American Journal of Analytical Chemistry, 2026, 17(5), 133-146
https://www.scirp.org/journal/ajac
ISSN Online: 2156-8278
ISSN Print: 2156-8251

Integrated Analytical Approach to Heavy Metals in E-Waste Contaminated Soils from Dakar

Khadidiatou Thiam[1], Robert Faomowé Foko[2], Aissatta Diakite[3], Aminata Sarr[2,4], Mohamed Samb[2], Jessica Carmelia Mbemba Peleka[2], Mathilda Osiris Mahouekpo[2], Fatoumata Bah[2,4], Cheikh Diop[2,4], Amadou Diop[1], Mamadou Fall[2,4], Mathilde Cabral[2,4], Aminata Touré[2,4]*

[1]Laboratoire de Chimie Analytique et de Bromatologie, Faculté de Médecine, Pharmacie et Odontostomatologie, Dakar, Sénégal
[2]Laboratoire de Toxicologie et Hydrologie, Faculté de Médecine, Pharmacie et Odontostomatologie, Dakar, Sénégal
[3]Laboratoire de Toxicologie et Hygiène Agro-Industrielle (LTHAI), UFR Sciences Pharmaceutiques et Biologiques, Université Félix Houphouët-Boigny, Abidjan, Côte d'Ivoire
[4]Centre Anti Poison du Sénégal, Dakar, Sénégal
Email: *robert.foko@ucad.edu.sn

How to cite this paper: Thiam, K., Foko, R.F., Diakite, A., Sarr, A., Samb, M., Peleka, J.C.M., Mahouekpo, M.O., Bah, F., Diop, C., Diop, A., Fall, M., Cabral, M. and Touré, A. (2026) Integrated Analytical Approach to Heavy Metals in E-Waste Contaminated Soils from Dakar. *American Journal of Analytical Chemistry*, **17**, 133-146.
https://doi.org/10.4236/ajac.2026.175010

Received: April 10, 2026
Accepted: May 12, 2026
Published: May 15, 2026

Abstract

Our study is part of an environmental analytical chemistry approach aimed at characterising soil contamination by heavy metals resulting from informal management activities of electrical and electronic equipment waste. Soil samples were collected from collection, dismantling, recycling, and control zones. After drying, sieving, and acid mineralization (HNO_3/HCl), pseudo-total concentrations of Pb, Cd, Cu, Zn, Fe, Mn, Cr, and Co were quantified by atomic absorption spectrometry (AAS). In parallel, pH and electrical conductivity were also measured. Principal component analysis (PCA) reduced the dimensionality of the dataset, highlighted the correlations among variables, and identified the sources of contamination. The results of the PCA show a clear differentiation between anthropogenic metals (Pb, Cd, Cu, Zn), which are strongly associated with informal recycling activities, and elements related to the natural geochemical background (Fe, Mn). The integration of analytical chemistry thus allows not only for the quantification of pollution but also for the interpretation of its dynamics and sources, constituting an essential lever for risk assessment and environmental decision-making.

Keywords

E-Waste, Heavy Metals, Analytical Chemistry,
Atomic Absorption Spectrometry, Principal Component Analysis

1. Introduction

The spread of new technologies and the high consumption of electrical and electronic equipment have led to the generation of a new type of waste known as waste electrical and electronic equipment (WEEE). This waste, originating from end-of-life appliances such as telephones, computers, batteries, and other electronic devices, constitutes one of the fastest-growing streams of solid waste in the world [1]. These devices also contain a complex mixture of materials, including hazardous heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As). Although playing an essential role in the proper functioning of electronic devices, these heavy metals are known for their impacts on human health and ecosystems, particularly in soils, where they can accumulate. To this end, inadequate management of electronic waste represents a major problem in developing countries. This often involves open-air storage, informal dismantling, and the burning of cables and casings, which facilitates the direct dispersion of these toxic metals into the soil [2] [3].

Once in the soil, the total concentration of a heavy metal, although not static, is a non-negligible indicator of the impact of these metals on the soil. It can be controlled by a complex interaction of the soil's physicochemical properties. Parameters such as soil pH and electrical conductivity (EC) govern the speciation, adsorption, and solubility of metals [4] [5]. Elements such as Cd and Zn are likely to see their solubilities increase significantly due to a decrease in pH. On the other hand, the presence of organic matter can either immobilise Pb through complexation or, conversely, facilitate the transport of certain metals in the form of soluble organometallic complexes [5].

In such a context where Senegal is facing a growing influx of electronic waste, the management of WEEE in cities like Dakar remains largely dominated by the informal sector, where activities are often carried out in the open, resulting in significant and localized soil contamination [2] [6]. Moreover, the local pedological context, characterized by ferruginous and sandy soils with low organic matter content under a Sahelian climate, creates conditions that can either promote the rapid vertical migration of mobile metals or, conversely, enhance surface retention through interactions with iron oxides [7].

Although several studies have documented the total concentrations of heavy metals in these e-waste-affected areas, understanding these multivariate interactions is essential to accurately assess environmental risks, predict the long-term fate of contaminants, and develop targeted remediation strategies.

To contribute to this, this study uses an integrated analytical approach combining soil analysis with multivariate statistics with the objectives of: (1) characterising the pseudo-total concentrations of heavy metals (Pb, Cd, Cu, Zn, Cr) in soils contaminated by informal e-waste recycling activities in the Dakar region; (2) analysing the main soil properties, particularly pH and electrical conductivity, across different contamination sites; and (3) elucidating the relationships between these parameters and the distribution of metals using principal component analysis (PCA) and Spearman rank correlation.

2. Materials and Methods

2.1. Selecting Site and Soil Samples

The study was conducted in the Dakar region, the capital of Senegal and the country's most densely populated region [8].

Site selection was carried out using the snowball sampling method, which involves tracing connections. Thus, an initial site where WEEE was handled was identified as the starting sample. This group was then asked to identify other WEEE handling sites in turn, and so on. Three occupational categories were considered in this study: collectors, dismantlers, and recyclers.

Soil samples were collected in the towns Mermoz (Mz), Guediawaye (G), Pikine (P), Rebeuss (R), Thiaroye (T), Fass (Fs), and Medina (Ma) (**Figure 1**).

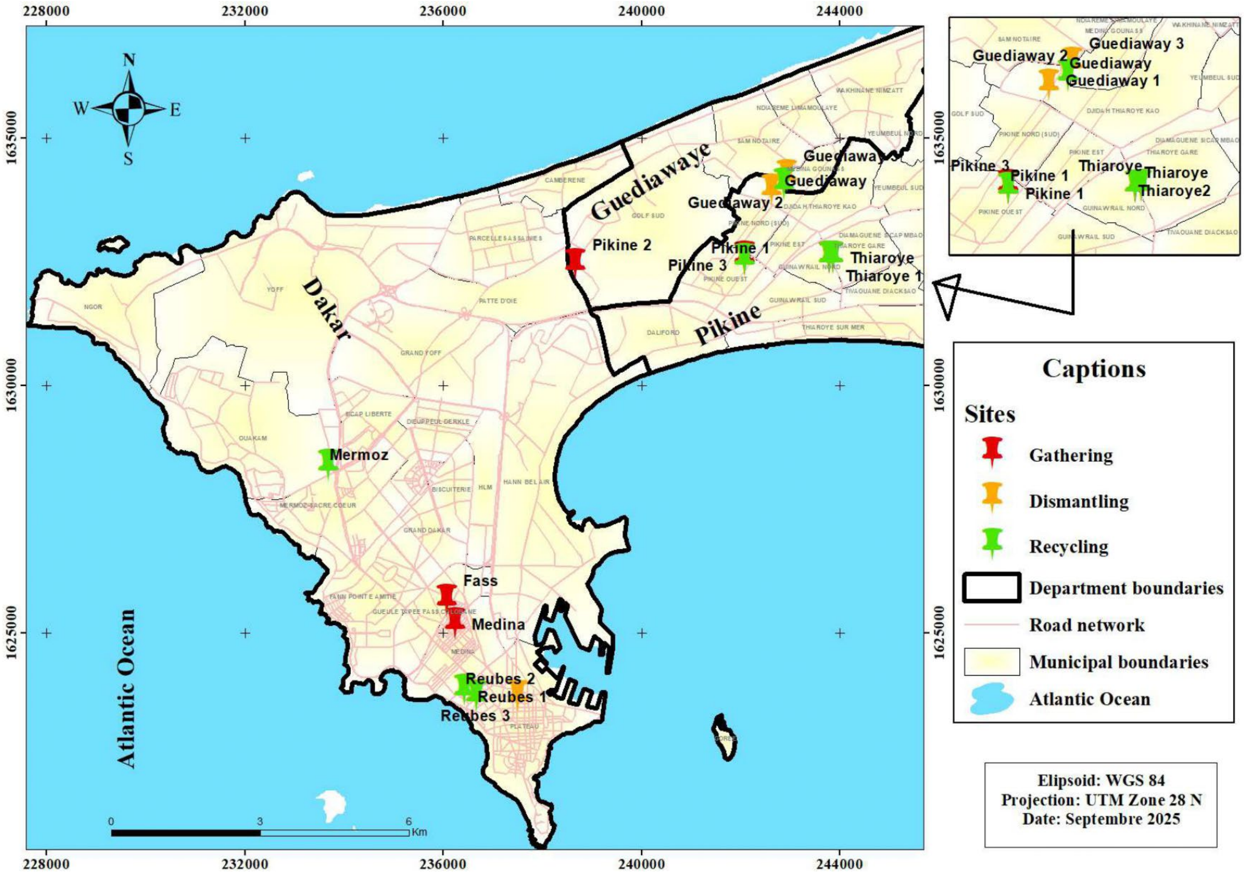


Figure 1. Geographical location of the sampling sites.

At each identified site, five soil subsamples were collected at a depth of 0 to 5 cm and used to obtain a soil/ash/dust composite representative of the site. Metal wire debris, stone fragments, grass, etc., were removed prior to analysis. The macroscopic appearance of the soils was examined, and the content of trace metal elements (TMEs) was assessed [9]. The samples collected were dried in an oven at 104˚C before being sieved, and samples with a particle size of less than 200 µm were retained for the remainder of the study. A commercially available, uncontaminated soil sample *sable de Fontainebleau* and a soil sample from a site without WEEE activity (Bambilor soil) were used as controls. During the sampling process, a total of twenty-two composite soil samples were collected. The samples were distributed as follows: two control sites (Bambilor and Fontainebleau), seven collection sites, eight dismantling sites, and five recycling sites.

2.2. pH and Conductivity

The pH was determined using a 1 M potassium chloride (KCl) solution at a soil-to-solution ratio of 1:2.5 (w/v). To do this, 5 g of soil was mixed with 12.5 ml of 1 M KCl solution. The mixture was then stirred magnetically for 30 minutes at room temperature. After decanting the resulting mixture, the pH of the supernatant was measured using a pH meter previously calibrated with buffer solutions of pH 4, 7, and 10.

Electrical conductivity, which reflects soil salinity and the overall concentration of dissolved ions, was measured using the distilled water extraction method. For this purpose, a soil-to-water ratio of 1:5 (w/v) was used to ensure consistent reproducibility regardless of the sample's particle size. The mixture was stirred for one hour, then left to settle. The electrical conductivity of the supernatant was determined using a calibrated conductivity meter. In accordance with the standard, the conductivity results were expressed in millisiemens per centimetre (mS/cm) and denoted as $CE_1/_5$ to indicate the extraction ratio used. To ensure the accuracy and reproducibility of the data, each pH and electrical conductivity measurement was carried out in triplicate, and the final value corresponds to the average of the three measurements.

2.3. Metal Concentrations

The pseudo-total fraction of extractable metals (Cr, Cu, Mn, Fe, Co, Cd, Pb, Zn) was determined using an acid digestion method from the American Public Health Association [10], with modifications to the protocol. Approximately 1 g of soil was transferred to a Teflon tube, followed by the addition of 4 ml of 50% (v/v) nitric acid (HNO_3) and 10 ml of 20% (v/v) hydrochloric acid (HCl). The tubes were covered and placed in a closed-circuit digestion unit on a hotplate for reflux digestion for 30 minutes. After cooling to room temperature, the contents of the tubes were filtered through Whatman No. 41 filter paper. The filtered solution was then transferred to a 50 ml volumetric flask and made up to the mark with distilled water. Solutions were stored at 4˚C until metal analysis by atomic absorption spectrometry.

Analytical quality control:

Metal quantification was performed using a flame atomic absorption spectrometer (Agilent Technologies 240 FS AA). Calibration was carried out with standard solutions prepared from certified stock solutions (1000 μg/mL, Agilent Technologies). Reagent blanks were included in each digestion batch (one blank per 10 samples) and were below the instrumental detection limit for all metals. Precision was assessed by analyzing duplicate samples (n = 3 per metal); relative standard deviations (RSD) were consistently below 10%. In the absence of a certified reference material, accuracy was evaluated through spike recovery tests. Soil samples were spiked with known amounts of each metal prior to digestion, and recoveries were calculated as (measured spiked concentration − measured unspiked concentration) / added concentration × 100. Mean recoveries ranged from 90% to 105% for all metals, confirming satisfactory accuracy. Calibration curves were accepted only if $R^2 > 0.995$.

Because the digestion procedure did not include hydrofluoric acid (HF), the measured concentrations correspond to the pseudo-total metal pool, which includes metals from oxides, carbonates, organic matter, and sulfides, but not the residual silicate-bound fraction.

2.4. Statistical

Statistical analyses were performed using R Studio and GraphPad Prism (version 8.00, GraphPad Software, La Jolla, California, USA). Given the non-normal distribution of metal concentrations (assessed by the Shapiro-Wilk test), Spearman's rank correlation coefficient (ρ) was used to evaluate monotonic associations between metals and soil parameters (pH, electrical conductivity). For each pair of variables, ρ was calculated and a hypothesis test (H_0: $\rho = 0$) was conducted. Due to the number of comparisons, p-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR) method [11] [12]. A significance threshold of $q < 0.05$ was adopted. The strength of correlations was interpreted based on $|\rho|$: ~0.1 (weak), ~0.3 (moderate), and ≥0.5 (strong).

Principal component analysis (PCA) was applied to the concentrations of the eight metals (Pb, Cd, Cu, Mn, Fe, Cr, Co, Zn) to explore the multivariate structure of contaminated soils [13]. PCA reduces dimensionality by identifying linear combinations (principal components) that capture the maximum variance. It allowed visualization of similarities between sampling sites and relationships between metals, identification of metal associations indicative of common sources, and distinction between anthropogenic inputs and the natural geochemical background. PCA results were visualized using biplots [14].

3. Results

3.1. pH and Electrical Conductivity

The pH and electrical conductivity (EC) measurements (**Table 1**) highlight variability between the studied sites.

The pH varies from 7.64 (Fontainebleau) to 8.39 (R-G_2), indicating an overall neutral to alkaline environment. The highest values are observed at R-G_2 (8.39) and C-P_2 (8.31), while D-T_2 (7.78) and R-Mz (7.77) exhibit the lowest pH levels.

These variations, although limited, can influence the bioavailability of metals, particularly lead and cadmium, whose solubility increases in more acidic conditions.

Table 1. Variation of pH and electrical conductivity.

	pH	C (mS/cm)
B	7.65 ± 0.14	0.03 ± 0.01
Fb	7.64 ± 0.13	0.01 ± 0.00
C-Fs	8.18 ± 0.04	0.9 ± 0.00
C-Ma	8.24 ± 0.03	0.9 ± 0.00
C-P_1	8.01 ± 0.06	0.5 ± 0.00
C-P_2	8.31 ± 0.00	2.13 ± 0.06
C-T	8.12 ± 0.02	0.73 ± 0.06
C-T_2	8.20 ± 0.07	0.60 ± 0.00
C-T_3	8.20 ± 0.07	1.27 ± 0.06
D-G_1	8.02 ± 0.08	0.40 ± 0.00
D-G_3	7.90 ± 0.07	1.70 ± 0.00
D-G_4	7.99 ± 0.08	2.83 ± 0.06
D-P_1	7.98 ± 0.04	4.83 ± 0.06
D-P_2	7.86 ± 0.16	1.7 ± 0.00
D-R_3	7.93 ± 0.11	1.2 ± 0.00
D-T_2	7.78 ± 0.32	1.5 ± 0.00
R-G_2	8.39 ± 0.07	1.60 ± 0.00
R-Mz	7.77 ± 0.22	4.43 ± 0.06
R-P_1	8.31 ± 0.00	0.50 ± 0.00
R-R_1	8.25 ± 0.51	4.53 ± 0.06
R-T	8.20 ± 0.05	2.57 ± 0.12
R-T_2	7.93 ± 0.27	0.47 ± 0.06

Note: Each code corresponds to a composite sample from a distinct site (C = collection, D = dismantling, R = recycling, B = Bambilor control, Fb = Fontainebleau control).

Electrical conductivity shows marked heterogeneity, with values ranging from 0.010 mS/cm (Fb) to 4.833 mS/cm (D-P_2). Recycling sites, such as D-P_2 (4.833 mS/cm) and R-Mz (4.433 mS/cm), display the highest levels, suggesting high salinity linked to the accumulation of soluble salts of anthropogenic origin, possibly associated with electronic waste. In contrast, the control sites (Bambilor, Fontainebleau) exhibit low EC values, indicating limited anthropogenic influence.

3.2. Metals Concentrations

The analysis of concentrations of Pb, Cd, Cu, Mn, Fe, Cr, Co, and Zn in the soils of collection, dismantling, and recycling sites for WEEE, compared to control sites

(Bambilor, Fontainebleau) and international guideline values (WHO, EU, US EPA), highlights variable metal contamination depending on the sites (**Figure 2**).

The thresholds used for comparison are: for the US EPA, the Regional Screening Levels (RSL) for residential soil [15]; for the EU, the values from Directive 86/278/EEC on the protection of the environment and in particular of the soil when sewage sludge is used in agriculture [16]; for the WHO, although no official soil guidelines exist, the commonly cited values from the WHO/EURO 1996 report on soil quality are used [17]. These international benchmarks were chosen because no national soil quality standards are currently available for Senegal, and they provide a widely recognized reference for assessing contamination levels.

Mn generally shows low concentrations (< 500 ppm), indicating limited anthropogenic influence.

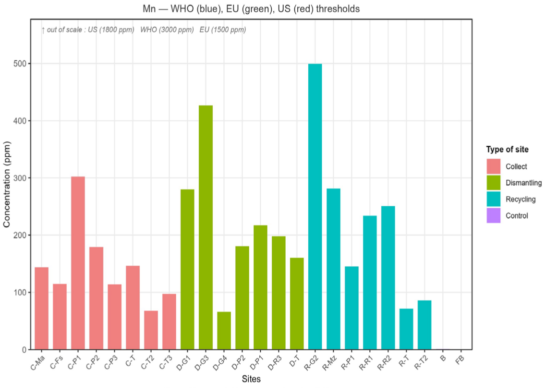


Figure: Heavy metal Mn concentrations by site type

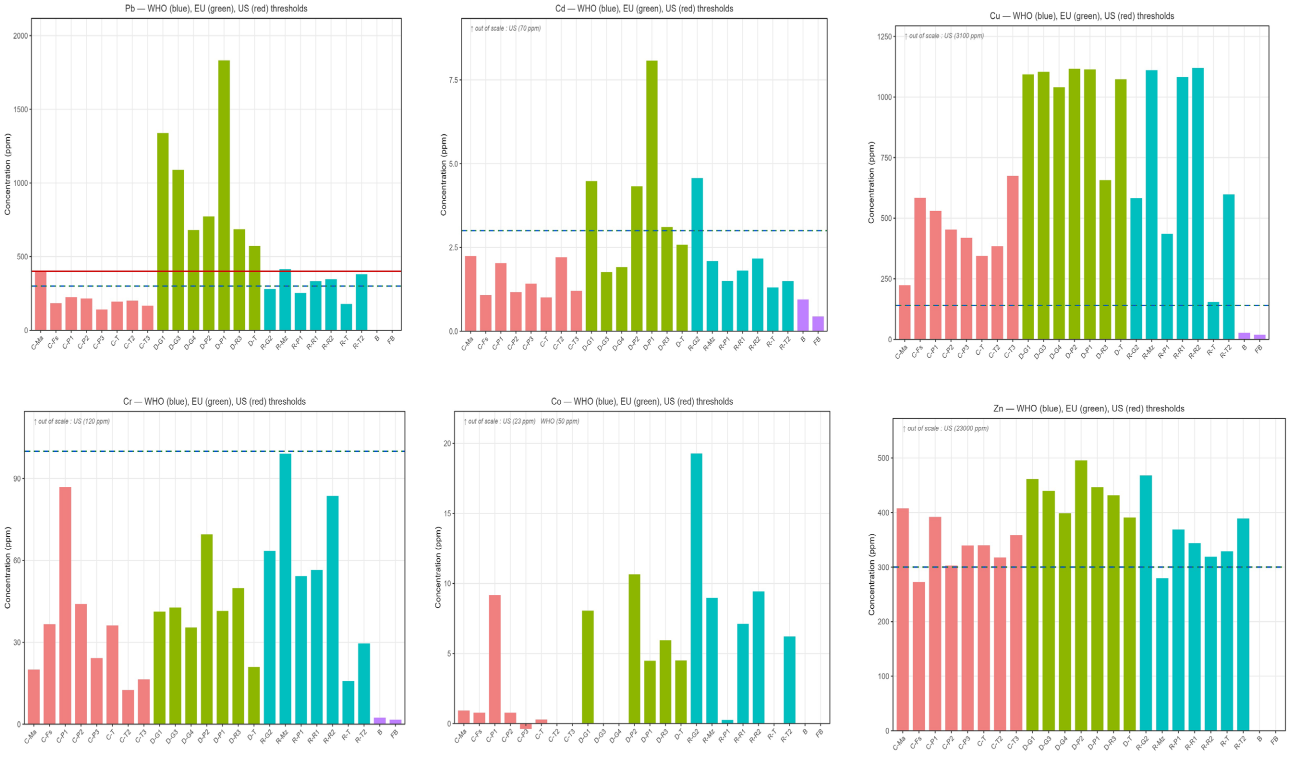
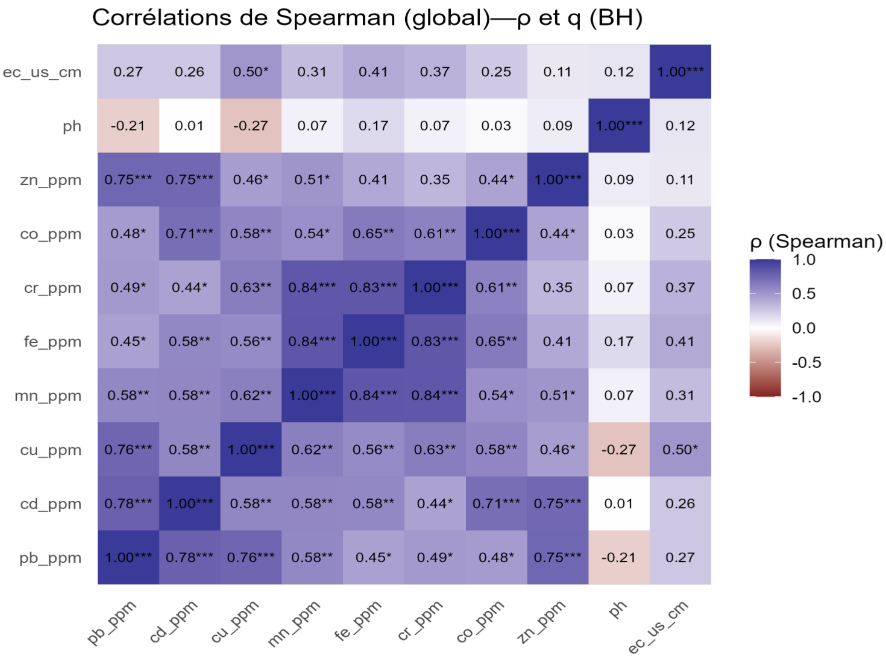


Figure 2. Heavy metal concentrations in soil samples.

The concentrations of Pb far exceed the guideline values at the majority of sites, particularly at D-P_1 (1833.16 ppm), D-G_1 (1339.06 ppm), and D-G_3 (1089.56 ppm), reaching more than four times the US EPA threshold. In contrast, the control sites show very low levels (4.00 ppm in Bambilor and 1.50 ppm in Fontainebleau), confirming the anthropogenic origin of the contamination. Cd generally shows concentrations compliant with WHO and EU thresholds, with some occasional exceedances in certain dismantling areas (D-P_1, D-G_1, R-G_2), but still well below US EPA limits. Cu shows marked enrichments (>1000 ppm) in several dismantling and recycling sites, notably D-G_3, D-P_1, D-P_2, and R-Mz, with exceedances of guideline values. The concentrations of Cr remain below regulatory thresholds, indicating low to moderate contamination, despite some higher levels observed locally. Co presents very low levels, often close to detection limits, indicating the absence of significant accumulation. Zn shows exceedances of WHO/EU values at certain dismantling sites (D-G_1, D-P_2, D-G_3), while remaining below the critical thresholds of the EPA.

3.3. Influence of pH and Conductivity

Spearman correlations (**Figure 3**) do not reveal a significant relationship between pH and metal concentrations ($|\rho| \leq 0.27$; $p > 0.20$), probably due to the low variability of pH in a neutral to slightly basic range.



	pb_ppm	cd_ppm	cu_ppm	mn_ppm	fe_ppm	cr_ppm	co_ppm	zn_ppm	ph	ec_us_cm
ec_us_cm	0.27	0.26	0.50*	0.31	0.41	0.37	0.25	0.11	0.12	1.00***
ph	-0.21	0.01	-0.27	0.07	0.17	0.07	0.03	0.09	1.00***	0.12
zn_ppm	0.75***	0.75***	0.46*	0.51*	0.41	0.35	0.44*	1.00***	0.09	0.11
co_ppm	0.48*	0.71***	0.58**	0.54*	0.65**	0.61**	1.00***	0.44*	0.03	0.25
cr_ppm	0.49*	0.44*	0.63**	0.84***	0.83***	1.00***	0.61**	0.35	0.07	0.37
fe_ppm	0.45*	0.58**	0.56**	0.84***	1.00***	0.83***	0.65**	0.41	0.17	0.41
mn_ppm	0.58**	0.58**	0.62**	1.00***	0.84***	0.84***	0.54*	0.51*	0.07	0.31
cu_ppm	0.76***	0.58**	1.00***	0.62**	0.56**	0.63**	0.58**	0.46*	-0.27	0.50*
cd_ppm	0.78***	1.00***	0.58**	0.58**	0.58**	0.44*	0.71***	0.75***	0.01	0.26
pb_ppm	1.00***	0.78***	0.76***	0.58**	0.45*	0.49*	0.48*	0.75***	-0.21	0.27

Figure 3. Correlations between physicochemical parameters and metals.

On the other hand, electrical conductivity shows positive correlations, particularly with Cu ($\rho \approx 0.50$; $p \approx 0.012$) and Fe ($\rho \approx 0.41$; $p \approx 0.048$), while other metals show weaker relationships ($\rho \approx 0.09 - 0.37$). These results suggest that the ionic charge of the medium can influence the mobility of metals through mechanisms of complexation for adsorption sites, and colloidal transport.

3.4. Principal Component Analysis

PCA (**Figure 4**) highlights a global gradient of metal contamination carried by the first axis (Dim1), reflecting the intensity of the concentrations. The second axis (Dim2) discriminates between two main groups: (i) Pb-Cd-Zn, associated with anthropogenic sources (batteries, soldering), and (ii) Fe-Mn-Cr-Co, reflecting more of the geochemical background or corrosion processes.

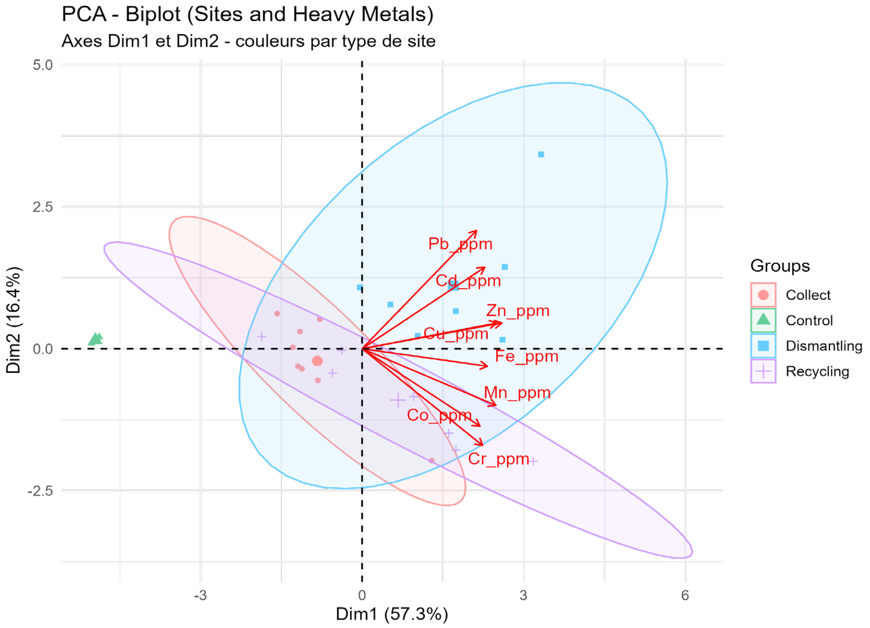


Figure 4. Principal component analysis of metal concentrations at the various sites.

The reference sites exhibit a homogeneous profile dominated by Fe, Mn, and Cr, with low concentrations of anthropogenic metals.

The dismantling sites show marked structuring, with high levels and differentiation between Pb-Cd-Cu-Mn and Cr-Co-Fe-Zn, suggesting chemical signatures related to mechanical and thermal processes.

The collection sites exhibit moderate structuring, indicating diffuse contamination. The second axis opposes Pb-Cd-Zn, linked to electronic components, to Cu-Cr-Fe, associated with alloys or the mineral substrate.

Recycling sites exhibit clear organization, with a separation between Zn-Cd-Mn-Co and Cr-Pb-Cu. This distribution suggests distinct sources, respectively linked to electronic components and thermomechanical activities.

The biplot confirms these trends. Dim1 (57.3% of variance) is dominated by Pb, Cd, Cu, and Zn, indicating a common anthropogenic signature associated with e-waste dismantling. Dim2 (16.4% of variance) is dominated by Fe, Mn, Cr, and Co, reflecting the natural geochemical background. The most contaminated samples project to the positive side of Dim1, while control samples cluster near the origin with low concentrations of anthropogenic metals.

4. Discussion

Throughout professional settings and daily activities, individuals are chronically exposed to complex mixtures of chemical contaminants, whose combined effects constitute a major public health issue [18] [19]. This exposure is particularly pronounced in low- and middle-income countries due to the predominance of informal hazardous waste management sectors. In Senegal, the management of waste from electrical and electronic equipment (WEEE) largely relies on this informal sector, characterized by the absence of environmental controls and protective measures, thereby promoting the dissemination of contaminants [6] [20].

In this context, soil analysis is a key step to understanding the mechanisms of indirect exposure. The results show that the distribution of metals is not significantly influenced by pH ($|\rho| < 0.3$; $p > 0.20$), probably due to the low variability observed (7.6 - 8.4). In this neutral to slightly alkaline range, the speciation and solubility of trace metals remain relatively stable, limiting their pH-dependent mobility [4] [21] [22]. Similar values have been reported at recycling sites in Ghana and Nigeria, confirming this trend toward moderate alkalinity [23] [24]. This alkalinity can promote the accumulation of metals in the soils, with the potential for subsequent remobilization.

Conversely, electrical conductivity (EC) appears as a determining factor. The positive correlations observed, particularly with copper ($\rho \approx 0.50$; $p \approx 0.012$), suggest that the ionic charge of the soil strongly influences the mobility of metals. A high EC, indicating increased salinity, promotes their mobilization through the formation of soluble complexes for adsorption sites, and colloidal transport [4] [5]. The measured values (0.033 to 4.833 mS/cm) indicate, in certain areas, an accumulation of anthropogenic salts resulting from informal WEEE treatment activities, including electronic waste and combustion by-products [25] [26].

The analysis of metals highlights high concentrations of lead, cadmium, and copper in the dismantling areas, confirming the role of these sites as major sources of contamination. These observations are consistent with the literature, which associates these environments with a high presence of metal ions and high conductivity [27]-[29]. Dismantling and incineration activities thus appear as the main sources of trace metal pollution [28] [30].

Principal component analysis (PCA) highlights a structuring of the data primarily explained by the first two axes (>70% of the variance), clearly distinguishing anthropogenic signatures from natural signatures. Principal component analysis (PCA) confirmed this distinction. The first axis (57.3% of variance) was dominated by Pb, Cd, Cu, and Zn—metals strongly associated with dismantling sites and electronic components [20] [30]. The second axis (16.4% of variance) grouped Fe, Mn, Cr, and Co, which are more abundant in collection and control sites, reflecting the natural geochemical background.

The biplot confirms this opposition between the anthropogenic and natural poles. The anthropogenic profile is particularly concerning due to the high toxicity of the involved metals (neurotoxicity, nephrotoxicity, carcinogenicity), while the metals associated with the geochemical background, although essential in low doses, can also pose risks in the case of chronic exposure [31] [32].

The collection sites occupy an intermediate position, reflecting a mixed influence between moderate contamination and natural signature. This heterogeneity, also observed in similar studies, highlights the variability of sources and the state of degradation of WEEE, and emphasizes the importance of identifying "hot spots" of contamination for better environmental monitoring [6] [33].

5. Conclusions

The dismantling and informal recycling activities of WEEE constitute a major source of metal contamination in soils, characterized by high enrichments in Pb, Cd, Cu, and Zn, often exceeding environmental safety thresholds. Although the physico-chemical properties of the soils modulate the mobility of metals, they do not alone explain the observed levels, confirming the primarily anthropogenic origin of this pollution.

Principal component analysis highlights a clear differentiation between natural and anthropogenic geochemical signatures, emphasizing the specific footprint of activities related to WEEE.

These elements advocate for the implementation of structured management strategies, including the formalization of treatment pathways, the strengthening of regulatory frameworks, and awareness-raising actions adapted to local contexts. Moreover, the integration of complementary approaches, particularly the study of bioavailability, metal speciation, and quantitative assessment of health risks, appears essential.

Acknowledgements

This study was supported by the *"Fonds d'Impulsion de la Recherche Scientifique et Technique du Sénégal"* (FIRST). We express our sincere gratitude to all organizations, local authorities, collectors, recyclers, and dismantlers of e-waste in the informal sector who participated in this study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Srivastav, A.L., Markandeya,, Patel, N., Pandey, M., Pandey, A.K., Dubey, A.K., *et al.* (2023) Concepts of Circular Economy for Sustainable Management of Electronic Wastes: Challenges and Management Options. *Environmental Science and Pollution Research*, **30**, 48654-48675. https://doi.org/10.1007/s11356-023-26052-y

[2] Dieng, D., Diop, C., Sonko, E.H.M., Gning, J.B., Djitte, M. and Gassama, C.I.D.

(2018) Gestion des déchets d'équipements électriques et électroniques (DEEE) au Sénégal: Acteurs et stratégie d'organisation de la filière. *International Journal of Biological and Chemical Sciences*, **11**, 2393-2407. https://doi.org/10.4314/ijbcs.v11i5.35

[3] Müller, E., Böni, H. and Wittmann, A. (2012) Les déchets solides municipaux en Afrique de l'Ouest: Entre pratiques informelles, privatisation et amélioration du service public. Programme IWWA (Gestion Intégrée des Déchets Solides en Afrique de l'Ouest).

[4] Alloway, B.J. (2013) Trace Metals and Metalloids in Soils and Their Bioavailability. *Heavy Metals in Soils*, **22**, 4-18.

[5] Sauvé, S., Hendershot, W. and Allen, H.E. (2000) Solid-solution Partitioning of Metals in Contaminated Soils: Dependence on Ph, Total Metal Burden, and Organic Matter. *Environmental Science & Technology*, **34**, 1125-1131. https://doi.org/10.1021/es9907764

[6] Mbodji, M. (2021) Study of the Environmental and Health Impacts of Waste Electrical and Electronic Equipment (WEEE) in Senegal: Case of the City of Dakar [Etude des Impacts environnementaux et sanitaires des déchets d'équipements électriques et électroniques (DEEE) au Sénégal: Cas de la ville de Dakar]. Thèse de doctorat, Université de Lyon Université Cheikh Anta Diop.

[7] Essington, M.E. (2015) Soil and Water Chemistry: An Integrative Approach. CRC Press.

[8] ANSD (2024) Annuaire Population du Sénégal 2024. Dakar, Sénégal Démographie ANdlSedl.

[9] Faomowe Foko, R., Mbodji, M., Kêdote, M., Diaw, M., Touré, M., Bah, F., *et al.* (2021) Risque chimique et santé respiratoire des manipulateurs des déchets d'équipements électriques et électroniques (DEEE) à Dakar (Sénégal). *Archives des Maladies Professionnelles et de l'Environnement*, **82**, 438-448. https://doi.org/10.1016/j.admp.2021.04.008

[10] APHA (2017) Standard Methods for the Examination of Water and Wastewater. 23 Edition, American Public Health Association, 2671 p.

[11] Kluger, D.M. and Owen, A.B. (2021) A Central Limit Theorem for the Benjamini-Hochberg False Discovery Proportion under a Factor Model. arXiv: 2104.08687.

[12] Benjamini, Y. and Yekutieli, D. (2001) The Control of the False Discovery Rate in Multiple Testing under Dependency. *The Annals of Statistics*, **29**, 1165-1188. https://doi.org/10.1214/aos/1013699998

[13] Jolliffe, I. (2025) Principal Component Analysis. In: Lovric, M., Ed., *International Encyclopedia of Statistical Science*, Springer, 1945-1948. https://doi.org/10.1007/978-3-662-69359-9_483

[14] Rencher, A.C. and Christensen, W.F. (2012) Principal Component Analysis. In: Rencher, A.C. and Christensen, W.F., Eds., *Methods of Multivariate Analysis*, Wiley, 405-433.

[15] US EPA (2024) Regional Screening Levels (RSL) for Chemical Contaminants at Superfund Sites.

[16] Commission, E. (1986) Council Directive 86/278/EEC of 12 June 1986 on the Protection of the Environment, and in Particular of the Soil, When Sewage Sludge Is Used in Agriculture. *Official Journal of the European Communities*, **181**, 6-12. https://eur-lex.europa.eu/eli/dir/1986/278/oj/nld

[17] World Health Organization (1996) Permissible Limits for Heavy Metals in Soil. *Guidelines for the Assessment of Soil Quality*, WHO/EURO, 1-80.

[18] Fiati Kenston, S.S., Su, H., Li, Z., Kong, L., Wang, Y., Song, X., *et al.* (2018) The Systemic Toxicity of Heavy Metal Mixtures in Rats. *Toxicology Research*, **7**, 396-407. https://doi.org/10.1039/c7tx00260b

[19] Landrigan, P.J., Fuller, R., Acosta, N.J.R., Adeyi, O., Arnold, R., Basu, N., *et al.* (2018) The Lancet Commission on Pollution and Health. *The Lancet*, **391**, 462-512. https://doi.org/10.1016/s0140-6736(17)32345-0

[20] Baldé, C.P., Forti, V., Gray, V., Kuehr, R. and Stegmann, P. (2017) The Global E-Waste Monitor 2017: Quantities, Flows, and Resources. Bonn/Geneva/Vienna United Nations University SP, Bonn, Germany.

[21] Kabata-Pendias, A. (2000) Trace Elements in Soils and Plants. CRC Press.

[22] Violante, A., Cozzolino, V., Perelomov, L., Caporale, A.G. and Pigna, M. (2010) Mobility and Bioavailability of Heavy Metals and Metalloids in Soil Environments. *Journal of Soil Science and Plant Nutrition*, **10**, 268-292. https://doi.org/10.4067/s0718-95162010000100005

[23] Owusu-Sekyere, K., Aladago, D.A., Leverenz, D., Oteng-Ababio, M. and Kranert, M. (2024) Environmental Impacts on Soil and Groundwater of Informal E-Waste Recycling Processes in Ghana. *Sustainability*, **16**, Article 4347. https://doi.org/10.3390/su16114347

[24] Adesokan, M.D., Adie, G.U. and Osibanjo, O. (2016) Soil Pollution by Toxic Metals near E-Waste Recycling Operations in Ibadan, Nigeria. *Journal of Health and Pollution*, **6**, 26-33. https://doi.org/10.5696/2156-9614-6-11.26

[25] Grant, K., Goldizen, F.C., Sly, P.D., Brune, M., Neira, M., van den Berg, M., *et al.* (2013) Health Consequences of Exposure to E-Waste: A Systematic Review. *The Lancet Global Health*, **1**, e350-e361. https://doi.org/10.1016/s2214-109x(13)70101-3

[26] Robinson, B.H. (2009) E-Waste: An Assessment of Global Production and Environmental Impacts. *Science of The Total Environment*, **408**, 183-191. https://doi.org/10.1016/j.scitotenv.2009.09.044

[27] Kayatz, B., Baroni, G., Hillier, J., Lüdtke, S., Heathcote, R., Malin, D., *et al.* (2019) Cool Farm Tool Water: A Global On-Line Tool to Assess Water Use in Crop Production. *Journal of Cleaner Production*, **207**, 1163-1179. https://doi.org/10.1016/j.jclepro.2018.09.160

[28] Wei, J., Li, H. and Liu, J. (2022) Heavy Metal Pollution in the Soil around Municipal Solid Waste Incinerators and Its Health Risks in China. *Environmental Research*, **203**, Article ID: 111871. https://doi.org/10.1016/j.envres.2021.111871

[29] Chaer, I., Cadi, A., Fakih, A.L., Khaddor, M. and Brigui, J. (2016) Détermination du degré de contamination du site de la décharge, non contrôlée, de la ville de Tanger par quelques métaux lourds [Determination of the Contamination Degree of Landfill Uncontrolled from Tangier by Some Heavy Metals]. *Journal of Materials and Environmental Science*, **7**, 541-546.

[30] Forti, V., Baldé, C.P., Kuehr, R. and Bel, G. (2020) Suivi des déchets d'équipements électriques et électroniques à l'échelle mondiale pour 2020: Quantités, flux et possibilités offertes par l'économie circulaire. Programme SCYCLE coadministré par l'Union interna-tionale des télécommunications (UIT) et l'Association internationale des déchets solides (ISWA).

[31] Chen, Y., Xu, X., Zeng, Z., Lin, X., Qin, Q. and Huo, X. (2019) Blood Lead and Cadmium Levels Associated with Hematological and Hepatic Functions in Patients from an E-Waste-Polluted Area. *Chemosphere*, **220**, 531-538. https://doi.org/10.1016/j.chemosphere.2018.12.129

[32] Tchounwou, P.B., Yedjou, C.G., Patlolla, A.K. and Sutton, D.J. (2012) Heavy Metal Toxicity and the Environment. In: Luch, A., Ed., *Molecular*, *Clinical and Environmental Toxicology*, Springer, 133-164. https://doi.org/10.1007/978-3-7643-8340-4_6

[33] Houessionon, M.G.K., Ouendo, E.D., Bouland, C., Takyi, S.A., Kedote, N.M., Fayomi, B., *et al*. (2021) Environmental Heavy Metal Contamination from Electronic Waste (e-Waste) Recycling Activities Worldwide: A Systematic Review from 2005 to 2017. *International Journal of Environmental Research and Public Health*, **18**, Article 3517. https://doi.org/10.3390/ijerph18073517