA	(Kennou et al., 2015)
Ghana (Kronum)			166	32	66	13	NA	(Akanchise et al., 2020)
(Amakom)			558	347	77	5.9	NA	
Nigeria (Calaba)			NA	44.7	NA	1.19	2215.36	(Ebong et al., 2019)
Egypt (Hurghada)			492	402	68	44.3	7959	(El Daba & Abd El Wahab, 2020)
Malaysia (Melaka and Negeri Sembilan)			61.25–96.70	0.40–61.63	8.38–346.82	0.47–1.88	20,190–58,123	(Hussein et al., 2021)
Thailand (Phra Nakhon Si Ayutthaya)			21.41–968.12	16.51–470.44	13.96–108.66	0.16–1.67	6471.44– 20,611.61	(Thongyuan et al., 2021)
UCC			52	14.3	35	0.102	30,890	(Hans Wedepohl, 1995)
World Background			63	20	54	0.5	35,000	(Kabata-Pendias & Mukherjee, 2007)
FAO/WHO			300	100	100	3	27,800	(Barakat et al., 2020)
EU			300	140	150	3	21,700	

NA not available. Results are given as mean values ± standard deviation and are expressed in mg/kg. Means sharing a letter are significantly different according to the Kruskal–Wallis test at a significant level of $p<0.05$. The letter "a" is for the comparison between all sites, and the letter "b" is for the comparison between sites inside the landfill

the highest mean concentration at station 10 located in Zone A, reaching 914 ± 263.55 mg/kg. In contrast, this station exhibits the lowest average concentration of Cd (3.67 ± 0.6 mg/kg). On the other hand, station 5 located inside Zone B shows the lowest mean concentration of Cu (67 ± 2 mg/kg) and Fe (15,025 ± 1034.71 mg/kg). In addition, the highest mean concentration of Cd (12.53 ± 0.91 mg/kg) and Cr (96.63 ± 2.04 mg/kg) is recorded at station 1 of Zone C and station 7 of Zone B. Finally, the lowest mean concentration of Cr is recorded at station 2 of Zone C and is about 7.53 ± 0.31 mg/kg.

Concentrations of trace metals in soil sampled at the vicinity of the dumpsite body follow the decreasing order: Fe (13,801.67 ± 2580.41 mg/k) > Zn (55.92 ± 12.4 mg/kg) > Cr (29.18 ± 4.2 mg/kg) > Cu (25.75 ± 10.45 mg/kg) > Cd (0.22 ± 0.15 mg/kg). These concentrations are different from those in the interior of the dumpsite body (Kruskal–Wallis test, $p<0.05$) but increase with the same trend. Except for Cd, these concentrations exceed those recorded in the control area and are 1.4, 1.5, 4.2, and 8.5 higher than those registered for Fe, Zn, Cu, and Cr respectively.

Pollution quantification

The geoaccumulation index

Results of Igeo calculated for soil in all studied stations are presented in Fig. 3 using a box plot diagram. According to Igeo values obtained, the soil of the control area is uncontaminated by Fe, Zn, Cu, and Cr and moderately to extremely contaminated by Cd.

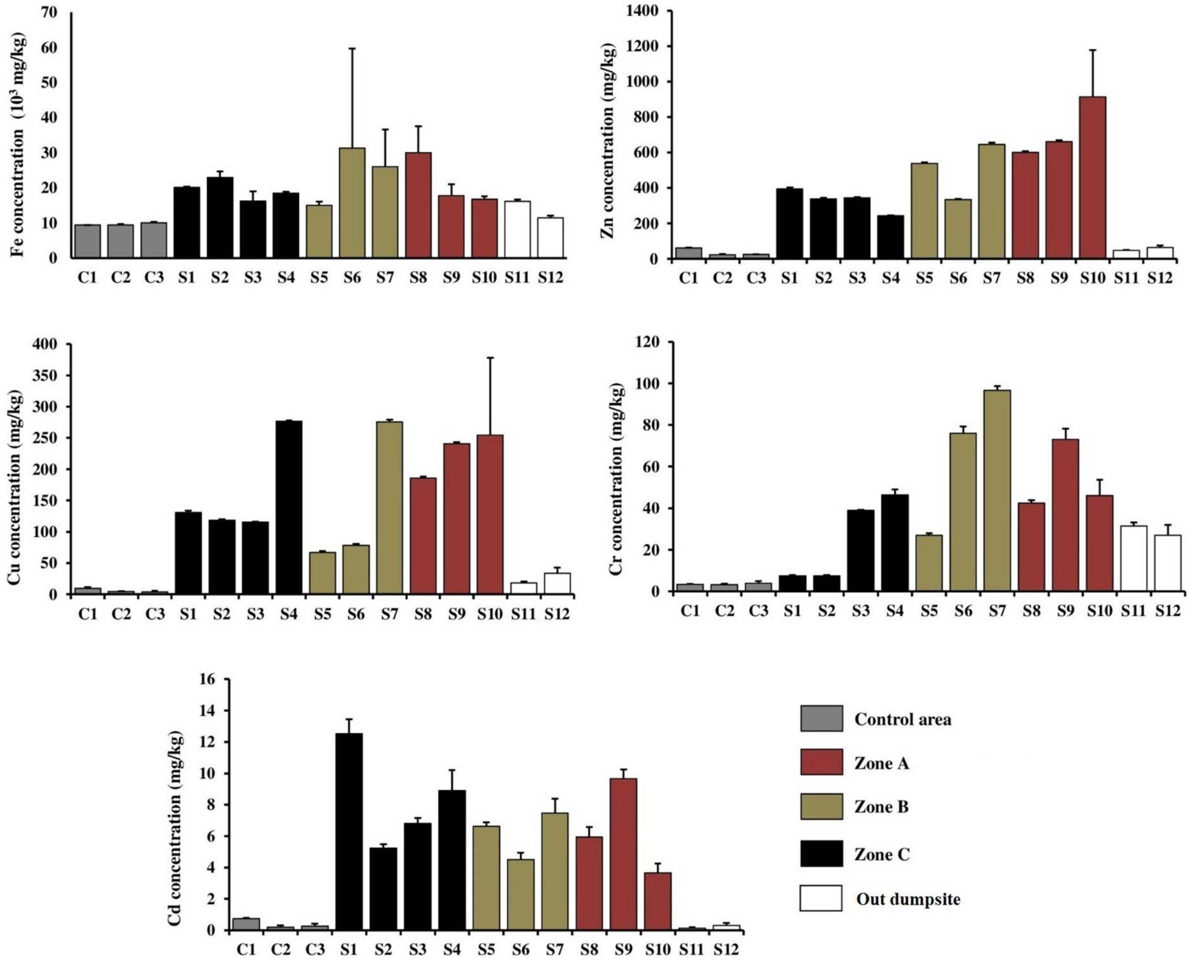


Fig. 2 Trace metal concentration in different stations

Furthermore, as expected, the soil inside the dumpsite body resulted contaminated at many points, but the results were heterogeneous. The mean values of Igeo for Fe qualified as uncontaminated soil in Zone C and Zone A. In contrast, soil can be ranked as uncontaminated to moderately contaminated by Fe for Zone B. In addition, the mean values of Igeo for Zn for the three zones inside the dumpsite body are between 1.5 and 4, which qualify soil as moderately contaminated to heavily contaminated. As for Zn, soil inside the dumpsite body can be ranked between moderately contaminated and heavily to extremely contaminated by Cu as Igeo mean values calculated for this trace metal exceed 1.5 in all the three zones inside the dumpsite body and reach 4.25 at Zone A. In contrast, Igeo mean values for Cr remain inferior to zero in Zone C, exceed zero in Zone A, and reach 1 in Zone B, meaning that soil is generally uncontaminated to moderately contaminated by Cr inside the dumpsite body. The Igeo mean values for Cd surpass 5 in all zones inside the dumpsite body revealing that soil in the dumpsite body is extremely contaminated by Cd. On the other hand, the soil outside the dumpsite body is uncontaminated by Fe, Zn, and Cr as their respective Igeo mean values do not exceed zero. However, Igeo mean values for Cu surpass zero and reach 1 indicating a moderate contamination status for this trace metal. In addition, Igeo mean values for Cd in the soil outside the dumpsite body vary between 2.5 and 5 ranking soil of this area between moderately to heavily contaminated and heavily to extremely contaminated.

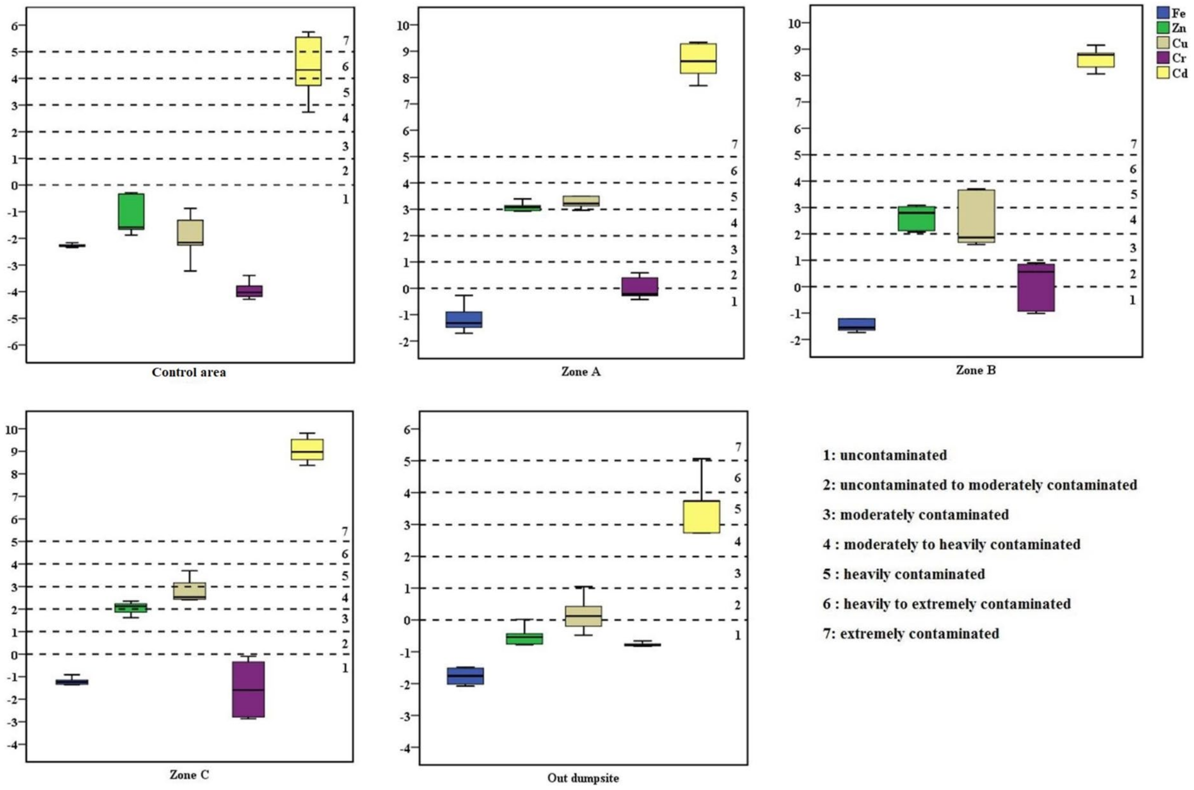
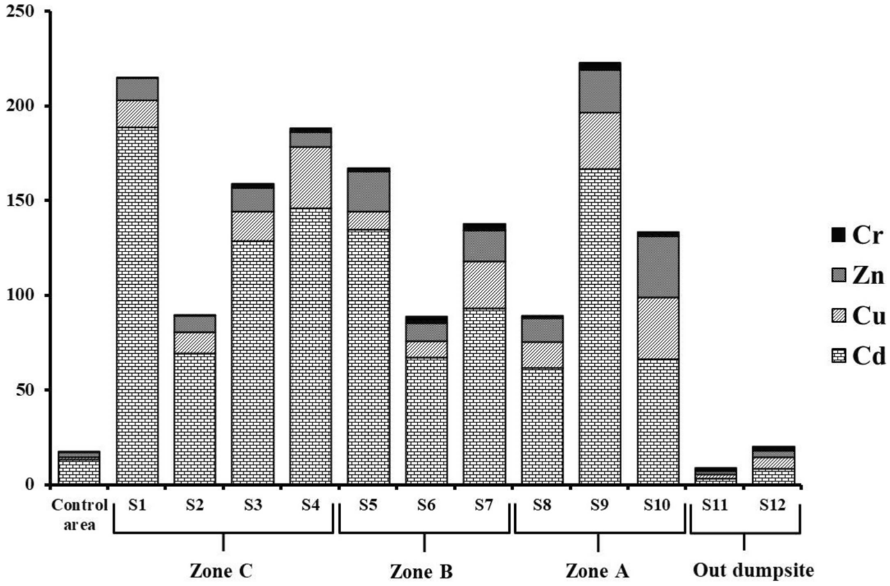


Fig. 3 Box-plots of Igeo

Enrichment factor

The enrichment factor of trace metals used in this study is computed to evaluate the increase of their concentrations regarding their natural amounts in the soil (Fig. 4). For Zn, soil in Zone C, Zone B, and Zone A is significant to very highly enriched with mean values varying from 7.79 ± 0.20 (S4) to 32.43 ± 9.59 (S10). However, the soil outside the dumpsite shows EF values ranging from 1.74 ± 0.15 to 3.33 ± 0.47, which reflects a minimal to modest enrichment. These values are very close to those recorded in soil belonging to the control area which is modestly enriched by Zn with EF values ranging between 1.50 ± 0.1 and 3.94 ± 0.09. For Cu, the soil inside the dumpsite body is also significant to very highly enriched with mean values varying from 8.32 ± 4.86 (S6) to 32.36 ± 0.8 (S4). However, the soil outside the dumpsite shows EF ranging from 2.43 ± 0.33 to 6.23 ± 1.47 indicating a moderate to significant enrichment in contrast to the soil in the control area which presents a minimal enrichment by Cu which varies between 0.89 ± 0.33 and 2.24 ± 0.38. For the harmful trace metals, Cd and Cr, the EF averages show conflicting values between these two metals for the soil inside the dumpsite body. EF for Cd presents dramatic values ranging from 61.20 ± 8.3 (S8) to 188.7 ± 11.99 (S1), which translate to an extremely high enrichment by Cd in whole stations. In contrast, average values of EF for Cr vary from 0.29 ± 0.03 (S1) to 3.71 ± 0.72 (S9), ranking soil inside the dumpsite body between less to moderately enriched by Cr. For the neighboring soil outside the dumpsite body, EF average values ranged between 2.50 ± 1.07 and 7.78 ± 4.1 and between 1.72 ± 0.1 and 2.06 ± 0.31 for Cd and Cr, respectively. These values classify soil outside the dumpsite body between "moderate enrichment" and "significant enrichment" for Cd and between "minimal enrichment" and "moderate enrichment" for Cr. For the soil in the control area, recorded EF values indicate a significant enrichment and a minimal enrichment for Cd (12.73 ± 8.71) and Cr (0.32 ± 0.06), respectively.

Fig. 4 Enrichment factor of trace metals



The pollution load index

Mean values and standard deviations of contamination factors of the five trace metals and the corresponding PLI in each zone are presented in Table 5. As expected, the soil is extremely deteriorated inside the dumpsite body with the highest PLI mean value registered in Zone A (6.82 ± 2.18). However, the minimum PLI mean value is recorded in Zone C (4.48 ± 1.51). PLI values present an increasing order of deterioration as follows: Zone C < Zone B < Zone A respecting, by the way, the age order of the three zones. In addition, the impact induced by trace metals inside the dumpsite body seems to be extended to the nearby soil as this later presents a PLI mean value of 1.09 ± 0.3, revealing a considerable pollution level and a probable deterioration of soil. In contrast, the soil of the control area is qualified to be unpolluted according to its low PLI mean value (0.52 ± 0.14).

The spatial distribution and the interpolation of trace metal concentrations inside the dumpsite body and nearby areas (Fig. 5) show heterogeneity in trace metal concentrations of soil and probable contamination of nearby areas. The same trend is highlighted by PERI which exhibits a higher value inside the dumpsite body with a decreasing trend from the center of the dumpsite body to nearby areas. However, the interpolation can reveal a considerable risk for the surrounding soil located in the east north east of the dumpsite especially.

Ecological risk indices

The ecological risk index of every single metal is computed to assess the single effect and to quantify the effect of all trace metals on living forms inside the dumpsite body and the nearby areas (Table 6). For the soil inside the dumpsite body, Cd presents the highest ecological risk (E^i_r) with a mean value surpassing widely 2093.14 ± 765.14 corresponding to a very high risk. Conversely, the lowest ecological risk is recorded for Cr and Zn with E^i_r values not exceeding 9.64 ± 4.07 and 2.64 ± 1.61, respectively, which indicates low risk. However, Cu presents a moderate ecological risk with a mean E^i_r value of 60.92 ± 30. In addition, the increasing order of ecological risk registered for analyzed trace metals was similar for the three zones investigated, namely Zone C, Zone B, and Zone A, and was as follows: Cr < Zn < Cu < Cd. In contrast, all trace metals have low risk in the soil outside the dumpsite body with a mean E^i_r remaining largely below 40, except for Cd which presents a moderate risk with a mean E^i_r of 63.73 ± 43.29. In contrast, trace metals in the soil of the control area do not show any ecological risk on living forms, except for Cd which records a mean E^i_r of 117.65 ± 79.19, revealing a considerable risk for organisms living in that soil. Moreover, PERI witch indicates the cumulative risk of all trace metals reveals that soil inside dumpsite bodies presents a very high risk for these

Table 5 The estimated CF and PLI for trace metals of different zones

Zone		CF					PLI
		Fe	**Zn**	**Cu**	**Cr**	**Cd**	
Inside dumpsite	**Zone A**	0.70 ± 0.25	13.95 ± 3.75	15.86 ± 4.86	1.54 ± 0.43	62.42 ± 25.36	6.82 ± 2.18
	Zone B	0.78 ± 0.54	9.72 ± 2.64	9.81 ± 7.11	1.90 ± 0.89	60.78 ± 13.95	6.12 ± 2.63
	Zone C	0.63 ± 0.09	6.34 ± 1.11	11.21 ± 4.93	0.72 ± 0.53	82.03 ± 28.83	4.83 ± 1.51
Out dumpsite		0.45 ± 0.08	1.08 ± 0.24	1.80 ± 0.73	0.83 ± 0.12	2.12 ± 1.44	1.09 ± 0.30
Control		0.31 ± 0.01	0.72 ± 0.37	0.43 ± 0.21	0.10 ± 0.02	3.92 ± 2.64	0.52 ± 0.14

organisms, with values for Zone C, Zone A, and Zone B reaching 2524.63, 1968.87, and 1886.09, respectively. However, there is no ecological risk associated with soil contamination near the dumpsite as well as in the control area referring to their respective PERI mean values of 75.47 ± 47.43.

Relationship between trace metals and soil properties

To determine the relationships between trace metals on one hand and between trace metals and the physicochemical soil parameters on the other hand, we used the Pearson correlation and the principal component analysis (PCA), which can provide information for the probable common origin of trace metals.

Pearson's correlation coefficients between trace metals and soil properties are presented in Table 7. The correlation between all trace metals is not significant inside the dumpsite body, whether positive or negative, except between Cu and Cr which is positively significant ($p < 0.05$). In addition, OM and CaCO3 show notable correlations with most the trace metals, while pH and electrical conductivity exhibit weak correlations. A significant positive correlation is recorded between OM and Fe, Zn, and Cr, while OM exhibits a moderat negative correlation with Cd. Moreover, CaCO3 shows a significant positive correlation with Zn and Cr.

Results of PCA illustrated in Fig. 6 show that Zn, Cu, and Cr are regrouped in the same cluster according to the first principal component F1 (32%) compared to Cd and Fe which form another cluster (Fig. 6a). However, the distribution of sample stations exhibits two dominant clusters according to the first principal component F1 (32%). The first cluster includes stations of Zone C while the second involves stations of Zone A (Fig. 6b).

Discussion

Trace metal content

The assessment of trace metal concentrations in soils exposed to anthropogenic activities is a key step in identifying the extent of metal pollution as well as the potential risk that these pollutants may pose to all organisms and human health. In this respect, the concentrations found can be compared with the reference

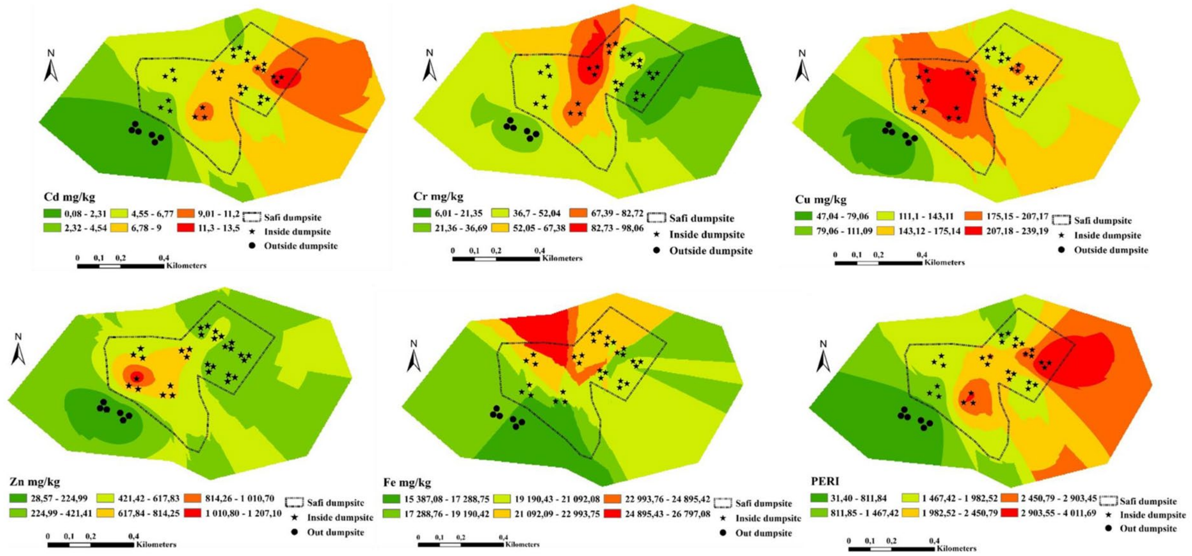


Fig. 5 Spatial distribution of trace metal concentrations and the PERI

thresholds set by the FAO, the WHO, and the EU (Barakat et al., 2020) and therefore qualify the general state of health of soils analyzed.

The concentrations of Zn, Cu, and Cd recorded outside the dumpsite exceed those in the upper continental crust (UCC) except for Cr and Fe. In addition, these concentrations remain inferior to the world background concentration (WBC) and limit values set by the FAO, WHO, and the European Union (EU). As expected, the recorded concentrations in the three zones inside the Safi dumpsite largely surpass concentrations in the control soil for all the analyzed metals, as well as UCC and WBC (except for Fe). Moreover, most of these concentrations inside the dumpsite body exceed the limit values fixed by the FAO, WHO, and EU except those related to Cr and Fe. These high levels are related to the dumping of various wastes such as plastics, metals, alloys, pigments, paints, and used batteries (El Fadili et al., 2022). Furthermore, the observed enrichment of soil by trace metals can be explained by the open burning of wastes by garbage collectors, leading to the generation of ash loaded with high trace metal concentrations (Bayuseno & Schmahl, 2010; Dung et al., 2018). The results recorded for the control soil taken as reference values for this study support the impact of metal pollutants on the dumpsite soil through anthropogenic dumping as the trace metal concentrations recorded in the control soil remain lower than those found in the dumpsite soil and even below the WHO, FAO, and EU guidelines. In addition, concentrations in the control soil were found to be lower than the concentrations in the UCC and WBC. Such a difference in concentrations in UCC and WBC might be related to the local soil physicochemical characteristics. In this context, it is important to note that a more comprehensive map of metal concentrations at a broader geographic scale, taking into account the

Table 6 The ecological factor index and potential ecological risk index of trace metals

Zone		E^i_r				**PERI**
		Zn	**Cu**	**Cr**	**Cd**	
Inside dumpsite	**Zone A**	13.95±3.75	79.29±24.28	3.08±0.87	1872.55±760.88	1968.87±789.78
	Zone B	9.72±2.64	49.03±35.53	3.80±1.77	1823.53±418.54	1886.09±458.58
	Zone C	6.34±1.11	56.07±24.65	1.44±1.06	2460.78±865.01	2524.63±891.84
Out dumpsite		1.08±0.24	9.00±3.65	1.67±0.24	63.73±43.29	75.47±47.43
Control		0.72±0.37	2.13±1.06	0.20±0.04	117.65±79.19	120.69±80.66

Table 7 The Pearson's correlation matrix for the TM concentrations and the physico-chemical properties of the soils

	Fe	Zn	Cu	Cr	Cd	pH	EC	OM	$CaCO_3$
Fe	1.00								
Zn	-0.07	1.00							
Cu	-0.03	0.33	1.00						
Cr	0.18	0.28	**0.47****	1.00					
Cd	-0.10	-0.25	0.15	-0.16	1.00				
pH	-0.33	-0.08	-0.03	-0.25	-0.18	1.00			
EC	-0.07	-0.10	-0.09	-0.16	-0.20	**0.52****	1.00		
OM	**0.52****	**0.39***	0.27	**0.51****	**-0.38***	**-0.52****	0.03	1.00	
$CaCO_3$	-0.27	**0.67****	0.30	**0.58****	-0.28	0.05	-0.28	0.20	1.00

*Significance level alpha = 0.05; **significance level alpha = 0.01

heterogeneity of the geochemical background across the national geologic extent, is needed better to assess the degree of pollution at local scales. Compared to other investigated waste disposal sites throughout Morocco, such as Marrakech landfill receiving more than 700 tons/day from a population of 1.3 million, Bengrir

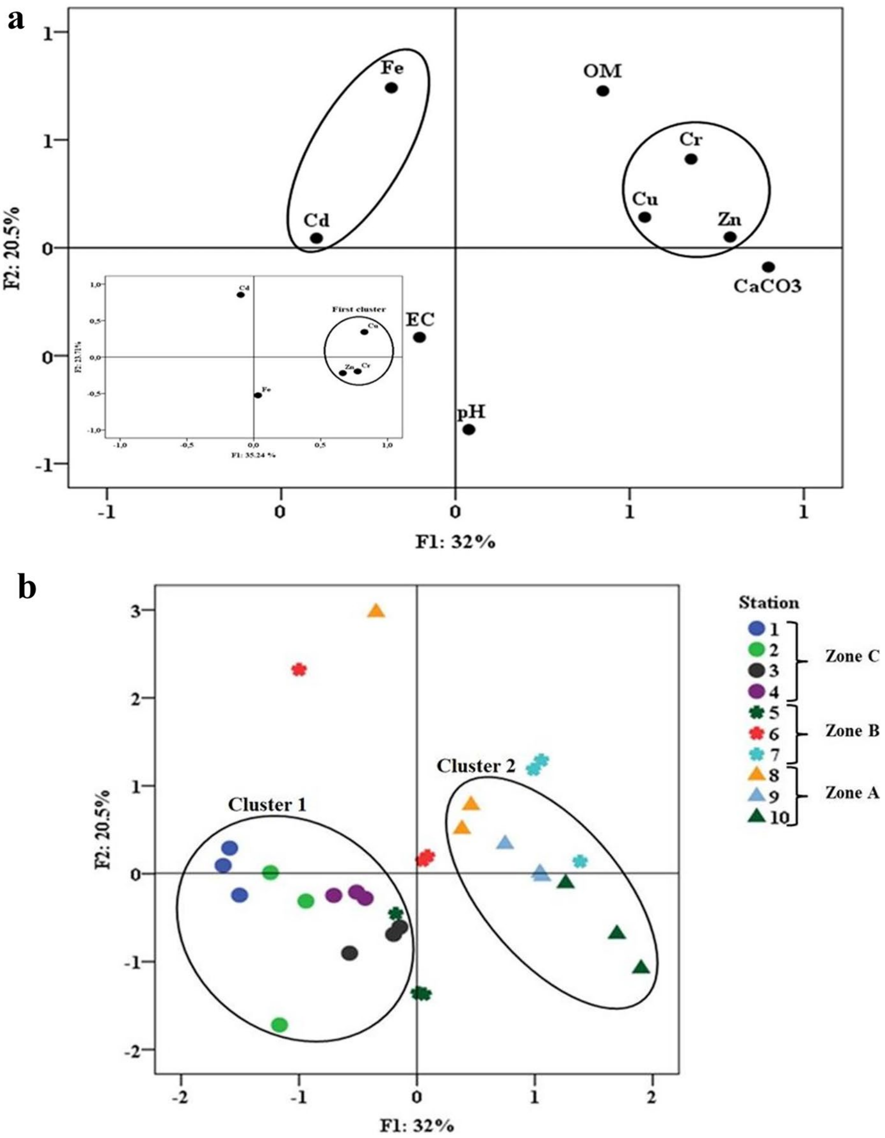


Fig. 6 **a** principal component analysis of trace metals and soil parameters of the dumpsite body. **b** Principal component analysis of sampling stations of the dumpsite body

dumpsite for 93 tons/day from about 100,000 habitants, and Ahfir for 32 tons/day from about 20,000 habitants (El Fadili et al., 2022; Nhari et al., 2014). The concentration of all trace metals registered in Safi dumpsite soils is higher than those recorded in Benguerir landfill by El Fadili et al. (2022) but inferior to those recorded by Kennou et al. (2015) in the Marrakech landfill, except for Cd. These two landfills are geographically close to the Safi dumpsite (about 121.5 km and 125 km apart from the Benguerir landfill and Marrakech landfill, respectively) and have similar climatic conditions. However, the nature of dumped waste differs greatly between the three landfills in that the Benguerir and Marrakech landfills are mainly domestic, whereas a large proportion of the waste from Safi and the surroundings consists of industrial wastes such as those related to the production of phosphate, cement, and canned fish. The difference observed in the contamination profile of every landfill is mainly related to landfill type (Wang et al., 2022), waste nature, soil nature, and other properties. Nevertheless, Zn and Fe are predominant in all these landfills compared to other metals (El Fadili et al., 2022; Fait et al., 2018; Kennou et al., 2015), whose metallic contamination profile is different from that reported by Nhari et al. (2014) in Ahfir city (north east of Morocco) where the surficial soil is highly enriched by lead. Furthermore, to be more exhaustive in our comparison, it is important to point out that the studied Moroccan landfills are not the same size and certainly not the same age, which might also impact their respective metallic pollution status. The Safi dumpsite remains among the oldest landfill in Morocco in addition to those of Marrakech and Casablanca cities. Old landfills in contrast to young landfills are characterized by basic soils favoring the fixation of considerable amounts of trace metals by precipitation (Yuan et al., 2017). In young landfills more than in the old landfill, acid soils loaded with humic and fluvic acids retain trace metals selectively and have an important role in the migration of these components by leaching process outside the landfill or to the deepest soil layers. Wang et al. (2022) emphasized the effect of the landfill age on the soil trace metal concentration and indicates that Cd concentration in the soil decrease as the age of the landfill increase compared to other trace metals. Moreover, this can be related to the trend of soil being alkaline with age and the alteration of surficial soils containing considerable amounts of trace metals. On an international scale, the concentrations recorded for all trace metals in the present study are consistent with previous works conducted in Ghana by Akanchise et al. (2020) in two landfills receiving a significant amount of e-waste and household waste. The same trend is recorded in other landfills recycling valuable wastes by waste workers and damping the organic ones (El Daba & Abd El Wahab, 2020; Thongyuan et al., 2021). In contrast to the open landfill (or dumpsites), the engineered landfill can reduce the contamination of soils by using numerous layers of geosynthetic clay liner, HDPE membranes, and protective geo-textiles that prevent the leachate migration which contaminate adjacent soils and the contamination of deep layer of soils by infiltration. In this type of landfill, low concentrations of trace metals are recorded. Adamcová et al. (2017) registered low concentrations of trace metals in the soil inside and outside the aged landfill of Stepanovic which do not exceed limits fixed by the FAO and WHO (Barakat et al., 2020). The study area is a non-engineered wild landfill, more similar to a dumpsite, where the infiltration of leachate accelerated by acid rainfalls, within the soil, leads probably to the contamination of the groundwater closest to the surface. The characteristics of the bioclastic limestone underlying the dumpsite improve groundwater contamination probability. Relatively loose layers characterizing these bioclastic limestones are pretty rich in solution pores with a low resistance of tensile strength (He et al., 2014). It remains consistent with previous works that emphasized groundwater contamination as a consequence of the infiltration of pollutants through permeable layers under landfills which present a considerable health risk (Asouam et al., 2021; Chofqi et al., 2004; Fatta et al., 1999).

Thus, as could be expected from previous research (Vaccari et al., 2018), metallic pollution seems to spread from the landfill body to the adjacent soil. Indeed, the concentration of metals in the soil adjacent to the dumpsite also exceeds the concentrations recorded in the control soil. In addition, the soil concentrations of Zn, Cu, and Cr in the vicinity of the dumpsite body surpass their respective UCC and WBC concentrations. The extension of the pollution from the dumpsite body to neighboring soil is a consequence of several routes, mainly the migration of the loaded leachate from the dumpsite to nearby soils (Makuleke & Ngole-Jeme, 2020) and the wind dissemination of fly ash loaded by trace metals (Velis & Cook, 2021). Surrounding soils are mostly agricultural, with barley and maize being the most locally cultivated crops at the regional scale. These crops are well known for their high capacity to concentrate trace metals, especially in their leaves (González et al., 2017; Poniedziałek et al., 2010; Sękara et al., 2005; Wuana & Okieimen, 2010). Their contamination by metallic pollutants might then threaten soil fauna, domestic animals, and human health by consuming contaminated crops and water wells.

Soil properties and trace metal contents

The physicochemical properties of soil affect greatly the behavior of trace metals and their bioavailability (Tack, 2010). The organic matter, pH, calcium carbonates, conductivity, and soil texture are significant soil properties influencing trace metal availability to soil organisms (Alloway, 2013; Hooda, 2010). Among the wide variety of wastes dumped in the landfill soil, organic matter is largely represented. At the level of the Safi dumpsite body, their content is sometimes two to five times higher than in the soil of the control area. The high content of OM recorded in the soil within the dumpsite body have the same trend as those reported for the landfill of Marrakech city (Morocco) (Kennou et al., 2015) and the landfill of The Kpone (Ghana) (Obiri-Nyarko et al., 2021). Several results indicated that OM could be involved in the trace metals behavior in the contaminated soil and hence their bioavailability (El Fadili et al., 2022; Kennou et al., 2015; Makuleke & Ngole-Jeme, 2020; Obiri-Nyarko et al., 2021). The humification process of organic matter releases humic and fluvic acids (Guggenberger, 2005), which by complexation or adsorption can bind with the mineral fraction of the soil, including trace metals (Lefèvre, 2015). In addition, the release of nutrients by the mineralization of organic matter increases the cation exchange capacity of the soil and reduces the available amount of trace metals for plants (El Fadili et al., 2022). These arguments are concordant with the positive relationships between the level of OM with all trace metals investigated in the dumpsite soil (Table 7), except for Cd which is negatively correlated with OM ($r = -0.38$, $p < 0.05$). The data in the literature are inconsistent in this regard in that some are consistent with our results while others show opposite patterns. For example, Bjerre and Schierup (1985) studied the influence of waterlogging on the availability and uptake of trace metals by oat grown in different soils and highlighted the negative effect of higher OM levels which decreases the transfer of Cd in the soil. In counterpart, the study conducted on the open landfill of Marrakech city by Kennou et al. (2015) indicated that the OM levels are positively correlated with Zn, Cu, Cd, Cr, and Pb concentrations; however, that correlation remains not significant as recorded by Obiri-Nyarko et al. (2021) within The Kpone landfill (Ghana) between the OM levels and Zn, Cu, Pb, and Hg concentrations compared to those recorded by the present study. In contrast, Makuleke and Ngole-Jeme (2020) around the closed Lumberstewart landfill registered a negative correlation between the OM levels and Fe, Zn, Cd, Cr, and Cu concentrations in surficial soil (0–30 cm). The authors explained such a negative correlation by the migration of trace metals to deep layers of the soil where their amounts surpass those found in the surficial soil. pH values recorded in the Safi dumpsite soils vary between 6.54 and 8.30 and indicate that soil is rather neuter to alkaline. Similar results were reported by previous studies conducted on numerous African landfills (Agbeshie et al., 2020; Ebong et al., 2019; El Fadili et al., 2022; Kennou et al., 2015). These results are related to the considerable amounts of calcium carbonates in the dumpsite soil which vary between 5.70 and 23.03%. Agbeshie et al. (2020) explain the alkalinity of the dumpsite soil to the high content of liming materials and alkali-earth metals in the soil and remain consistent with the ascertainment in the landfill of Marrakech where the alkalinity is related to carbonates such as CaCO3 and MnCO3 (Kennou et al., 2015). The pH is greatly involved in many trace metal processes in the soil as solubilization, precipitation, adsorption, and desorption (Kouchou et al., 2020) and thus controls their mobility (Ennaji et al., 2020). Furthermore, calcium carbonates are highly correlated with Zn, Cr, and Cu indicating that they can influence their concentrations through a selective retention process towards these metals. However, these calcium carbonates show weak negative correlations with Cd and Fe suggesting that such a retention mechanism between calcium carbonates and these two metals is not very evident (Table 7). In addition, as the electrical conductivity (EC) reflects the number of soluble salts in the soil, the mean value of EC obtained in our results (e.g., 3.43 ms/cm) reveals that soil in the dumpsite body is moderately saline (Shirokova et al., 2000). These results are consistent with those recorded by Kennou et al. (2015) in the landfill of Marrakech city but remain superior to those recorded by Agbeshie et al. (2020) in the landfill of Sunyani municipality (Ghana) and by Gujre et al. (2021) in the landfill of Guwahati city (India) adjacent to a Ramsar site. On the other hand, EC shows a very weak negative correlation with Cd and Cr and is not correlated with Zn, Cu, and Fe which means that it does not influence the content of trace metals and does not affect directly the behavior of these pollutants in the Safi dumpsite soil.

Surface soil is the appropriate layer for the formation of the clay-humus complex. The high organic matter content, the presence of clay used to cover wastes, and cations linked with elevated conductivity within the landfill soil promote the formation of the clay-humus complex involved in the fixation of trace metals in the soil (Borůvka & Drábek, 2011).

Origin and spatial variation of trace metals

The metallic pollution profile change from one landfill (or dumpsite) to another as the behavior of trace metals in soil is related to several parameters such as trace metals origin, soil properties, and the valence state of trace metals (Kabata-Pendias, 1993). The anthropogenic source of trace metals is confirmed by the results of pollution indices (Igeo, CF, and EF) which present high values exceeding those of lithogenic metals. However, the lack of correlation between trace metals (Pearson test, $p > 0.05$), except for Cu and Cr (Pearson test, $p < 0.05$) (Table 7), indicates that these trace metals do not derive from the same type of waste, even though they all originally result from anthropogenic activities of dumping wastes. In contrast to our study, El Fadili et al. (2022) in the landfill of Bengrir (Morocco) and Thongyuan et al. (2021) in the landfill of Phra Nakhon Si Ayutthaya province (Thailand) recorded a very strong correlation between Zn, Cu, Cr, and Cd. They concluded that anthropogenic activities are likely the most probable source of these pollutants. In addition, the clustering formed by Zn, Cu, and Cr for the first cluster and Cd and Fe for the second (Fig. 6) indicates that these metals can present the same profile but not the same behavior in the dumpsite soil. Moreover, trace metals from the anthropogenic origin are very mobile which increases their bioavailability compared to those of lithogenic origin (Kabata-Pendias, 1993).

The difference observed in the contamination profile of every landfill is related to waste nature and soil properties. This difference can be observed in the same landfill as the case of our study area. Concentrations of Zn and Cr are significantly different (Kruskal–Wallis test, $p < 0.05$) between zones A, B, and C compared to Cu, Cd, and Fe which present the same trend of concentration within all zones (Table 4). This variability is illustrated more clearly in the results of the interpolation (Fig. 5) exhibiting an increasing trend of contamination related to the age of studied zones. Besides, the oldest Zone A exhibits the largest surface which surpasses those of zone B an A. In addition, in the first years of exploitation of the dumpsite, Zone A received a great amount of waste reduced by open burning practices. The open burning generates ashes loaded with trace metals which increase concentrations of trace metals and corroborates with the contamination state of Zone A. Moreover, the mean value of PLI combining the CF of all studied trace metals shows the following decreasing order of contamination as Zone A > Zone B > Zone C which matches well with the order of the age of the three studied zones within the landfill.

Contamination and ecological state

The uncontaminated state by trace metals of the soil of the control area is defined according to the result of Igeo and EF except for Cd which qualifies control soils as significantly enriched by Cd which presents also considerable risk according to their respective E^i_r. These results can be explained by the lack of local background concentration and the use of universal background concentration for all trace metals where the background concentration of Cd is fifty times lower than the WBC for Cd. The use of universal background in some cases can overestimate the pollution state of the studied soil. In addition, the summative contamination by all trace metals indicates that control soil is not deteriorated and has a low risk to all living beings and humans according to the result of PERI.

On the other hand, according to Igeo and EF results, the contamination state of the soil of the dumpsite body is alarming. These results are related to high-level concentrations of trace metals, especially toxic ones (Cd and Cr). Moreover, previous works emphasized the relationship between the deterioration of soil quality and the contamination by trace metals in landfills (Akanchise et al., 2020;

Akoto et al., 2016; El Fadili et al., 2022; Makuleke & Ngole-Jeme, 2020; Thongyuan et al., 2021; Wang et al., 2020). Moreover, the soil inside the dumpsite body is moderate to highly polluted by Zn and Cu. This result remains consistent with previous works on municipal dumpsites in Bengrir city (Morocco), Guwahati city (India), and Chiang Rak Noi municipality (Thailand) (El Fadili et al., 2022; Gujre et al., 2021; Thongyuan et al., 2021). In addition, the soil of the dumpsite body is extremely contaminated by Cd and weakly contaminated by Cr and exhibits the same trend of pollution as the landfill of Marrakech city (Kennou et al., 2015). This contamination state is strongly related to the anthropogenic activity of dumping wastes. The dumpsite of Safi received numerous wastes in nature including wastes from artisanal activities such as pottery, tannery, and ceramic in addition to wastes from the fish canning industry. These wastes are highly loaded by Cd and Cr in addition to household waste such as batteries, wireless, and plastic (Mmereki et al., 2016; Singh et al., 2019). The value of PLI obtained translates the summative effects of all trace metals and reveals that soils inside the dumpsite deteriorate, where the Cd contributes more than 50% in the degradation of the quality of soils. The deterioration of the soil as the biotope of numerous fauna and flora imposes a very high ecological risk. This risk is evaluated by PERI which is the summative risk of studied trace metals. In our study, Cd contributed with more than 90% of the PERI computed compared to other trace metals, which translates to a very high ecological risk and consist with results recorded by El Fadili et al. (2022) in the soil of the open landfill of Bengrir city contaminated by Cd and Pb. Toxic trace metals such as Cd, Cr, Pb, As, and Hg contribute considerably to the increasing risk for all organisms due to their existence in the soil. Iqbal et al. (2021) reveal in a young landfill a considerable risk exhibited by the contamination of the soil with a low concentrations of Cd and Pb. The risk associated with the contamination of the soil of the dumpsite of Safi city can be more alarming if we considered other toxic trace metals not measured in the current study such as arsenic, lead, and mercury. The ecological risk posed by the contamination of the soils of the dumpsite by trace metals affects animals spending their life or a part of their life cycle in this area. Soil-dwelling invertebrates such as snails, ants, and earthworms are among the most affected animals by soil contamination (Baroudi et al., 2020; Verma et al., 2022). The Safi dumpsite is populated by these invertebrates that accumulate trace metals in their vital organs posing to them numerous issues. Furthermore, the effects can involve their behavior, fecundity, nutrition, and survival in extreme cases (Dar et al., 2019). In addition, small vertebrates and birds that frequent landfills to search for prey or materials to build nests are not spared from this contamination. The dumpsite of Safi is frequented mostly by cattle egrets, storks, and seagulls. These animals can accumulate trace metals by inhaling aerosol and flying ash, ingesting plastic or other wastes, and having dermal contact with contaminated soil (Scaramozzino et al., 2019). Therefore, this can affect the growth and development of certain parts of the animals, such as the length of the primary wings and beak. Waste workers and shepherds frequenting the dumpsite are also exposed to the pollution of soils by trace metals through the same pathways as animals. Moreover, in addition to waste workers, the local population is highly exposed. Indeed, consuming the milk and meat of livestock that graze in the landfill, in addition to the crops of the neighboring fields by the population, increases the possibility of transmitting trace metals to humans and thus increases the incidence of diseases associated (Chaithanya et al., 2021; Neeratanaphan et al., 2017; Ruchuwararak et al., 2019).

The contamination by trace metals caused by the dumpsite spreads to neighboring areas due to several factors. Migration of leachate generated by water contained in wastes and rainfall water, in addition to the wind as the motor of dissemination of aerosol and ash, contributes to the expansion of the pollution by trace metals. According to Igeo and EF, the soil of the nearby area is contaminated by Cu and Cd, especially. This fact indicates that the surrounding soil of the dumpsite is deteriorated and corroborates with the result of PLI (Table 5). In addition, the interpolation of the PERI (Fig. 5) reveals an expansion of the pollution and the associated ecological risk from the center to the East and the northeast of the dumpsite, which match well with the direction of dominating wind in the Safi city (Minoubi et al., 2013).

Conclusions

The study is the first contribution to explore the pollution state of the dumpsite and its surrounding area in the province of Safi city. It reveals considerable soil trace metal contamination inside the dumpsite surpassing the background concentrations according to results of the CF and Igeo and remains consistent with other works conducted in other dumpsites worldwide. Trace metals extend outside the dumpsite to the surrounding area as indicated by the interpolation of soil trace metal concentration, which resulted by their migration by leaching and the wind action. For instance, the order of soil enrichment by trace metals is Cd > Cu > Zn > Cr > Fe, confirmed by Igeo and EF. However, this enrichment is more highlighted inside the dumpsite. On the other hand, evaluating the quality of soils and associated ecological risk using PLI and PERI indicate that Safi dumpsite is a hotspot of trace metals pollutants with deteriorating quality of soils. In addition, the concentration and the behavior of trace metals are affected by soil properties such as OM and CaCO3 and by the age of the dumpsite zone. PCA suggests that the trace metals may have originated from degraded waste that was dumped in the area. These results shed light on the ecological issues related to soil pollution with trace metals associated with inappropriate waste management methods. However, the evaluation of the potential threats to human health is paramount. Therefore, we are conducting further studies to investigate the transfer of trace metals from contaminated soils towards edible plants and invertebrates (snails) and evaluate the risk to human health, especially settlers near the dumpsite and also people consuming edible plants and snails picked from the dumpsite. Additionally, we focused on the rainy season in this research. However, it will be interesting to devote future contributions to studying the seasonal pattern of soil metal contamination in the Safi dumpsite and surrounding area. This preliminary work enriches pieces of knowledge about the quality of the environment of Safi city, and local stakeholders can use it to choose adequate methods to restore this polluted area.

Author contribution Conceptualization: A.B., H.A., and A.D. Methodology: A.B., H.A., and A.D. Formal analysis: A.B. and H.A. Writing original draft preparation: A.B., A.D and H.A. Writing review and editing: A.B., A.D., G.V., and H.A. Supervision: A.D., H.A., and G.V. All authors have read and agreed to the published version of the manuscript.

Availability of data and materials The authors confirm that the data supporting the finding of this study are available within the article and its supplementary material. Raw data that support the findings of this study are available from the corresponding author, upon reasonable request.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Abdel-Shafy, H. I., & Mansour, M. S. M. (2018). Solid waste issue: Sources, composition, disposal, recycling, and valorization. *Egyptian Journal of Petroleum, 27*(4), 1275–1290. https://doi.org/10.1016/j.ejpe.2018.07.003

Abdu, N., Abdullahi, A. A., & Abdulkadir, A. (2017). Heavy metals and soil microbes. *Environmental Chemistry Letters, 15*(1), 65–84. https://doi.org/10.1007/s10311-016-0587-x

Adamcová, D., Radziemska, M., Ridošková, A., Bartoň, S., Pelcová, P., Elbl, J., Kynický, J., Brtnický, M., & Vaverková, M. D. (2017). Environmental assessment of the effects of a municipal landfill on the content and distribution of heavy metals in *Tanacetum vulgare* L. *Chemosphere, 185*, 1011–1018. https://doi.org/10.1016/j.chemosphere.2017.07.060

Agamuthu, P. (2013). Landfilling in developing countries. *Waste Management & Research, 31*(1), 1–2. https://doi.org/10.1177/0734242X12469169

Agbeshie, A. A., Adjei, R., Anokye, J., & Banunle, A. (2020). Municipal waste dumpsite: Impact on soil properties and heavy metal concentrations, Sunyani, Ghana. *Scientific African, 8*, e00390. https://doi.org/10.1016/j.sciaf.2020.e00390

Akanchise, T., Boakye, S., Borquaye, L. S., Dodd, M., & Darko, G. (2020). Distribution of heavy metals in soils from abandoned dump sites in Kumasi, Ghana. *Scientific African, 10*, e00614. https://doi.org/10.1016/j.sciaf.2020.e00614

Akoto, O., Nimako, C., Asante, J., & Bailey, D. (2016). Heavy metals enrichment in surface soil from abandoned waste disposal sites in a hot and wet tropical area. *Environmental Processes, 3*(4), 747–761. https://doi.org/10.1007/s40710-016-0183-x

Alam, R., Ahmed, Z., & Howladar, M. F. (2020). Evaluation of heavy metal contamination in water, soil and plant around the open landfill site Mogla Bazar in Sylhet, Bangladesh. *Groundwater for Sustainable Development, 10*, 100311. https://doi.org/10.1016/j.gsd.2019.100311

Alikhan, S., & Arib, F. (2019). Des solutions sociales et innovantes pour une gestion durable des déchets au Maroc.

SSE Knowledge Hub for the SDGs. Avalaible online: https://knowledgehub.unsse.org/fr/knowledge-hub/des-solutions-sociales-et-innovantes-pour-une-gestion-durable-des-dechets-au-maroc-3/ (accessed on 5 May 2023)

Alloway, B. J.(2013). Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability (3rd Ed). Springer: Dordrecht, The Netherlands. https://doi.org/10.1007/978-94-007-4470-7

Andaloussi, K., Achtak, H., Nakhcha, C., Haboubi, K., & Stitou, M. (2021). Assessment of soil trace metal contamination of an uncontrolled landfill and its vicinity: The case of the city of 'Targuist' (Northern Morocco). *Moroccan Journal of Chemistry*, *9*(2). https://doi.org/10.48317/imist.prsm/morjchem-v9i2.23680

Arya, S., Rautela, R., Chavan, D., & Kumar, S. (2021). Evaluation of soil contamination due to crude E-waste recycling activities in the capital city of India. *Process Safety and Environmental Protection, 152*, 641–653. https://doi.org/10.1016/j.psep.2021.07.001

Asouam, S., Faik, F., El Morjani, Z. E. A., & Abioui, M. (2021). The geological and hydrogeological characteristics of Tamelast landfill site in Agadir, Morocco. *E3S Web of Conferences*, *234*, 00085. https://doi.org/10.1051/e3sconf/202123400085

Ayt Ougougdal, M., Chaibi, M., Mercier, D., Maquaire, O., Maanan, M., Costa, S., Charif, A., & Ragaru, E. (2020). The typology of slope slides of the cliff coast of Safi-Morocco, and the role of the clay layer in triggering failure. *Journal of African Earth Sciences*, *168*, 103878. https://doi.org/10.1016/j.jafrearsci.2020.103878

Barakat, A., Ennaji, W., Krimissa, S., & Bouzaid, M. (2020). Heavy metal contamination and ecological-health risk evaluation in peri-urban wastewater-irrigated soils of Beni-Mellal city (Morocco). *International Journal of Environmental Health Research, 30*(4), 372–387. https://doi.org/10.1080/09603123.2019.1595540

Barbieri, M., Sappa, G., Vitale, S., Parisse, B., & Battistel, M. (2014). Soil control of trace metals concentrations in landfills: A case study of the largest landfill in Europe, Malagrotta, Rome. *Journal of Geochemical Exploration, 143*, 146–154. https://doi.org/10.1016/j.gexplo.2014.04.001

Bar-On, Y. M., Phillips, R., & Milo, R. (2018). The biomass distribution on Earth. *Proceedings of the National Academy of Sciences, 115*(25), 6506–6511. https://doi.org/10.1073/pnas.1711842115

Baroudi, F., Al Alam, J., Fajloun, Z., & Millet, M. (2020). Snail as sentinel organism for monitoring the environmental pollution; a review. *Ecological Indicators*, *113*, 106240. https://doi.org/10.1016/j.ecolind.2020.106240

Bayuseno, A. P., & Schmahl, W. W. (2010). Understanding the chemical and mineralogical properties of the inorganic portion of MSWI bottom ash. *Waste Management, 30*(8–9), 1509–1520. https://doi.org/10.1016/j.wasman.2010.03.010

Bjerre, G. K., & Schierup, H. H. (1985). Influence of waterlogging on availability and uptake of heavy metals by oat grown in different soils. *Plant and Soil, 88*(1), 45–56. https://doi.org/10.1007/BF02140665

Borah, P., Gujre, N., Rene, E. R., Rangan, L., Paul, R. K., Karak, T., & Mitra, S. (2020). Assessment of mobility and environmental risks associated with copper, manganese and zinc in soils of a dumping site around a Ramsar site. *Chemosphere*, *254*, 126852. https://doi.org/10.1016/j.chemosphere.2020.126852

Borůvka, L., & Drábek, O. (2011). Heavy metal distribution between fractions of humic substances in heavily polluted soils. *Plant, Soil and Environment*, *50*(8), 339–345. https://doi.org/10.17221/4041-PSE

Brtnický, M., Pecina, V., Baltazár, T., Vašinová Galiová, M., Baláková, L., Bęś, A., & Radziemska, M. (2020). Environmental impact assessment of potentially toxic elements in soils near the runway at the international airport in Central Europe. *Sustainability, 12*(17), 7224. https://doi.org/10.3390/su12177224

Chaithanya, M. S., Das, B., & Vidya, R. (2021). Investigation of contamination pathway and human health risk assessment from metals in milk from the cows grazing in an industrial area: A mass balance approach. https://doi.org/10.21203/rs.3.rs-462351/v1

Chandrasekaran, A., Ravisankar, R., Harikrishnan, N., Satapathy, K. K., Prasad, M. V. R., & Kanagasabapathy, K. V. (2015). Multivariate statistical analysis of heavy metal concentration in soils of Yelagiri Hills, Tamilnadu, India – Spectroscopical approach. *Spectrochimica Acta Part a: Molecular and Biomolecular Spectroscopy, 137*, 589–600. https://doi.org/10.1016/j.saa.2014.08.093

Charzyński, P., Plak, A., & Hanaka, A. (2017). Influence of the soil sealing on the geoaccumulation index of heavy metals and various pollution factors. *Environmental Science and Pollution Research, 24*(5), 4801–4811. https://doi.org/10.1007/s11356-016-8209-5

Chen, H., Wang, L., Hu, B., Xu, J., & Liu, X. (2022). Potential driving forces and probabilistic health risks of heavy metal accumulation in the soils from an e-waste area, southeast China. *Chemosphere*, *289*, 133182. https://doi.org/10.1016/j.chemosphere.2021.133182

Chofqi, A., Younsi, A., Lhadi, E. K., Mania, J., Mudry, J., & Veron, A. (2004). Environmental impact of an urban landfill on a coastal aquifer (El Jadida, Morocco). *Journal of African Earth Sciences, 39*(3–5), 509–516. https://doi.org/10.1016/j.jafrearsci.2004.07.013

Cocârţă, D. M., Neamţu, S., & Reşetar Deac, A. M. (2016). Carcinogenic risk evaluation for human health risk assessment from soils contaminated with heavy metals. *International Journal of Environmental Science and Technology, 13*(8), 2025–2036. https://doi.org/10.1007/s13762-016-1031-2

Dahchour, A., & Hajjaji, S. E. (2020). Management of solid waste in Morocco. In A. M. Negm & N. Shareef (Eds.), *Waste Management in MENA Regions* (pp. 13–33). Springer International Publishing. https://doi.org/10.1007/978-3-030-18350-9_2

Dar, M. I., Green, I. D., & Khan, F. A. (2019). Trace metal contamination: Transfer and fate in food chains of terrestrial invertebrates. *Food Webs*, *20*, e00116. https://doi.org/10.1016/j.fooweb.2019.e00116

DesMarias, T. L., & Costa, M. (2019). Mechanisms of chromium-induced toxicity. *Current Opinion in Toxicology, 14*, 1–7. https://doi.org/10.1016/j.cotox.2019.05.003

Ebong, G. A., Dan, E. U., Inam, E., & Offiong, N. O. (2019). Total concentration, speciation, source identification and associated health implications of trace metals in Lemna dumpsite soil, Calabar, Nigeria. *Journal of King Saud*

University-Science, 31(4), 886–897. https://doi.org/10.1016/j.jksus.2018.01.005

Dung, T., Vassilieva, E., Swennen, R., & Cappuyns, V. (2018). Release of trace elements from bottom ash from hazardous waste incinerators. *Recycling, 3*(3), 36. https://doi.org/10.3390/recycling3030036

El Daba, A. E. M., & Abd El Wahab, M. (2020). Heavy metal contamination and physicochemical properties of soils in municipal solid waste dumpsite, Hurghada, Red Sea, Egypt. *Egyptian Journal of Aquatic Biology and Fisheries*, *24*(7), 913–930. https://doi.org/10.21608/ejabf.2020.133811

El Fadili, H., Ben Ali, M., Touach, N., El Mahi, M., & Mostapha Lotfi, E. (2022). Ecotoxicological and pre-remedial risk assessment of heavy metals in municipal solid wastes dumpsite impacted soil in Morocco. *Environmental Nanotechnology, Monitoring & Management*, *17*, 100640. https://doi.org/10.1016/j.enmm.2021.100640

El Hamzaoui, E. H., El Baghdadi, M., Oumenskou, H., Aadraoui, M., & Hilali, A. (2020). Spatial repartition and contamination assessment of heavy metal in agricultural soils of Beni-Moussa, Tadla plain (Morocco). *Modeling Earth Systems and Environment, 6*(3), 1387–1406. https://doi.org/10.1007/s40808-020-00756-3

Ennaji, W., Barakat, A., El Baghdadi, M., & Rais, J. (2020). Heavy metal contamination in agricultural soil and ecological risk assessment in the northeast area of Tadla plain, Morocco. *Journal of Sedimentary Environments, 5*(3), 307–320. https://doi.org/10.1007/s43217-020-00020-9

Ertani, A., Mietto, A., Borin, M., & Nardi, S. (2017). Chromium in agricultural soils and crops: A review. *Water, Air, & Soil Pollution, 228*(5), 190. https://doi.org/10.1007/s11270-017-3356-y

Essien, J. P., Inam, E. D., Ikpe, D. I., Udofia, G. E., & Benson, N. U. (2019). Ecotoxicological status and risk assessment of heavy metals in municipal solid wastes dumpsite impacted soil in Nigeria. *Environmental Nanotechnology, Monitoring & Management*, *11*, 100215. https://doi.org/10.1016/j.enmm.2019.100215

Fait, S., Fakhi, S., ElMzibri, M., Malek, O. A., Rachdi, B., Faiz, Z., Fougrach, H., Badri, W., Smouni, A., & Fahr, M. (2018). Behavior of As, Cd Co, Cr, Cu, Pb, Ni, and Zn at the soil/plant interface around an uncontrolled landfill (Casablanca, Morocco). *Remediation Journal, 28*(4), 65–72. https://doi.org/10.1002/rem.21577

Fatta, D., Papadopoulos, A., & Loizidou, M. (1999). A study on the landfill leachate and its impact on the groundwater quality of the greater area. *Environmental Geochemistry and Health, 21*(2), 175–190. https://doi.org/10.1023/A:1006613530137

Foti, L., Dubs, F., Gignoux, J., Lata, J.-C., Lerch, T. Z., Mathieu, J., Nold, F., Nunan, N., Raynaud, X., Abbadie, L., & Barot, S. (2017). Trace element concentrations along a gradient of urban pressure in forest and lawn soils of the Paris region (France). *Science of the Total Environment, 598*, 938–948. https://doi.org/10.1016/j.scitotenv.2017.04.111

Genchi, G., Sinicropi, M. S., Lauria, G., Carocci, A., & Catalano, A. (2020). The effects of cadmium toxicity. *International Journal of Environmental Research and Public Health, 17*(11), 3782. https://doi.org/10.3390/ijerph17113782

González, Á., del Mar Gil-Diaz, M., & del Carmen Lobo, M. (2017). Metal tolerance in barley and wheat cultivars: Physiological screening methods and application in phytoremediation. *Journal of Soils and Sediments, 17*(5), 1403–1412. https://doi.org/10.1007/s11368-016-1387-4

Guggenberger, G. (2005). Humification and mineralization in soils. *Microorganisms in soils: Roles in genesis and functions*, 85–106. https://doi.org/10.1007/3-540-26609-7_4

Gujre, N., Mitra, S., Soni, A., Agnihotri, R., Rangan, L., Rene, E. R., & Sharma, M. P. (2021). Speciation, contamination, ecological and human health risks assessment of heavy metals in soils dumped with municipal solid wastes. *Chemosphere*, *262*, 128013. https://doi.org/10.1016/j.chemosphere.2020.128013

Hakanson, L. (1980). An ecological risk index for aquatic pollution control. *A Sedimentological Approach. Water Research, 14*(8), 975–1001. https://doi.org/10.1016/0043-1354(80)90143-8

Hans Wedepohl, K. (1995). The composition of the continental crust. *Geochimica Et Cosmochimica Acta, 59*(7), 1217–1232. https://doi.org/10.1016/0016-7037(95)00038-2

He, L., Zhao, L., Li, J., Ma, J., Lui, R., Wang, S., & Zhao, W. (2014). Complex relationship between porosity and permeability of carbonate reservoirs and its controlling factors: A case study of platform facies in Pre-Caspian Basin. *Petroleum Exploration and Development, 41*(2), 225–234. https://doi.org/10.1016/S1876-3804(14)60026-4

Hilali, A., El Baghdadi, M., Barakat, A., Ennaji, W., & El Hamzaoui, E. H. (2020). Contribution of GIS techniques and pollution indices in the assessment of metal pollution in agricultural soils irrigated with wastewater: Case of the Day River, Beni Mellal (Morocco). *Euro-Mediterranean Journal for Environmental Integration, 5*(3), 52. https://doi.org/10.1007/s41207-020-00186-8

Hilali, A., El Baghdadi, M., & Halim, Y. (2022). Environmental monitoring of heavy metals distribution in the agricultural soil profile and soil column irrigated with sewage from the Day River, Beni-Mellal City (Morocco). *Modeling Earth Systems and Environment*. https://doi.org/10.1007/s40808-022-01592-3

Hooda, P. S. (Ed.). (2010). *Trace Elements in Soils* (1st ed.). Wiley. https://doi.org/10.1002/9781444319477

Hussein, M., Yoneda, K., Mohd-Zaki, Z., Amir, A., & Othman, N. (2021). Heavy metals in leachate, impacted soils and natural soils of different landfills in Malaysia: An alarming threat. *Chemosphere*, *267*, 128874. https://doi.org/10.1016/j.chemosphere.2020.128874

Idowu, I. A., Atherton, W., Hashim, K., Kot, P., Alkhaddar, R., Alo, B. I., & Shaw, A. (2019). An analyses of the status of landfill classification systems in developing countries: Sub Saharan Africa landfill experiences. *Waste Management, 87*, 761–771. https://doi.org/10.1016/j.wasman.2019.03.011

Iqbal, A., Tabinda, A. B., & Yasar, A. (2021). Environmental risk assessment of a young landfill site and its vicinity for possible human exposure. *Human and Ecological Risk Assessment: An International Journal, 27*(1), 258–273. https://doi.org/10.1080/10807039.2019.1706152

Kabata-Pendias, A. (1993). Behavioural properties of trace metals in soils. *Applied Geochemistry, 8*, 3–9. https://doi.org/10.1016/S0883-2927(09)80002-4

Kabata-Pendias, A., & Mukherjee, A. B. (2007). *Trace elements from soil to human*. Springer, Berlin Heidelberg. https://doi.org/10.1007/978-3-540-32714-1

Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). *What a waste 2.0: A global snapshot of solid waste management to 2050*. World Bank. https://doi.org/10.1596/978-1-4648-1329-0

Kennou, B., El Meray, M., Romane, A., & Arjouni, Y. (2015). Assessment of heavy metal availability (Pb, Cu, Cr, Cd, Zn) and speciation in contaminated soils and sediment of discharge by sequential extraction. *Environmental Earth Sciences*, *74*(7). https://doi.org/10.1007/s12665-015-4609-y

Korzeniowska, J., & Krąż, P. (2020). Heavy metals content in the soils of the Tatra National Park Near Lake Morskie Oko and Kasprowy Wierch—A case study (Tatra Mts, Central Europe). *Minerals, 10*(12), 1120. https://doi.org/10.3390/min10121120

Kouali, H., Achtak, H., Chaouti, A., Elkalay, K., & Dahbi, A. (2020). Assessment of trace metal contamination in surficial fine-grained sediments and mussel, *Mytilus galloprovincialis* from Safi areas in the northwestern Atlantic coast of Morocco. *Regional Studies in Marine Science*, *40*, 101535. https://doi.org/10.1016/j.rsma.2020.101535

Kouali, H., Chaouti, A., Achtak, H., Elkalay, K., & Dahbi, A. (2022a). Contamination and ecological risk assessment of trace metals in surface sediments from coastal areas (El Jadida, Safi and Essaouira) along the Atlantic coast of Morocco. *Journal of African Earth Sciences*, *186*, 104417. https://doi.org/10.1016/j.jafrearsci.2021.104417

Kouali, H., Chaouti, A., Achtak, H., Elkalay, K., & Dahbi, A. (2022b). Trace metal contents in the mussel *Mytilus galloprovincialis* from Atlantic coastal areas in northwestern Morocco: Levels of contamination and assessment of potential risks to human health. *Marine Pollution Bulletin*, *179*, 113680. https://doi.org/10.1016/j.marpolbul.2022.113680

Kouchou, A., El Ghachtouli, N., Duplay, J., Ghazi, M., Elsass, F., Thoisy, J. C., Bellarbi, M., Ijjaali, M., & Rais, N. (2020). Evaluation of the environmental and human health risk related to metallic contamination in agricultural soils in the Mediterranean semi-arid area (Saiss plain, Morocco). *Environmental Earth Sciences, 79*(6), 131. https://doi.org/10.1007/s12665-020-8880-1

Kumar, V., Pandita, S., Singh Sidhu, G. P., Sharma, A., Khanna, K., Kaur, P., Bali, A. S., & Setia, R. (2021). Copper bioavailability, uptake, toxicity and tolerance in plants: A comprehensive review. *Chemosphere*, *262*, 127810. https://doi.org/10.1016/j.chemosphere.2020.127810

Kumar, V., Sharma, A., Kaur, P., Singh Sidhu, G. P., Bali, A. S., Bhardwaj, R., Thukral, A. K., & Cerda, A. (2019). Pollution assessment of heavy metals in soils of India and ecological risk assessment: A state-of-the-art. *Chemosphere, 216*, 449–462. https://doi.org/10.1016/j.chemosphere.2018.10.066

Lefèvre, R. (2015). *Matière organique stable du sol: Dynamique et mécanismes de (dé)stabilisation* [Phdthesis, Université Pierre et Marie Curie - Paris VI]. https://tel.archives-ouvertes.fr/tel-01238875

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*, 1–14. https://doi.org/10.1155/2020/8872475

Minoubi, A., El Khalidi, K., Chaibi, M., Zourarah, B., Poizot, E., & Amrouni, O. (2013). Variation morphosédimentaire saisonnière et impact de la tempête de Janvier 2009 sur la côte de Safi, Maroc.

Mmereki, D., Li, B., Baldwin, A., Hong, L., 2016. The generation, composition, collection, treatment and disposal system, and impact of E-waste. *E-Waste in Transition-From Pollution to Resource,* 65–93. https://doi.org/10.5772/61332

Müller, G. (1969). Index of geoaccumulation in sediments of the Rhine river. *Geojournal*, *2*, 108–118. https://www.scienceopen.com/document?vid=4b875795-5729-4c05-9813-64951e2ca488

Naidu, R., Biswas, B., Willett, I. R., Cribb, J., Kumar Singh, B., Paul Nathanail, C., Coulon, F., Semple, K. T., Jones, K. C., Barclay, A., & Aitken, R. J. (2021). Chemical pollution: A growing peril and potential catastrophic risk to humanity. *Environment International*, 156, 106616. https://doi.org/10.1016/j.envint.2021.106616

Nanda, S., & Berruti, F. (2021). Municipal solid waste management and landfilling technologies: A review. *Environmental Chemistry Letters, 19*(2), 1433–1456. https://doi.org/10.1007/s10311-020-01100-y

Nannoni, F., Mazzeo, R., Santolini, R., & Protano, G. (2017). Multi-matrix environmental monitoring to assess heavy element distribution around a municipal solid waste landfill in Italy. *International Journal of Environmental Science and Technology, 14*(12), 2591–2602. https://doi.org/10.1007/s13762-017-1342-y

Naveen, B. P., Sumalatha, J., & Malik, R. K. (2018). A study on contamination of ground and surface water bodies by leachate leakage from a landfill in Bangalore. *India. International Journal of Geo-Engineering, 9*(1), 27. https://doi.org/10.1186/s40703-018-0095-x

Neeratanaphan, L., Khamma, S., Benchawattananon, R., Ruchuwararak, P., Appamaraka, S., & Intamat, S. (2017). Heavy metal accumulation in rice (*Oryza sativa*) near electronic waste dumps and related human health risk assessment. *Human and Ecological Risk Assessment: An International Journal, 23*(5), 1086–1098. https://doi.org/10.1080/10807039.2017.1300856

Nhari, F., Sbaa, M., Vasel, J. L., Mohamed, F., & El Morhit, M. (2014). Soil contamination of the landfill uncontrolled by heavy metals: Case of the landfill of Ahfir-Saidia (Eastern Morocco). *Journal of Materials and Environmental Science, 5*, 1477–1484.

Obiri-Nyarko, F., Duah, A. A., Karikari, A. Y., Agyekum, W. A., Manu, E., & Tagoe, R. (2021). Assessment of heavy metal contamination in soils at the Kpone landfill site, Ghana: Implication for ecological and health risk assessment. *Chemosphere*, *282*, 131007. https://doi.org/10.1016/j.chemosphere.2021.131007

Okonkwo, S. I., Idakwo, S. O., & Ameh, E. G. (2021). Heavy metal contamination and ecological risk assessment of soils around the pegmatite mining sites at Olode area, Ibadan southwestern Nigeria. *Environmental Nanotechnology, Monitoring & Management*, *15*, 100424. https://doi.org/10.1016/j.enmm.2020.100424

Oumenskou, H., El Baghdadi, M., Barakat, A., Aquit, M., Ennaji, W., Karroum, L. A., & Aadraoui, M. (2018). Assessment of the heavy metal contamination using GIS-based approach and pollution indices in agricultural soils from Beni Amir irrigated perimeter, Tadla plain. *Morocco. Arabian Journal of Geosciences, 11*(22), 692. https://doi.org/10.1007/s12517-018-4021-5

Pecina, V., Brtnický, M., Baltazár, T., Juřička, D., Kynický, J., & Vašinová Galiová, M. (2021). Human health and ecological risk assessment of trace elements in urban soils of 101 cities in China: A meta-analysis. *Chemosphere*, *267*, 129215. https://doi.org/10.1016/j.chemosphere.2020.129215

Poniedziałek, M., Sękara, A., Jędrszczyk, E., & Ciura, J. (2010). Phytoremediation efficiency of crop plants in removing cadmium, lead and zinc from soil. *Folia Horticulturae, 22*(2), 25–31. https://doi.org/10.2478/fhort-2013-0155

Rafiq, F., Techetach, M., Achtak, H., Boundir, Y., Kouali, H., Sisouane, M., Mandri, B., Cherifi, O., & Dahbi, A. (2022). First assessment of domestic and industrial effluents impact on intertidal zone of Safi coastline (west of Morocco): Physicochemical characteristics and metallic trace contamination. *Desalination and Water Treatment, 245*, 167–177. https://doi.org/10.5004/dwt.2022.27974

Rai, P. K., Lee, S. S., Zhang, M., Tsang, Y. F., & Kim, K. H. (2019). Heavy metals in food crops: Health risks, fate, mechanisms, and management. *Environment International, 125*, 365–385. https://doi.org/10.1016/j.envint.2019.01.067

Rinklebe, J., Antoniadis, V., Shaheen, S. M., Rosche, O., & Altermann, M. (2019). Health risk assessment of potentially toxic elements in soils along the Central Elbe River, Germany. *Environment International, 126*, 76–88. https://doi.org/10.1016/j.envint.2019.02.011

Ruchuwararak, P., Intamat, S., Tengjaroenkul, B., & Neeratanaphan, L. (2019). Bioaccumulation of heavy metals in local edible plants near a municipal landfill and the related human health risk assessment. *Human and Ecological Risk Assessment: An International Journal, 25*(7), 1760–1772. https://doi.org/10.1080/10807039.2018.1473755

Sarkar, A., Ravindran, G., & Krishnamurthy, V. (2013). A brief review on the effect of cadmium toxicity: From cellular to organ level. *International Journal of Bio-Technology and Research (IJBTR), 3*, 17–36.

Scaramozzino, P., Battisti, S., Desiato, R., Tamba, M., Fedrizzi, G., Ubaldi, A., Neri, B., Abete, M. C., & Ru, G. (2019). Application of a risk-based standardized animal biomonitoring approach to contaminated sites. *Environmental Monitoring and Assessment, 191*(8), 526. https://doi.org/10.1007/s10661-019-7653-3

Sękara, A., Poniedziałek, M., Ciura, J., & Jędrszczyk, E. (2005). Cadmium and lead accumulation and distribution in the organs of nine crops: Implications for phytoremediation. *Polish Journal of Environmental Studies, 14*, 509–516.

Shaheen, S. M., Tsadilas, C. D., & Rinklebe, J. (2013). A review of the distribution coefficients of trace elements in soils: Influence of sorption system, element characteristics, and soil colloidal properties. *Advances in Colloid and Interface Science, 201–202*, 43–56. https://doi.org/10.1016/j.cis.2013.10.005

Shanker, A., Cervantes, C., Lozatavera, H., & Avudainayagam, S. (2005). Chromium toxicity in plants. *Environment International, 31*(5), 739–753. https://doi.org/10.1016/j.envint.2005.02.003

Shirokova, Y., Forkutsa, I., & Sharafutdinova, N. (2000). Use of electrical conductivity instead of soluble salts for soil salinity monitoring in Central Asia. *Irrigation and Drainage Systems, 14*(3), 199–206. https://doi.org/10.1023/A:1026560204665

Siddiqua, A., Hahladakis, J. N., & Al-Attiya, W. A. K. A. (2022). An overview of the environmental pollution and health effects associated with waste landfilling and open dumping. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-022-21578-z

Singh, N., Duan, H., Ogunseitan, O. A., Li, J., & Tang, Y. (2019). Toxicity trends in e-waste: A comparative analysis of metals in discarded mobile phones. *Journal of Hazardous Materials*, *380*, 120898. https://doi.org/10.1016/j.jhazmat.2019.120898

Tack, F. M. G. (2010). Trace elements: general soil chemistry, principles and processes. *Trace elements in soils* (pp. 9–37). https://doi.org/10.1002/9781444319477.ch2

Taghavi, M., Darvishiyan, M., Momeni, M., Eslami, H., Fallahzadeh, R. A., & Zarei, A. (2023). Ecological risk assessment of trace elements (TEs) pollution and human health risk exposure in agricultural soils used for saffron cultivation. *Scientific Reports, 13*(1), 4556. https://doi.org/10.1038/s41598-023-31681-x

Teta, C., & Hikwa, T. (2017). Heavy metal contamination of ground water from an unlined landfill in Bulawayo. *Zimbabwe. Journal of Health and Pollution, 7*(15), 18–27. https://doi.org/10.5696/2156-9614-7.15.18

Thongyuan, S., Khantamoon, T., Aendo, P., Binot, A., & Tulayakul, P. (2021). Ecological and health risk assessment, carcinogenic and non-carcinogenic effects of heavy metals contamination in the soil from municipal solid waste landfill in Central, Thailand. *Human and Ecological Risk Assessment: An International Journal, 27*(4), 876–897. https://doi.org/10.1080/10807039.2020.1786666

Tóth, G., Hermann, T., Szatmári, G., & Pásztor, L. (2016). Maps of heavy metals in the soils of the European Union and proposed priority areas for detailed assessment. *Science of the Total Environment, 565*, 1054–1062. https://doi.org/10.1016/j.scitotenv.2016.05.115

Vaccari, M., Vinti, G., & Tudor, T. (2018). An analysis of the risk posed by leachate from dumpsites in developing countries. *Environments, 5*(9), 99. https://doi.org/10.3390/environments5090099

Velis, C. A., & Cook, E. (2021). Mismanagement of plastic waste through open burning with emphasis on the global south: A systematic review of risks to occupational and public health. *Environmental Science & Technology, 55*(11), 7186–7207. https://doi.org/10.1021/acs.est.0c08536

Verma, F., Singh, S., Singh, J., Dhaliwal, S. S., Parkash, C., Kumar, V., & Kumar, R. (2022). Assessment of heavy metal contamination and its effect on earthworms in different types of soils. *International Journal of Environmental Science and Technology, 19*(5), 4337–4350. https://doi.org/10.1007/s13762-021-03297-z

Vinti, G., Bauza, V., Clasen, T., Medlicott, K., Tudor, T., Zurbrügg, C., & Vaccari, M. (2021). Municipal solid waste management and adverse health outcomes: A systematic review. *International Journal of Environmental Research and Public Health, 18*(8), 4331. https://doi.org/10.3390/ijerph18084331

Vinti, G., Bauza, V., Clasen, T., Tudor, T., Zurbrügg, C., & Vaccari, M. (2023). Health risks of solid waste management practices in rural Ghana: A semi-quantitative approach toward a solid waste safety plan. *Environmental Research*, *216*, 114728. https://doi.org/10.1016/j.envres.2022.114728

Vural, A., Gundogdu, A., Akpinar, I., & Baltaci, C. (2017). Environmental impact of Gümüşhane City, Turkey, waste area in terms of heavy metal pollution. *Natural Hazards, 88*(2), 867–890. https://doi.org/10.1007/s11069-017-2896-1

Wackernagel, H. (1995). Ordinary kriging. *Multivariate geostatistics.* Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-662-03098-1_11

Wang, S., Han, Z., Wang, J., He, X., Zhou, Z., & Hu, X. (2022). Environmental risk assessment and factors influencing heavy metal concentrations in the soil of municipal solid waste landfills. *Waste Management, 139*, 330–340. https://doi.org/10.1016/j.wasman.2021.11.036

Wang, X., Dan, Z., Cui, X., Zhang, R., Zhou, S., Wenga, T., Yan, B., Chen, G., Zhang, Q., & Zhong, L. (2020). Contamination, ecological and health risks of trace elements in soil of landfill and geothermal sites in Tibet. *Science of The Total Environment*, *715*, 136639. https://doi.org/10.1016/j.scitotenv.2020.136639

Wang, Z., Sun, Y., Yao, W., Ba, Q., & Wang, H. (2021). Effects of cadmium exposure on the immune system and immunoregulation. *Frontiers in Immunology*, *12*, 695484. https://doi.org/10.3389/fimmu.2021.695484

Weissmannová, D., Mihočová, C., & Pavlovský. (2019). Potential ecological risk and human health risk assessment of heavy metal pollution in industrial affected soils by coal mining and metallurgy in Ostrava, Czech Republic. *International Journal of Environmental Research and Public Health, 16*(22), 4495. https://doi.org/10.3390/ijerph16224495

Wuana, R., & Okieimen, F. E. (2011). Heavy metals in contaminated soils: A review of sources, chemistry, risks and best available strategies for remediation. *ISRN Ecology, 2011*, 1–20. https://doi.org/10.5402/2011/402647

Wuana, R. A., & Okieimen, F. E. (2010). Phytoremediation potential of maize (*Zea mays* L.). A review. *African Journal of General Agriculture, 6*(4), 275–287.

Yassine, A., Taoufik, E. R., Rachid, H., Driss, D., Mohamed, N., Abdelmajid, H., & Hanane, H. (2021). Assessing the contamination of trace toxic elements in the soils of sugar beet field (Beni-Mellal, Morocco). *Arabian Journal of Geosciences, 14*(9), 822. https://doi.org/10.1007/s12517-021-07217-w

Yuan, Z., He, C., Shi, Q., Xu, C., Li, Z., Wang, C., Zhao, H., & Ni, J. (2017). Molecular insights into the transformation of dissolved organic matter in landfill leachate concentrate during biodegradation and coagulation processes using ESI FT-ICR MS. *Environmental Science & Technology, 51*(14), 8110–8118. https://doi.org/10.1021/acs.est.7b02194

Zeng, D., Chen, G., Zhou, P., Xu, H., Qiong, A., Duo, B., Lu, X., Wang, Z., & Han, Z. (2021). Factors influencing groundwater contamination near municipal solid waste landfill sites in the Qinghai-Tibetan plateau. *Ecotoxicology and Environmental Safety*, *211*, 111913. https://doi.org/10.1016/j.ecoenv.2021.111913

Zwolak, A., Sarzyńska, M., Szpyrka, E., & Stawarczyk, K. (2019). Sources of soil pollution by heavy metals and their accumulation in vegetables: A review. *Water, Air, & Soil Pollution, 230*(7), 164. https://doi.org/10.1007/s11270-019-4221-y

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.