

Assessment of Heavy Metal Contamination in Soils from Street Garages in Dar es Salaam Using EDXRF

Aloyce P. Kinemelo

kinemeloaloyce@gmail.com

Tume ya Nguvu za Atomu Tanzania

Pius W. Shirima

Tume ya Nguvu za Atomu Tanzania

Furaha M. Chuma

Tume ya Nguvu za Atomu Tanzania

Hellen E. Kiyengo

Tume ya Nguvu za Atomu Tanzania

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Abstract

This study assessed heavy-metal contamination in soils associated with informal street garages in Ilala, Temeke, and Kinondoni, Dar es Salaam, Tanzania. Polarised energy-dispersive X-ray fluorescence was used to analyse 41 soil samples comprising 38 garage-soil composites and three district-specific reference controls. Copper, zinc, and lead were the principal analytes; cadmium was not detected above the procedural reporting limit of detection of 6.60 mg/kg in garage soils. District mean concentrations ranged from 183.99 to 549.01 mg/kg for copper, 796.68 to 1,878.70 mg/kg for zinc, and 107.95 to 294.09 mg/kg for lead. Pooled mean concentrations were 314.19, 1,229.00, and 200.59 mg/kg, respectively, while lower medians indicated localised hotspots. The maximum copper and lead concentrations, 3,868.37 and 1,707.91 mg/kg, respectively, occurred at Ilala paint-related sites; the maximum zinc concentration, 10,521.81 mg/kg, occurred at a Temeke oil-change site. District-specific pollution load indices were 4.38 in Ilala, 2.84 in Temeke, and 4.91 in Kinondoni. Exploratory Kruskal-Wallis tests found no statistically significant district differences ($p \geq 0.052$). The findings indicate elevated metal concentrations and support improved waste containment, hotspot cleanup, and routine monitoring.

Introduction

Heavy metals are persistent elements that may accumulate in soils following repeated anthropogenic inputs. At elevated concentrations, several metals can adversely affect soil organisms, plants, and people exposed through soil or dust pathways (Ahmad et al., 2021; Çayır et al., 2025; FAO & UNEP, 2021; Hou et al., 2025; Mkhonza et al., 2026; Oladimeji et al., 2025). Despite the fact that some elements, such as Cu and Zn, are required biologically at trace levels, the accumulation of these elements in available urban soils necessitate site-specific evaluation (Canadian Council of Ministers of the Environment [CCME], 2024; U.S. Environmental Protection Agency [U.S. EPA], 2024). Waste-disposal sites in particular have repeatedly been shown to raise soil heavy-metal levels well above background, whether at municipal refuse dumps or at sites used for cultivation near such dumps (Ahmad et al., 2021; Nyiramigisha et al., 2021; Okebalama et al., 2024).

Informal street garages commonly undertake vehicle repair, welding, oil changes, painting, battery servicing, and replacement of mechanical components. These activities can release metal-bearing wastes, including used lubricating oils, paint residues, batteries, brake and tyre debris, scrap metals, and electronic components, directly onto unpaved ground (Ale, 2025; Duru et al., 2024; Gyimah et al., 2022; Konadu et al., 2023; Mahugija & Sheikh, 2018; Okebalama et al., 2024). Comparable studies of automobile-mechanic and vehicle-servicing environments have reported elevated metal burdens in surface soils, particularly for Cu, Zn, and Pb (Ale, 2025; Daniel et al., 2025; Duru et al., 2024; Gyimah et al., 2022; Konadu et al., 2023; Mahugija & Sheikh, 2018).

Dar es Salaam is the largest commercial and industrial city in Tanzania and hosts numerous formal and informal vehicle-service locations within its road network and urban neighbourhoods (Kibassa et al.,

2013; Kwikima and Mhagama, 2023; Ligate & Ntarisa, 2026; Mkhonza et al., 2026; Mwegoha & Kihampa, 2010). Nevertheless, elemental distributions within and between garage environments are likely heterogeneous because waste-management practices, repair activities, surface conditions, and drainage differ among sites (Duru et al., 2024; Kazapoe et al., 2025; Ligate & Ntarisa, 2026). Therefore, this research quantified Cr, Fe, Ni, Cu, Zn, As, Hg, Pb, and Cd in 38 independent garage-soil composites collected from Ilala, Temeke, and Kinondoni districts using EDXRF. It also evaluated primary pollution indicators for Cu, Zn, and Pb relative to the available district-specific reference soils in Ilala, Temeke, and Kinondoni.

Materials and methods

Study area

The study was conducted in Dar es Salaam Region on the Indian Ocean coast of Tanzania, approximately between 6°36'-7°00' S and 39°00'-39°33' E. The region has a tropical coastal climate with high temperature and humidity and bimodal rainfall, including long rains from March to May and short rains from October to December. The study focused on Ilala, Temeke, and Kinondoni districts, where informal vehicle-repair activities are common within densely populated commercial and transport corridors. These garages undertake repairs, oil changes, welding, painting, battery servicing, and replacement of vehicle components, activities that may deposit metal-bearing wastes on surrounding surface soils.

Soil sampling and sample allocation

A total of 41 soil samples, each weighing approximately 100–200 g, were collected during the dry season from battery-service areas, paint-related areas, oil-change areas, and other automobile-repair zones. At each designated garage activity area, five surface subsamples were collected from the 0–10 cm layer using a soil trowel and combined to form one composite sample. Each composite represented the particular garage/activity area from which it was collected. Paint-related and oil-change composites were collected independently for their respective garage activity areas and were treated as independent environmental sampling units. Sampling locations at different garages were separated by approximately 20–40 m where site layout and slope permitted. The final dataset comprised 38 garage-soil composites: 10 from Ilala (five paint-related and five oil-change), 14 from Temeke (eight paint-related and six oil-change), and 14 from Kinondoni (six paint-related and eight oil-change). Three additional soils, each collected away from garage operations, were designated as district-specific reference controls: ILCA from Ilala, TCB from Temeke, and the Kinondoni control. The total of 41 analytical samples therefore includes three controls and should not be interpreted as 41 garage-soil samples.

Sample preparation and EDXRF analysis

Before preparation, all working surfaces, apparatus, and sample containers were cleaned and decontaminated (International Organization for Standardization [ISO], 2017). Each composite soil sample was air-dried for one day and then oven-dried at $60 \pm 1^\circ\text{C}$ for two days. The dried soil was

disaggregated using a mortar and pestle, passed through a 0.5 mm polystyrene sieve, and stored in well-labelled polythene bags. A 4 g dry mass of each sieved soil was thoroughly mixed and homogenised with 0.9 g cellulose binder. The mixture was pressed into 32 mm diameter pellets under a load of 15 tons to obtain reproducible irradiation and counting geometry (Croffie et al., 2020; Jenkins et al., 2025; Marsay et al., 2025; Ravansari et al., 2020; Silva et al., 2021; Sut-Lohmann et al., 2022; Weindorf & Chakraborty, 2020). Total elemental concentrations in the pellets were determined by polarised energy-dispersive X-ray fluorescence (PE-EDXRF) at the TAEC XRF Laboratory in Arusha. The spectrometer was operated at 50 kV and 0.5 mA and used a Si(Li) detector, a multichannel analyser, and fundamental-parameter quantification software. To enhance sensitivity across the elemental range, highly oriented pyrolytic graphite (HOPG) was used for low-energy elements (Na-V), a molybdenum target for intermediate-energy elements (Cr-Zr), and a Barkla aluminium-oxide (Al_2O_3) target for high-energy elements (Y-Ce). Each pellet was placed in a cleaned sample holder, introduced to the excitation chamber through the automated sample changer, and measured under a time-based programme. Calibration was carried out daily, and each pellet was measured three times under repeat conditions. Routine calibration, replicate measurement, and verification with reference materials are important for obtaining reliable XRF results from heterogeneous soil matrices (Briffa et al., 2022; Jiang et al., 2025; Qu et al., 2021; Romzaykina et al., 2025).

Quality assurance and data handling

Analytical quality control and laboratory calibration were conducted by analysing the Montana Soil certified reference material, NIST SRM 2711a (Montana II Soil), using the same complete drying-to-measurement procedure applied to the garage-soil composites, including air drying, oven drying, disaggregation, sieving, binder addition, homogenisation, pellet pressing, and PE-EDXRF measurement (Fedeli et al., 2024; ISO, 2017; Jenkins et al., 2025; National Institute of Standards and Technology [NIST], 2026). Four supplied CRM determinations were used to calculate the observed CRM mean concentration, sample standard deviation (SD), relative standard deviation (RSD), percentage recovery $[(\text{observed CRM mean}/\text{certificate value}) \times 100]$, and relative bias $[(\text{observed CRM mean} - \text{certificate value})/\text{certificate value} \times 100]$ (Table 1). For each element, the laboratory compared the observed CRM response with the corresponding certified CRM value and established a CRM-derived element-specific calibration correction factor. The laboratory applied these calibration correction factors to the raw PE-EDXRF sample results and their associated analytical SDs before issuing the laboratory reports.

Accordingly, the district data sheets supplied for the present study contain final reported, CRM-adjusted concentrations and analytical SDs, rather than raw instrument outputs. All concentration summaries, activity-type comparisons, district-control comparisons, contamination factors, pollution load indices, and supplementary individual-sample values in this manuscript were calculated from those final reported values. Table 1 presents the observed CRM comparison used to establish the CRM-derived element-specific calibration correction factors; it should not be interpreted as an independent post-correction validation of the final reported soil concentrations. The observed CRM comparison differed by element, including a + 34.3% relative difference for Zn. The full-procedure CRM workflow therefore

provides calibration control for the final reported results, although independent validation using a separate CRM or another analytical method would provide stronger external confirmation.

The same TAEC PE-EDXRF configuration, pellet-preparation procedure, and NIST SRM 2711a (Montana II Soil) had previously been verified using a full procedural binder blank. In that validation, the absolute deviations between the measured and certified concentrations for study-relevant elements ranged from 0.16% to 7.68%, and procedural reporting LODs were reported for each analyte (Table 2). The present study uses these full-procedure values as procedural reporting LODs, rather than equipment-only sensitivity figures. They are not described as formal method detection limits (MDLs) or limits of quantification (LOQs), because the available validation record does not document the number of blank replicates or the statistical calculation used to derive MDL or LOQ values. Cd was not detected above the 6.60 mg/kg procedural reporting LOD in any garage-soil sample. No additional post-report correction was performed in the present study. The $\pm$ terms in the supplied result sheets were treated as reported analytical SDs rather than independent spatial replicates.

Table 1

CRM calibration comparison for the supplied four determinations of NIST SRM 2711a (Montana II Soil) analysed by PE-EDXRF. The observed CRM comparison was used to establish CRM-derived element-specific calibration correction factors before final sample results were reported. SD = sample standard deviation; RSD = relative standard deviation; recovery = observed CRM mean/certificate value $\times$ 100; relative bias = (observed CRM mean – certificate value)/certificate value $\times$ 100.

Element	Observed CRM mean $\pm$ SD (mg/kg)	Certificate value (mg/kg)	RSD (%)	Recovery (%)	Relative bias (%)
As	98.53 $\pm$ 1.42	107.00	1.44	92.1	-7.9
Hg	18.48 $\pm$ 1.57	7.42	8.49	249.0	+ 149.0
Cd	65.98 $\pm$ 1.93	54.10	2.93	122.0	+ 22.0
Cr	142.78 $\pm$ 2.16	52.30	1.51	273.0	+ 173.0
Pb	1,626.58 $\pm$ 1.88	1,400.00	0.12	116.2	+ 16.2
Cu	159.33 $\pm$ 1.38	140.00	0.86	113.8	+ 13.8
Zn	556.00 $\pm$ 47.05	414.00	8.46	134.3	+ 34.3
Mn	492.05 $\pm$ 7.54	675.00	1.53	72.9	-27.1
Co	131.60 $\pm$ 2.27	9.89	1.72	1330.6	+ 1230.6
Fe	32,198.53 $\pm$ 35.70	28,200.00	0.11	114.2	+ 14.2
Ni	22.43 $\pm$ 0.56	21.70	2.48	103.3	+ 3.3

Table 2
 Historical procedural reporting LODs for the same TAEC PE-EDXRF configuration and pellet-preparation procedure using NIST SRM 2711a (Montana II Soil) and a full procedural binder blank. Absolute deviation is the absolute relative difference between measured and certified concentrations. These procedural reporting LODs are not formal MDLs.

Element	Procedural reporting LOD (mg/kg)	Historical absolute deviation (%)
As	1.31	1.91
Hg	0.94	7.68
Cd	6.60	4.33
Cr	15.70	3.61
Pb	0.85	7.14
Cu	1.79	0.16
Zn	1.35	5.36
Mn	14.10	0.77
Co	21.70	3.64
Fe	5.00	3.55
Ni	2.70	6.77
Statistical and pollution-index analysis		

Concentrations are reported in mg/kg. The district data sheets contained final reported, CRM-adjusted concentrations and their reported analytical SDs; raw PE-EDXRF output values were not reprocessed in this study. Each of the 38 garage-soil composites was treated as an independent environmental sampling unit for district- and activity-type summaries; replicate pellet measurements were analytical replicates and were not treated as additional spatial observations. Means, standard deviations, medians, and ranges are presented because of skewed distributions and isolated hotspots. Values reported as 0.000 were retained as reported and were counted as not reported above zero only when summarising reporting frequency. Cd, which was reported as 0.000 in all garage-soil records, was treated as not detected above the 6.60 mg/kg procedural reporting LOD. Other 0.000 results were not automatically classified as below the corresponding procedural reporting LOD because sample-specific censoring flags were not supplied. For Cu, Zn, and Pb, exploratory Kruskal-Wallis tests were used to compare distributions among districts (two-sided alpha = 0.05); epsilon-squared was calculated as the effect-size estimate (Kruskal & Wallis, 1952; Tomczak & Tomczak, 2014). Because sampling points are spatially clustered within garage environments, these tests are descriptive/exploratory and do not establish citywide population differences.

Following Tomlinson et al. (1980), the contamination factor was calculated as $CF = \frac{C_n}{C_{ref}}$ where C_n is the mean concentration in garage soils and C_{ref} is the concentration in the available local reference-control sample from the same district, and the pollution load index was calculated as the cube root of the product of $CF(Cu)$, $CF(Zn)$, and $CF(Pb)$. This index-based approach has previously been applied to comparable automobile-workshop soils in West Africa (Daniel et al., 2025; Duru et al., 2024; Gyimah et al., 2022). CF and PLI were calculated only for Cu , Zn , and Pb because Cd was not detected above the 6.60 mg/kg procedural reporting LOD and no reliable numeric Cd values were supplied. District-specific indices were calculated for Ilala, Temeke, and Kinondoni using one local reference-control sample per district. These indices are screening indicators based on single local controls and should not be treated as substitutes for a regional geochemical background dataset.

Results and discussion

Primary metal concentrations and spatial heterogeneity

The 38 garage soils showed broad concentration ranges for the three primary metals. Ilala had the highest district mean Cu (549.01 mg/kg) and Pb (294.09 mg/kg), whereas Temeke had the highest district mean Zn (1,878.70 mg/kg). However, means were influenced by a small number of high-concentration samples, as shown by the lower medians and wide ranges in Table 3. For this reason, the results should be interpreted as evidence of heterogeneous, site-specific contamination rather than uniform contamination throughout each district. The district-level spread, skewness, and hotspot behaviour of Cu , Zn , and Pb are illustrated in Fig. 2.

Table 3
Primary metal concentrations in garage soils by district. Values are mean ± standard deviation [median; range].

District	n	Cu (mg/kg)	Zn (mg/kg)	Pb (mg/kg)
Ilala	10	549.01 ± 1,170.63 [165.84; 78.44-3,868.37]	924.67 ± 627.90 [835.34; 366.85-2,547.40]	294.09 ± 500.74 [142.59; 58.55-1,707.91]
Temeke	14	276.67 ± 501.88 [64.77; 18.59-1,607.63]	1,878.70 ± 3,507.02 [539.66; 82.29-10,521.81]	107.95 ± 114.11 [84.36; 0.00-441.23]
Kinondoni	14	183.99 ± 130.24 [126.36; 41.93-379.19]	796.68 ± 470.20 [652.12; 275.02-1,472.27]	226.44 ± 181.65 [127.23; 55.21-574.47]
All garage soils	38	314.19 ± 670.55 [124.44; 18.59-3,868.37]	1,229.00 ± 2,179.54 [560.12; 82.29-10,521.81]	200.59 ± 288.14 [99.50; 0.00–1,707.91]

The highest individual Cu (3,868.37 mg/kg) and Pb (1,707.91 mg/kg) values occurred at Ilala paint-related locations, whereas the highest Zn concentration (10,521.81 mg/kg) occurred at a Temeke oil-change location. The activity-type summary in Table 4 shows that paint-related areas had higher mean Cu and Pb concentrations (367.23 and 277.67 mg/kg, respectively) than oil-change areas (261.16 and 123.50 mg/kg, respectively), whereas oil-change areas had the higher mean Zn concentration (1,599.59 versus 858.41 mg/kg). These patterns are descriptive because they are strongly influenced by hotspot samples and do not identify specific waste sources without site-level source-apportionment evidence (Duru et al., 2024; Kazapoe et al., 2025; Konadu et al., 2023; Mahugija & Sheikh, 2018). The contrast between paint-related and oil-change composites is further visualised in Fig. 3.

Table 4 Primary metal concentrations in garage soils by activity type. Values are mean ± standard deviation [median; range].

Activity type	n	Cu (mg/kg)	Zn (mg/kg)	Pb (mg/kg)
Paint-related	19	367.23 ± 858.85 [113.92; 18.59-3,868.37]	858.41 ± 577.51 [598.69; 82.29-2,547.40]	277.67 ± 385.20 [103.50; 35.87-1,707.91]
Oil-change	19	261.16 ± 425.10 [124.67; 41.93-1,607.63]	1,599.59 ± 3,023.45 [525.82; 256.87-10,521.81]	123.50 ± 98.66 [95.26; 0.00-441.23]
Broader EDXRF elemental profile				

The supplied results also contained Cr, Fe, Ni, As, and Hg. Cd was reported as 0.000 in all 38 garage-soil records and, based on the 6.60 mg/kg procedural reporting LOD, was treated as not detected; it is therefore not included in the descriptive concentration statistics. Cr, Fe, Ni, Cu, and Zn were reported above zero in all 38 garage soils. Hg was reported above zero in 37/38 samples, while As was reported above zero in 10/38 samples. The reporting frequencies for As and Hg should not be interpreted as a formal quantified-detection frequency because sample-specific LOD-censoring flags were not supplied. The concentration ranges and hotspot locations in Table 5 demonstrate that the analysed dataset extends beyond the original Cu-Zn-Pb focus and supports a broader discussion of potentially toxic elements.

Table 5

Broader elemental profile of the 38 garage-soil samples. Cd was not detected above the 6.60 mg/kg procedural reporting LOD and is therefore not included. Where an entry in the supplied analytical sheets read 0.000, it was treated here as a result not reported above zero.

Element	Reported > 0	Mean $\pm$ SD (mg/kg)	Median (mg/kg)	Range (mg/kg)	Highest observation
Cr	38/38 (100.0%)	117.96 $\pm$ 112.07	75.18	28.43-463.95	Ilala oil (463.95)
Fe	38/38 (100.0%)	31,456.54 $\pm$ 33,107.53	21,990.59	8,957.86– 170,661.57	Temeke oil (170,661.57)
Ni	38/38 (100.0%)	31.35 $\pm$ 33.74	17.03	4.46-126.55	Kinondoni paint (126.55)
Cu	38/38 (100.0%)	314.19 $\pm$ 670.55	124.44	18.59-3,868.37	Ilala paint (3,868.37)
Zn	38/38 (100.0%)	1,229.00 $\pm$ 2,179.54	560.12	82.29-10,521.81	Temeke oil (10,521.81)
As	10/38 (26.3%)	1.26 $\pm$ 2.51	0.00	0.00-9.08	Temeke oil (9.08)
Hg	37/38 (97.4%)	1.92 $\pm$ 1.36	1.71	0.00-7.84	Ilala paint (7.84)
Pb	37/38 (97.4%)	200.59 $\pm$ 288.14	99.50	0.00–1,707.91	Ilala paint (1,707.91)

Fe covers a wide range here, which fits with variable soil mineralogy plus some entrained metal-rich material; the elevated Cr, Ni, and Hg seen at a few sites are worth a closer look in follow-up work. What this dataset cannot do is separate geogenic from anthropogenic sources, or pin specific concentrations on particular garage activities. Still, high Cu, Zn, Pb, and other elements keep turning up together at the same paint- and oil-related sites, which looks more like localised waste handling and deposition than any general pattern across urban soil (Ale, 2025; Duru et al., 2024; Okebalama et al., 2024; Oladimeji et al., 2025).

Exploratory comparison among districts

District means did differ, but the exploratory non-parametric analysis turned up no statistically significant differences between districts for any of the three primary metals at $\alpha = 0.05$ (Table 6); Pb came close to the conventional threshold without quite reaching it. That fits with the considerable within-district variability already visible in Table 3, which is also the reason medians and ranges are reported alongside the arithmetic means rather than instead of them. No post-hoc pairwise tests were performed because the global Kruskal-Wallis tests were not statistically significant.

Table 6
Exploratory Kruskal-Wallis comparison of Cu, Zn, and Pb among Ilala (n = 10), Temeke (n = 14), and Kinondoni (n = 14). *Negative ϵ^2 values were set to zero.

Metal	Kruskal-Wallis H (df = 2)	p value	ϵ^2	Exploratory effect
Cu	4.73	0.094	0.078	Small
Zn	1.33	0.513	0.000*	Negligible
Pb	5.91	0.052	0.112	Small

Local reference comparison, contamination factor, and pollution load index

The supplied dataset contains one district-specific reference-control sample from each district: ILCA from Ilala, TCB from Temeke, and a Kinondoni control. The reported control concentrations were 38.61 mg/kg Cu, 868.71 mg/kg Zn, and 53.05 mg/kg Pb for Ilala; 81.87 mg/kg Cu, 510.73 mg/kg Zn, and 58.55 mg/kg Pb for Temeke; and 31.25 mg/kg Cu, 210.45 mg/kg Zn, and 42.60 mg/kg Pb for Kinondoni. These are final laboratory-reported CRM-adjusted values. Because local control concentrations differ substantially between districts, especially for Zn, contamination factors and PLI values were calculated separately for each district.

Table 7
District-specific comparison of garage-soil means with the available local reference control. CF = garage-soil mean / local reference-control concentration.

District	Cu: control / garage mean / CF	Zn: control / garage mean / CF	Pb: control / garage mean / CF
Ilala	38.61 / 549.01 / 14.22	868.71 / 924.67 / 1.06	53.05 / 294.09 / 5.54
Temeke	81.87 / 276.67 / 3.38	510.73 / 1,878.70 / 3.68	58.55 / 107.95 / 1.84
Kinondoni	31.25 / 183.99 / 5.89	210.45 / 796.68 / 3.79	42.60 / 226.44 / 5.32

Table 8 gives the district-specific CFs and PLIs. Against their own local controls, Ilala had a PLI of 4.38, Temeke had a PLI of 2.84, and Kinondoni had a PLI of 4.91. All values were above 1, which, following the classification of Tomlinson et al. (1980), indicates deterioration in soil quality relative to the respective local control. The CFs and PLIs were calculated from final laboratory-reported CRM-adjusted garage-soil and control concentrations. Each district-specific reference is a single soil sample; therefore, the PLI and CF values are screening-level indicators and should be interpreted cautiously. The CRM comparison in Table 1 was used to establish CRM-derived element-specific calibration correction factors and is not an independent post-correction validation of the final values. Independent confirmation using a separate CRM or another analytical method would strengthen future assessments. A district-level screening summary of CF and PLI is presented in Fig. 4.

Table 8 District-specific contamination factors and pollution load indices for Ilala, Temeke, and Kinondoni. PLI is the cube root of $[CF(Cu) \times CF(Zn) \times CF(Pb)]$.

District	CF Cu	CF Zn	CF Pb	PLI
Ilala	14.22	1.06	5.54	4.38
Temeke	3.38	3.68	1.84	2.84
Kinondoni	5.89	3.79	5.32	4.91

Interpretation and study limitations

This study provides a baseline assessment of informal-garage soils in the three districts, but several limitations should be acknowledged. Although each reference-control soil was collected away from garage operations, one reference soil from each district constitutes the control dataset; consequently, these values cannot represent the natural background of Dar es Salaam soils generally, and additional controls matched to soil type are required. Future sampling should also document a priori control-site selection criteria, including land use, distance from garages and major roads, and soil-type comparability. The composite design reduces small-scale variability within each garage/activity area, but the results remain representative of the sampled garages and should not be extrapolated uncritically to all garages in the districts. Samples collected within the same garage cluster or activity zone may also be spatially correlated and are therefore not fully independent observations. The concentrations and analytical SDs used in this study are final laboratory-reported values that had already been adjusted using CRM-derived element-specific calibration correction factors. Because the same CRM comparison was used to establish these factors, Table 1 is not an independent external validation of the final reported concentrations. Future work should include a second independently analysed CRM and, where feasible, confirmation by another analytical method, particularly for Zn, Cr, Hg, and Co. The available procedural reporting LODs were established from a full procedural blank under the same setup; however, a formal MDL/LOQ validation requires the blank-replicate design and statistical calculation to be documented. Finally, the observed contamination does not by itself establish human exposure, bioavailability, source apportionment, groundwater contamination, or health risk (Ahmad et al., 2021; Li et al., 2022; Moukadiri et al., 2024; Oladimeji et al., 2025).

Conclusions

The results indicate that garage soils in Ilala, Temeke, and Kinondoni contain highly variable Cu, Zn, and Pb concentrations, with clear local hotspots. Mean Cu and Pb were highest in Ilala; mean Zn was highest in Temeke. The peak Cu and Pb readings both came from paint-related sites in Ilala, and the peak Zn reading from an oil-change site in Temeke. All three districts returned PLI values above 1 against their own district controls: 4.38 in Ilala, 2.84 in Temeke, and 4.91 in Kinondoni. These indices were calculated from final laboratory-reported CRM-adjusted concentrations and therefore provide screening evidence of elevated concentrations relative to the available local controls. Practically, this supports containment

and segregation of used oil, paint residues, batteries, scrap metal, and other garage waste; improved drainage and paved work areas; targeted investigation and cleanup of hotspot soils; and routine soil monitoring with stronger QA/QC reporting. Future monitoring should include routine batch-specific Montana Soil or other matrix-matched CRM checks, a second independently analysed CRM, procedural blanks, procedural reporting LODs, and fully documented MDL and LOQ validation. Larger district-specific background datasets, sampling across wet and dry seasons, and assessments of bioavailability or exposure are also needed before health-risk conclusions are drawn.

Declarations

Ethical responsibilities of authors

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Competing interests:

The authors have no competing interests to declare that are relevant to the content of this article.

Ethics approval and consent to participate:

Not applicable. The study involved environmental soil sampling only and did not involve human participants, human data, or animals.

Institutional permission

Field sampling and laboratory analyses were conducted through the Tanzania Atomic Energy Commission (TAEC).

Supplementary materials

Supplementary Table S1 presents the final laboratory-reported CRM-adjusted concentrations of Cr, Fe, Ni, Cu, Zn, As, Hg, and Pb in the 38 garage-soil composites and the three district-specific reference-control soils. Supplementary Table S2 provides the district-level mean concentrations, local-control values, contamination factors, and pollution load indices used in the calculations.

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Author Contribution

P.S. conceived and designed the study, coordinated sample collection, and contributed to the methodology and investigation. A.K. performed data curation and statistical analysis, prepared the initial manuscript draft, and managed the manuscript revision and submission process. F.C. contributed to laboratory analysis, quality assurance, and interpretation of the results. H.K. contributed to supervision, validation, and critical review of the manuscript. All authors read and approved the final manuscript.

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Data Availability

The analysed data supporting the findings of this study are included in this article and its Supplementary Information files. The underlying raw EDXRF measurement data and associated laboratory records are available from the corresponding author upon reasonable request.

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Figures

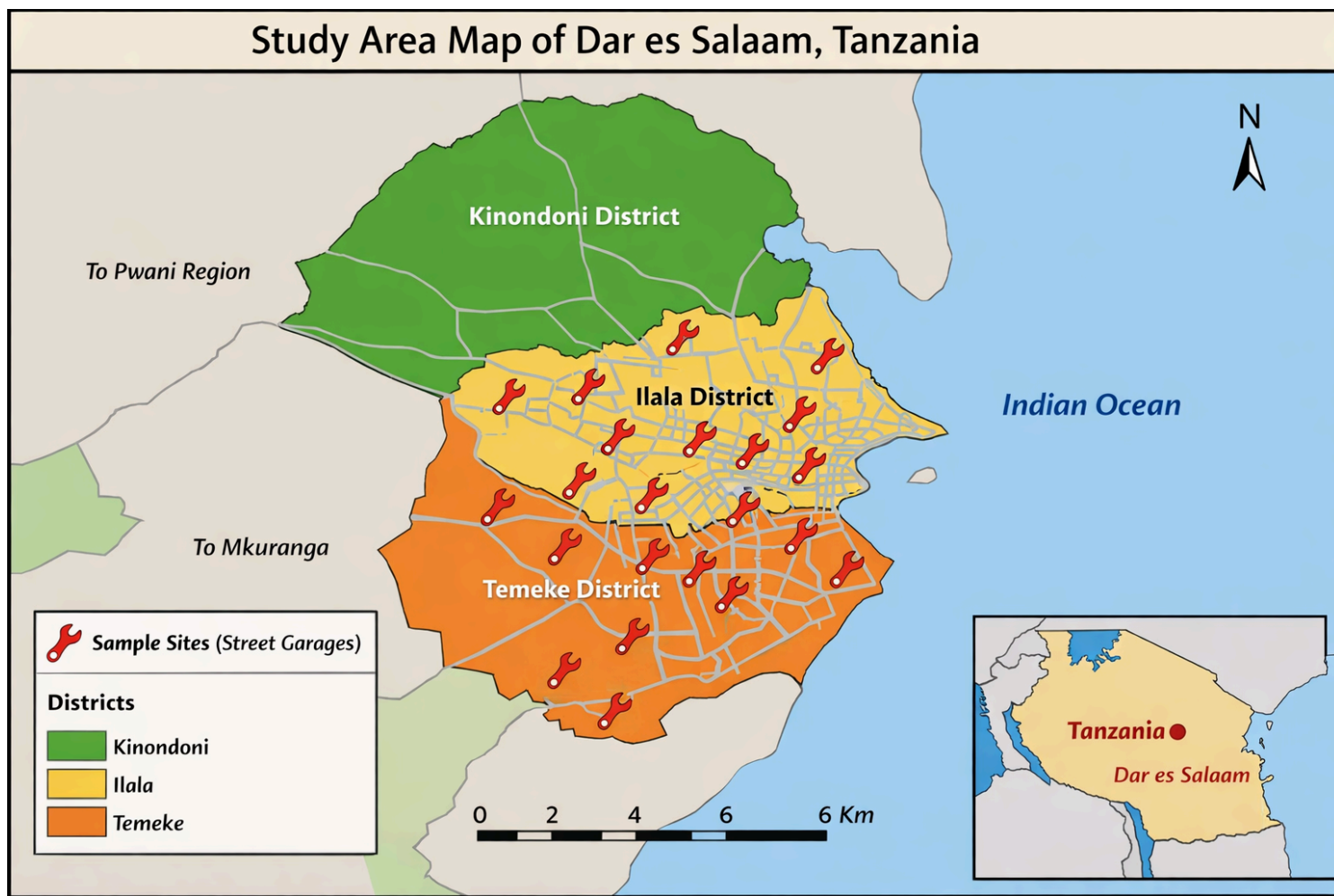


Figure 1

Study area and street-garage sampling locations in Dar es Salaam, Tanzania

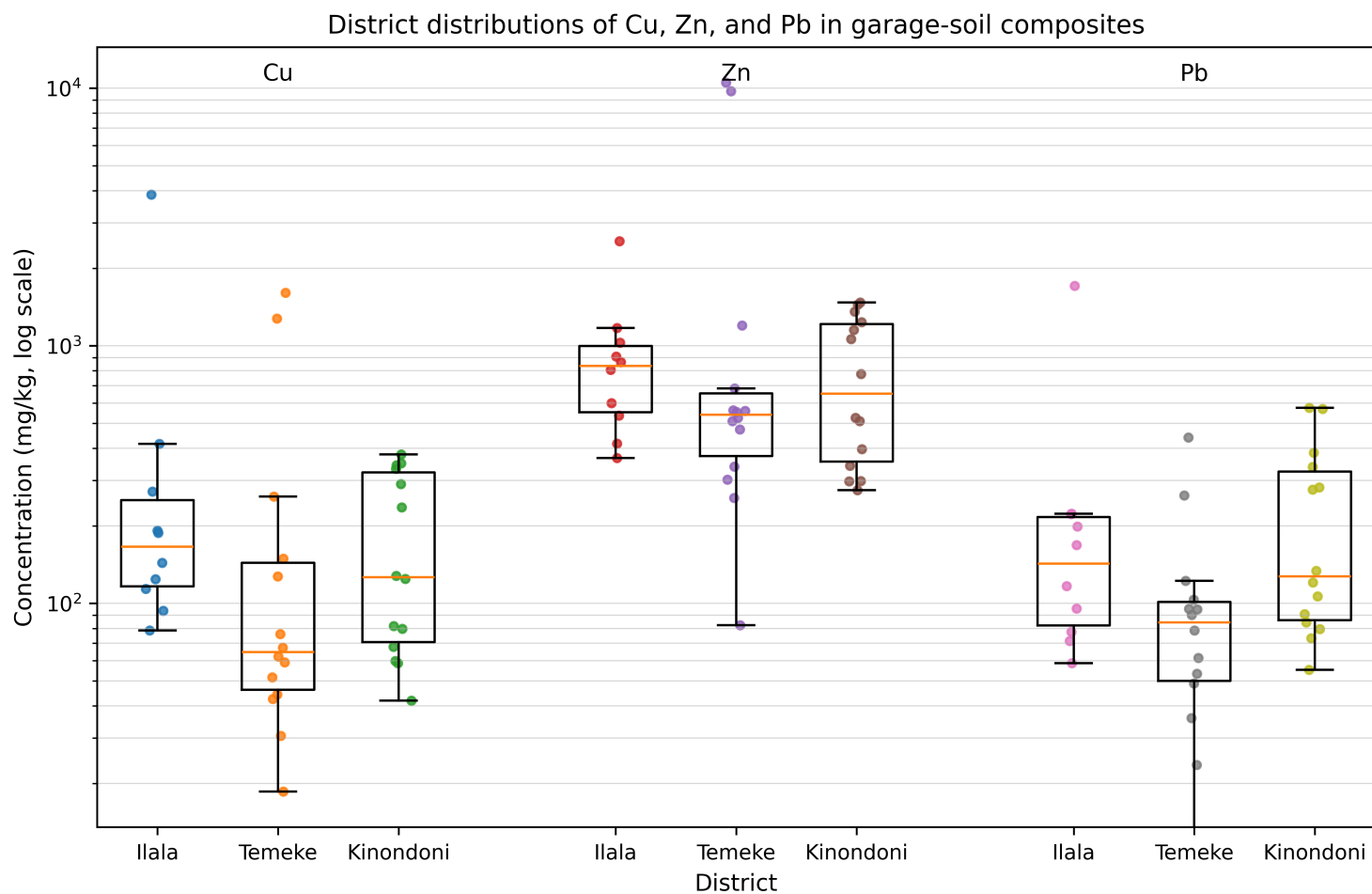


Figure 2

Distribution of Cu, Zn, and Pb concentrations in garage-soil composites by district. Boxes show the median and interquartile range, whiskers extend to $1.5 \times$ IQR, points represent individual composite samples, and the y-axis is logarithmic.

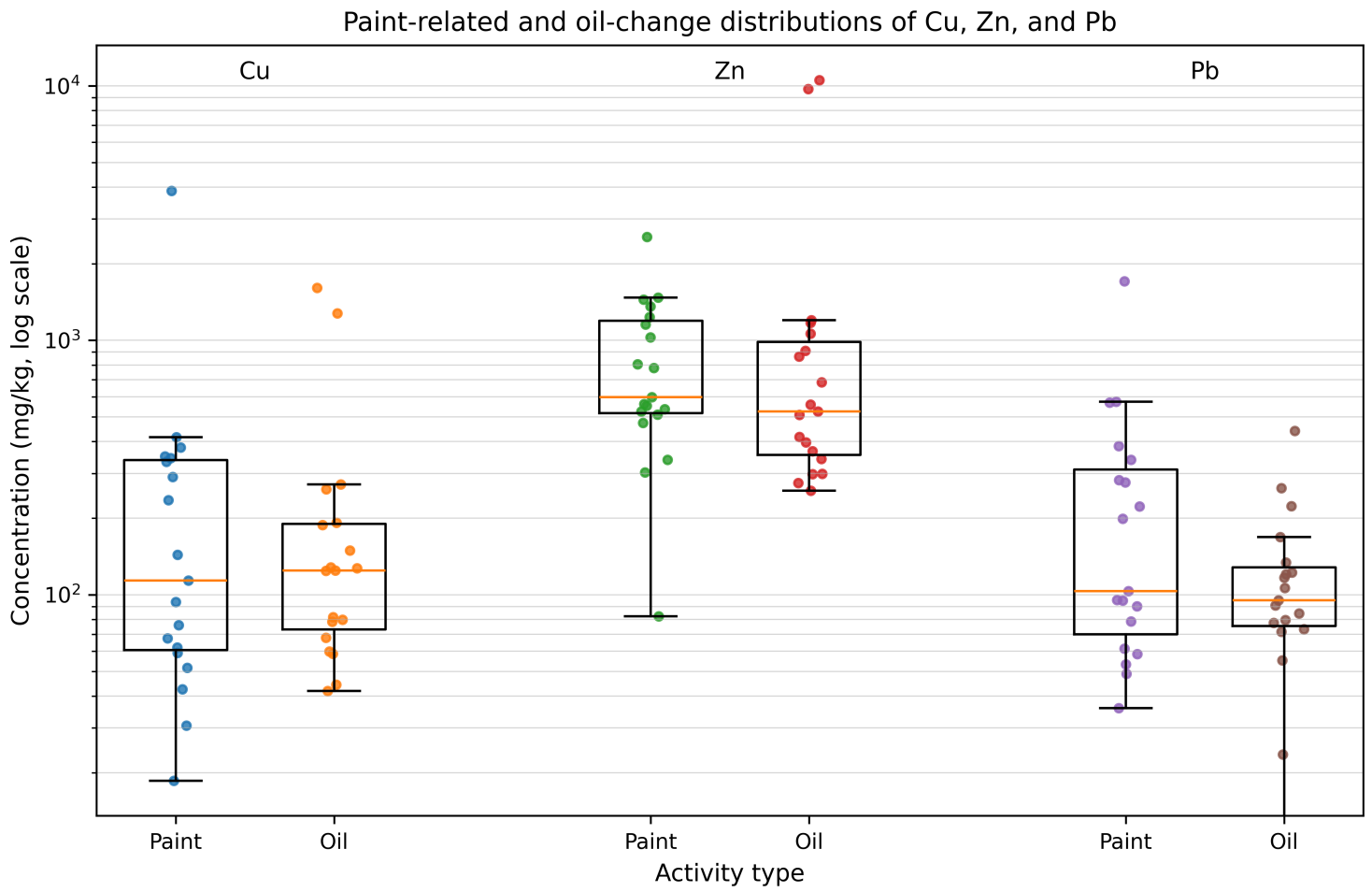


Figure 3

Distribution of Cu, Zn, and Pb concentrations in paint-related and oil-change garage-soil composites. Boxes show the median and interquartile range, whiskers extend to $1.5 \times \text{IQR}$, points represent individual composite samples, and the y-axis is logarithmic.

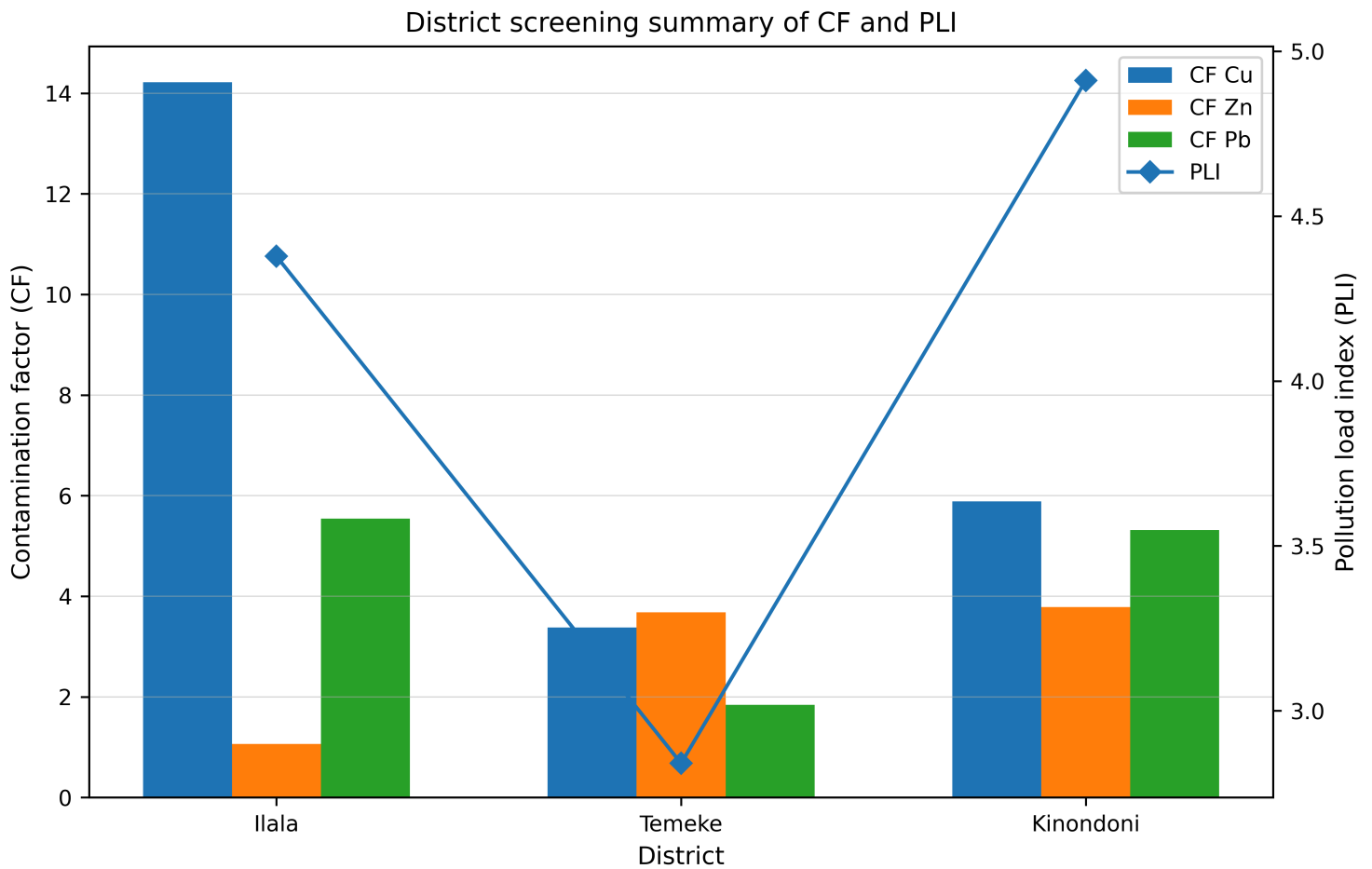


Figure 4

District screening summary of contamination factors (CF) for Cu, Zn, and Pb, with pollution load index (PLI) shown separately. CF and PLI were calculated using one local reference-control soil per district.

Supplementary Files

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