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SPATIAL DISTRIBUTION AND SOURCE APPORTIONMENT OF HEAVY METAL CONTAMINATION IN STREET-ROASTED PLANTAIN ACROSS URBAN MICROENVIRONMENTS IN BENIN CITY, NIGERIA

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ABSTRACT

Spatial information on the origins of heavy metal contamination in street-vended foods is essential for evidence-based urban food-safety governance. This study combined the Geo-accumulation Index (Igeo), Contamination Factor (CF), Pollution Load Index (PLI), Pearson correlation, Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) to characterise the spatial variability and source apportionment of iron (Fe), zinc (Zn), copper (Cu) and lead (Pb) in street-roasted plantain (Musa paradisiaca L.) from ten urban microenvironments in Benin City, Nigeria. Concentrations were determined by atomic absorption spectrophotometry. Copper exceeded the FAO/WHO limit of 0.5 mg/kg at all ten sites, peaking at 2.67 mg/kg at New Benin, whereas Pb and Zn stayed below their limits everywhere. The PLI exceeded unity at every site, from 1.63 (Iyaro) to 2.60 (New Benin), indicating city-wide enrichment above background. PCA resolved two components explaining 80.5% of variance: PC1 (57.9%) loaded positively on Fe, Zn and Cu with a contrasting negative Pb loading, and PC2 (22.6%) was Pb-dominated. Only Zn-Cu was significantly correlated (r = 0.67, p < 0.05), and HCA independently separated Fe-Zn-Cu from Pb. These results indicate two contrasting pathways, a diffuse commercial-cookware signal for Fe-Zn-Cu and a traffic-linked signal for Pb, informing targeted regulation of street-food vending.

Keywords: *Heavy metals; source apportionment; Pollution Load Index; Principal Component Analysis; street-roasted plantain; Benin City*

1. INTRODUCTION

Urban street-food environments in sub-Saharan Africa exist within complex pollution settings shaped by diverse land-use activities (Frazzoli, 2020). Residential, commercial, industrial and transportation zones contribute differently to environmental contamination, producing substantial spatial variation in heavy metal concentrations in ambient air, deposited particulates, roadside dust and urban soils (Imathiu, 2017; Onakpa *et al.*, 2018). Consequently, street-vended foods prepared in these environments are exposed to spatially heterogeneous contamination pressures that reflect the dominant anthropogenic activities surrounding each vending location (Alelign *et al.*, 2023).

Street-roasted plantain (*Musa paradisiaca* L.; locally known as boli) is one of the most widely consumed street foods in southern Nigeria, and its safety has been examined in several Nigerian cities (Makanjuola & Adepegba, 2016; Bello *et al.*, 2022). Preparation typically involves roasting over open charcoal braziers in roadside environments, exposing the food to atmospheric deposition of particulates throughout cooking and vending (Oluwadamilare *et al.*, 2023; Olufunso & Dennis, 2024). The resulting heavy metal burden therefore represents an integration of multiple environmental inputs, including combustion emissions, resuspended road dust, commercial and workshop particulates, metallic cookware leaching and charcoal-derived contaminants (Alabi & Afolabi, 2024; Faurat *et al.*, 2024; Oyet & Samuel, 2020). Because these pathways are strongly influenced by local land use, heavy metal concentrations in roasted plantain are expected to vary substantially across urban microenvironments (Opeolu *et al.*, 2010).

Previous studies of heavy metals in Nigerian street foods have reported the occurrence of Fe, Zn, Cu, Pb, Cd and Cr and have largely focused on comparing measured concentrations with FAO/WHO permissible limits (Iwegbue *et al.*, 2013; Makanjuola & Adepegba, 2016; Bello *et al.*, 2022). While these investigations provide important baseline information, they have generally adopted a descriptive approach focused on concentration reporting and regulatory-exceedance assessment. Little attention has been given to identifying contamination sources, evaluating spatial heterogeneity, or linking contamination patterns to the urban activities that generate them (Orisakwe *et al.*, 2012; Oluwadamilare *et al.*, 2023). Such information is critical because effective management of street-food safety requires not only knowledge of contaminant levels but also an understanding of their origins and spatial distribution.

Source apportionment of environmental heavy metals commonly employs complementary geochemical and multivariate tools. The Geo-accumulation Index (Igeo; Müller, 1969) and Contamination Factor (CF; Hakanson, 1980) quantify enrichment relative to geochemical background, while the Pollution Load Index (PLI; Tomlinson *et al.*, 1980) integrates contamination across metals into a single site-level index. Multivariate techniques such as Pearson correlation, PCA and HCA are widely used to identify co-varying metals, distinguish pollution sources and characterise spatial patterns in environmental matrices including urban dust, agricultural soils and food crops (Bortey-Sam *et al.*, 2015; Kharazi *et al.*, 2021; Mfam *et al.*, 2023). Although these geochemical and multivariate tools are individually well established, their combined use to apportion sources and map intra-urban contamination patterns in street-vended foods in southern Nigeria remains limited.

Benin City, the capital of Edo State and one of Nigeria's largest and most rapidly growing urban centres, with a population that has expanded substantially since the 2006 national census (NPC, 2009), provides an instructive setting for source-oriented spatial analysis because of its diverse urban land-use structure (Olayiwola & Igbavboa, 2014). The city contains busy markets, major transport hubs and arterial roads, a central business district, and residential and educational corridors that differ markedly in their pollution-generating activities (Oviasogie, 2020). New Benin, for example, hosts one of the city's largest markets alongside dense informal metal-fabrication, welding and auto-parts activity, whereas the Ekenwan axis is a predominantly residential and educational corridor (anchored by the University of Benin Ekenwan campus and surrounding residential quarters) carrying steady through-traffic toward the peri-urban south. Arterial nodes such as 2nd East Circular, Adolor, Airport Road and Ring Road are characterised by intense vehicular activity and commercial transport, and Iyaro is dominated by a large motor park and associated commercial-transport operations. These land-use contrasts create conditions under which commercial-workshop and traffic-related metal signatures can be expected to exhibit distinct spatial patterns within street-vended foods.

Understanding how these activities influence contamination patterns is essential for designing targeted interventions. Commercial and workshop clusters may contribute Fe-, Zn- and Cu-rich particulates through metal fabrication, welding and the handling of metallic materials, whereas transport corridors are more likely to contribute Pb-bearing road dust, brake-wear particles and other traffic-derived contaminants. Consequently, the spatial distribution of heavy metals in roasted plantain may serve as an indicator of the dominant environmental pressures operating within different urban microenvironments.

The objectives of this study were therefore to (i) characterise Igeo, CF and PLI for Fe, Zn, Cu and Pb at ten sampling locations in Benin City; (ii) apply PCA and HCA to identify principal contamination sources and site groupings; (iii) examine the relationship between contamination patterns and land use; (iv) map the composite spatial risk landscape using a multi-metric framework; and (v) provide targeted, source-differentiated recommendations for the environmental management of street-food vending zones in Benin City.

2. Materials and Methods

2.1 Study Area and Sampling

The study was conducted in Benin City (6.34°N, 5.63°E), spanning three metropolitan local government areas: Oredo, Ikpoba-Okha and Egor. Ten purposively selected sampling locations represented the major urban microenvironments of the city, spanning markets, motor parks, arterial roads, the central business district, and residential and educational corridors; the locations, their local government areas, dominant land use and sample numbers are summarised in Table 1. Land use at each site was characterised from high-resolution satellite imagery (Google Earth Pro) supported by field reconnaissance. Freshly roasted plantain samples (n = 5 per location; n = 50 total) were collected during the dry season from street vendors at each location, stored at -4 °C, and processed within 24 h following the protocol of Bello *et al.* (2022).

Table 1. Sampling locations, dominant surrounding land use and number of samples collected in Benin City.

Location	Dominant land use / surrounding activity	Samples (n)
2nd East Circular	High-traffic arterial road	5
Iyaro	Motor park / commercial-transport hub	5
Sapele Road	Commercial arterial road	5
Agbado	Residential	5
New Benin	Major market with dense informal metal-working, welding and auto-parts trade	5
Uselu	Residential–commercial	5
Ekenwan	Residential–educational corridor with through-traffic	5
Airport Road	Airport-traffic corridor	5
Adolor	Commercial, high-traffic	5
Ring Road	Central business district	5
Total: 10 locations, 50 samples	**50**	

n = number of samples per location.

2.2 Chemical Analysis

Homogenised dried plantain samples (3.0 g) were digested in concentrated H_2SO_4/HNO_3 (10:5 cm^3), filtered, and made up to 25 cm^3. Concentrations of Fe, Zn, Cu and Pb were determined by flame atomic absorption spectrophotometry (Uraku *et al.*, 2021). Five analytical replicates were performed per sample; results are expressed as mean ± standard deviation (mg/kg). Quality assurance included certified reference standards and spike-recovery tests (94–98%). Differences among sites were assessed by one-way ANOVA with Tukey's HSD ($p < 0.05$; XLSTAT).

2.3 Geochemical Pollution Indices

2.3.1 Geo-accumulation Index (Igeo)

Igeo was calculated following Müller (1969):

$$I_{geo} = log_2\left[\frac{C_n}{1.5 \times B_n}\right] \qquad (1)$$

where Cn is the measured metal concentration (mg/kg) and Bn the geochemical background concentration. Background values used were Fe = 5.0, Zn = 2.0, Cu = 0.5 and Pb = 0.01 mg/kg (estimated urban background for Nigeria; Onakpa *et al.*, 2018; Orisakwe *et al.*, 2012). Igeo classes were assigned as: class 0, unpolluted (Igeo of 0 or below); class 1, unpolluted to moderately polluted (0–1); class 2, moderately polluted (1–2); class 3, moderately to heavily polluted (2–3); class 4, heavily polluted (3–4); class 5, heavily to extremely polluted (4–5); and class 6, extremely polluted (above 5).

2.3.2 Contamination Factor (CF)

CF was computed as:

$$CF = \frac{C_{measured}}{C_{background}} \qquad (2)$$

where CF < 1 indicates low contamination; 1–3 moderate; 3–6 considerable; and > 6 very high contamination (Hakanson, 1980).

2.3.3 Pollution Load Index (PLI)

PLI integrates the CF values of all metals at a site:

$$PLI = (CF_{Fe} \times CF_{Zn} \times CF_{Cu} \times CF_{Pb})^{\frac{1}{n}} \qquad (3)$$

where n is the number of metals (4). PLI < 1 indicates background conditions, whereas PLI > 1 indicates site deterioration (Tomlinson *et al.*, 1980).

2.4 Multivariate Statistical Analysis

Pearson correlation coefficients were calculated for all metal pairs across the ten sampling locations. PCA was applied to standardised (z-score) metal concentration data to identify orthogonal source factors; components with eigenvalue > 1 were retained (Kaiser criterion; El Behairy *et al.*, 2022). HCA used Ward's linkage with Euclidean distance on the standardised data to group sampling locations and metals independently (Smoliński *et al.*, 2014). The coefficient of variation (CV = SD/mean × 100%) was calculated for each metal at each site to assess source heterogeneity (Ogunwale *et al.*, 2021). All multivariate analyses were conducted in Python 3.11 (scikit-learn v1.4; SciPy v1.12).

3. Results

3.1 Heavy Metal Concentrations

Metal concentrations across all ten sampling locations are summarised in Table 2. Fe ranged from 6.45 to 9.13 mg/kg, Zn from 2.27 to 4.68 mg/kg, Cu from 0.91 to 2.67 mg/kg, and Pb from 0.02 to 0.05 mg/kg. New Benin recorded the highest concentrations of Fe, Zn and Cu, whereas the highest Pb was recorded at 2nd East Circular. Copper exceeded the FAO/WHO permissible limit of 0.5 mg/kg at every location, while Pb and Zn remained below their respective limits of 0.1 and 25 mg/kg throughout. One-way ANOVA with Tukey's HSD confirmed statistically significant inter-site differences for Cu ($p < 0.001$) and Pb ($p < 0.05$) but not for Fe or Zn ($p > 0.05$). Spatially, the elevated Fe, Zn and Cu values were concentrated around the New

Benin market node, whereas the highest Pb values were distributed along the eastern arterial network (2nd East Circular, Adolor, Airport Road), pointing to two contrasting distribution patterns examined further below.

Table 2. Heavy metal concentrations (mean ± SD, mg/kg; n = 5) in street-roasted plantain at ten locations in Benin City, with FAO/WHO permissible limits.

Location	Fe	Zn	Cu	Pb
2nd East Circular	6.45±0.65	2.64±0.52	1.15±0.26	0.05±0.01
Iyaro	6.96±1.72	2.27±0.38	1.12±0.20	0.02±0.01
Sapele Road	8.72±1.96	2.80±1.36	1.27±0.16	0.03±0.01
Agbado	8.55±1.49	2.76±0.44	0.91±0.15	0.02±0.01
New Benin	9.13±2.23	4.68±4.08	2.67±0.39	0.02±0.00
Uselu	7.52±0.87	2.28±0.45	1.65±0.72	0.02±0.00
Ekenwan	8.07±1.19	2.74±0.46	1.83±0.20	0.02±0.00
Airport Road	7.76±0.63	2.27±0.28	1.91±0.42	0.03±0.01
Adolor	8.68±1.69	2.36±0.56	1.20±0.28	0.03±0.00
Ring Road	7.65±0.59	2.78±0.33	1.16±0.22	0.03±0.01
FAO/WHO limit	—	25	0.5	0.1

SD = standard deviation; — = no established limit.

3.2 Geochemical Pollution Indices

Contamination Factor, Geo-accumulation Index and Pollution Load Index values are presented in Table 3. Copper was the metal of greatest geochemical concern: its CF was considerable (CF > 3) at New Benin (5.34), Airport Road (3.82), Ekenwan (3.66) and Uselu (3.30), and moderate (1–3) at all remaining sites, so that Cu enrichment above background was universal. The corresponding Igeo classified Cu as 'moderately polluted' (class 2) at New Benin (1.83), Airport Road (1.35), Ekenwan (1.29) and Uselu (1.14), and as 'unpolluted to moderately polluted' (class 1) elsewhere. For Pb, CF ranged from 2 to 5 and Igeo peaked at 2nd East Circular (0.62), reflecting the elevated Pb at that arterial site, although in absolute terms Pb remained below the FAO/WHO food limit. Fe and Zn Igeo values were generally low (0.76 or below), the main exception being New Benin, where Igeo-Zn reached 0.64 and Igeo-Fe 0.28. The PLI exceeded unity at every location, ranging from 1.63 at Iyaro to 2.60 at New Benin; New Benin therefore carried the heaviest aggregate multi-metal burden, but the city-wide PLI > 1 shows that even the least-impacted sites were enriched above background, driven principally by the universal Cu excess.

Table 3. Contamination Factor (CF), Geo-accumulation Index (Igeo) and Pollution Load Index (PLI) for each metal at the ten sampling locations.

Location	CF-Fe	CF-Zn	CF-Cu	CF-Pb	Igeo-Fe	Igeo-Zn	Igeo-Cu	Igeo-Pb	PLI
2nd East Circular	1.29	1.32	2.30	5.00	-0.22	-0.18	0.62	1.74	**2.10**
Iyaro	1.39	1.14	2.24	2.00	-0.11	-0.40	0.58	0.42	**1.63**
Sapele Road	1.74	1.40	2.54	3.00	0.22	-0.10	0.76	1.00	**2.08**
Agbado	1.71	1.38	1.82	2.00	0.19	-0.12	0.28	0.42	**1.71**
New Benin	1.83	2.34	5.34	2.00	0.28	0.64	**1.83**	0.42	**2.60**
Uselu	1.50	1.14	3.30	2.00	0.00	-0.40	**1.14**	0.42	**1.83**
Ekenwan	1.61	1.37	3.66	2.00	0.11	-0.13	**1.29**	0.42	**2.01**
Airport Road	1.55	1.14	3.82	3.00	0.05	-0.40	**1.35**	1.00	**2.12**
Adolor	1.74	1.18	2.40	3.00	0.21	-0.35	0.68	1.00	**1.96**

Location	CF-Fe	CF-Zn	CF-Cu	CF-Pb	Igeo-Fe	Igeo-Zn	Igeo-Cu	Igeo-Pb	PLI
Ring Road	1.53	1.39	2.32	3.00	0.03	-0.11	0.63	1.00	**1.96**

Bold Igeo-Cu values denote Igeo class 2 (moderately polluted, Igeo between 1 and 2). CF: <1 low, 1–3 moderate, 3–6 considerable, >6 very high. PLI > 1 indicates enrichment above background.

3.3 Pearson Correlation Analysis

The correlation matrix (Figure 1) showed that Zn and Cu were the only significantly correlated pair ($r = 0.67$, $p < 0.05$). Fe was positively but non-significantly associated with Zn ($r = 0.55$) and Cu ($r = 0.38$), so that Fe, Zn and Cu together formed a loosely co-varying group consistent with a shared, diffuse origin. Lead behaved differently: it correlated negatively and non-significantly with Fe ($r = -0.48$), Zn ($r = -0.19$) and Cu ($r = -0.31$), indicating that Pb inputs were largely independent of the Fe-Zn-Cu group and consistent with a separate contamination pathway. The weaker-than-expected significance of the Fe-Zn-Cu associations (only Zn-Cu reaching $p < 0.05$ at $n = 10$) indicates that, while these three metals tend to move together, their common source is diffuse rather than a single dominant point source.

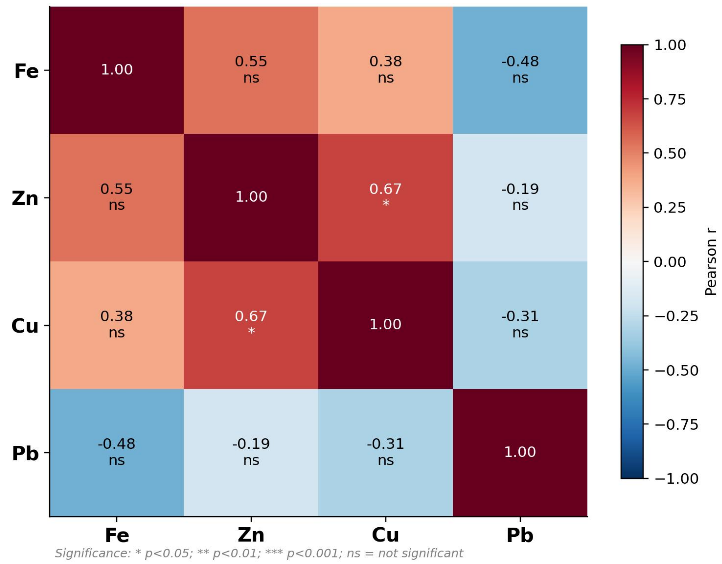

Figure 1. Pearson correlation matrix (r values) for Fe, Zn, Cu and Pb across the ten sampling locations. Colour intensity indicates correlation strength and direction (warm = positive; cool = negative). Only the Zn–Cu pair is significant at $p < 0.05$.

3.4 Principal Component Analysis (PCA) and Source Apportionment

PCA of the standardised concentrations yielded two components with eigenvalues > 1, together explaining 80.5% of total variance (Figure 2). PC1 accounted for 57.9% of the variance and carried strong positive loadings for Zn (+0.87), Fe (+0.84) and Cu (+0.84), with a contrasting negative loading for Pb (-0.64); this component represents the diffuse commercial-workshop and cookware metal group. PC2 accounted for 22.6% of the variance and was dominated by a positive Pb loading (+0.76), isolating the traffic-related Pb signal. In the biplot, New Benin was projected at the extreme positive end of PC1, confirming its distinct Fe-Zn-Cu character, whereas the eastern arterial sites were displaced along PC2 in the direction of the Pb vector. The clear separation of the Fe-Zn-Cu vectors from the Pb vector provides the principal evidence for two contrasting source pathways operating across the city.

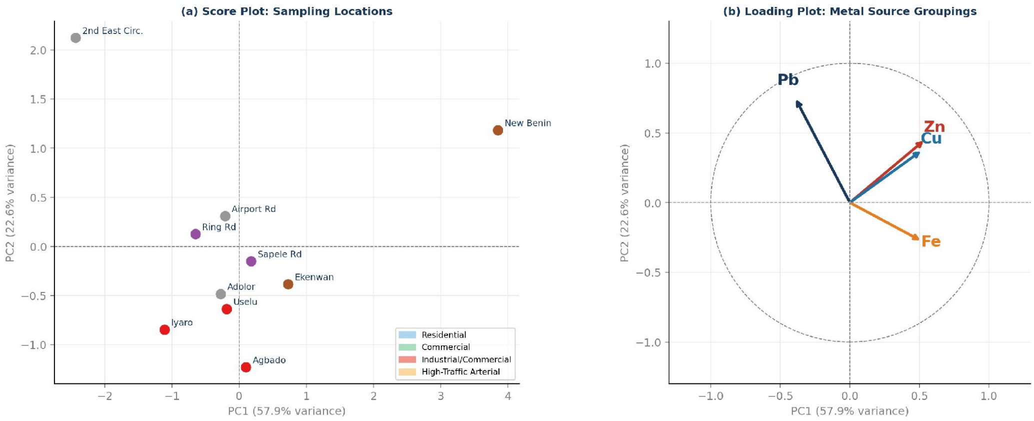

Figure 2. Principal Component Analysis of standardised heavy metal concentrations: (a) score plot of sampling locations; (b) loading plot showing the Fe–Zn–Cu group on PC1 (57.9%) separated from Pb on PC2 (22.6%). Percentages indicate explained variance.

3.5 Hierarchical Cluster Analysis (HCA)

HCA provided an independent check on the PCA grouping (Figure 3). Clustering of the metals separated Fe, Zn and Cu into one tight group, with Zn and Cu joining first and Fe attaching to them, while Pb formed its own isolated branch. This metal dendrogram reproduces the PCA structure by an entirely independent classification method, reinforcing the distinction between the diffuse Fe-Zn-Cu group and the independent Pb signal. Clustering of the sampling locations distinguished New Benin, with its elevated Cu and Zn, from the remaining sites, within which the higher-Pb arterial locations formed a recognisable sub-group separate from the lower-impact residential and commercial sites.

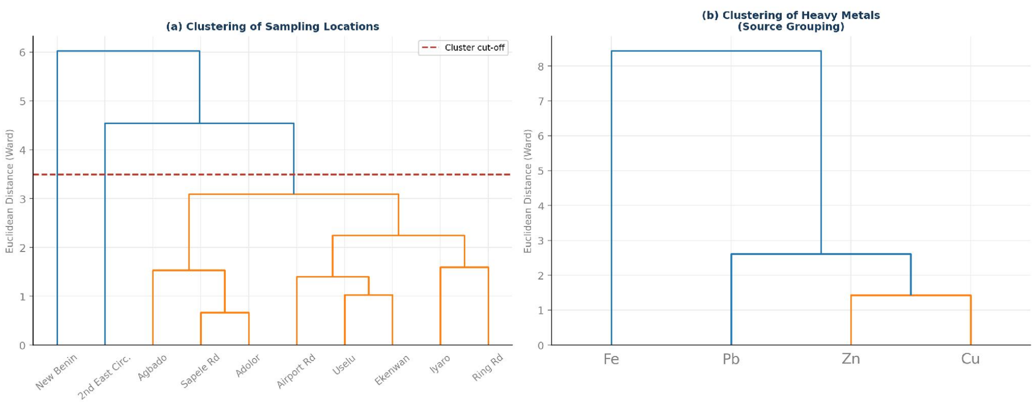

Figure 3. Hierarchical Cluster Analysis (Ward's linkage, Euclidean distance): (a) dendrogram of sampling locations; (b) dendrogram of metals showing a tight Fe–Zn–Cu group distinct from an isolated Pb branch.

3.6 Contamination Heterogeneity

The coefficient of variation differed markedly among metal-site combinations (Figure 4). Most combinations showed CV values below about 50%, consistent with relatively steady, diffuse inputs. The conspicuous exception was Zn at New Benin, whose CV of 87% greatly exceeded every other metal-site combination. Such a high CV is the signature of an intermittent or spatially concentrated point source superimposed on a more diffuse background, rather than a steady city-wide input, and identifies New Benin as the site where short-term exposure may episodically exceed the level implied by mean concentrations alone.

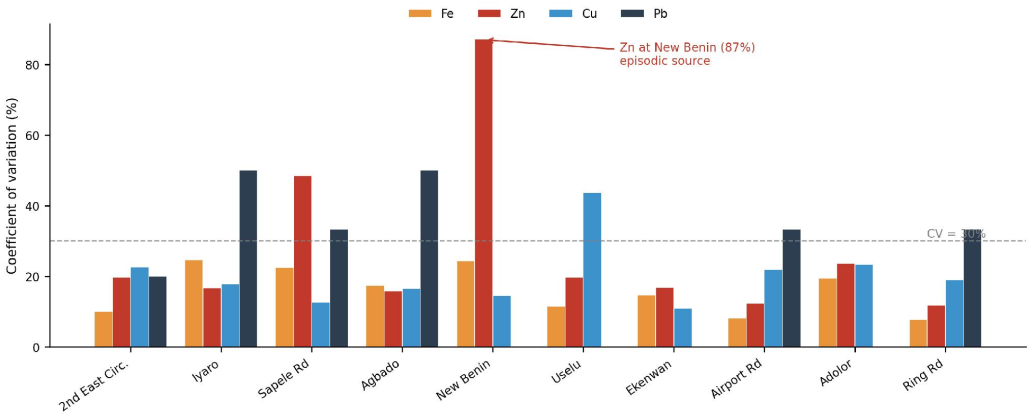

Figure 4. Coefficient of variation (CV %) for each metal at the ten sampling locations. Zn at New Benin (87%) greatly exceeds all other metal–site combinations, indicating an episodic point source; a CV of about 50% is a conventional threshold for spatially heterogeneous inputs.

3.7 Composite Spatial Risk Mapping

Integrating all four metals into a single normalised contamination score produced the composite spatial risk map (Figure 5). The map reveals a two-node hotspot structure: a primary node at New Benin, driven by the Fe-Zn-Cu enrichment, and a secondary node along the eastern arterial corridor (2nd East Circular and Adolor), driven by elevated Pb. Airport Road and Ekenwan formed intermediate-risk nodes, while Iyaro and Agbado were the lowest-scoring sites and provide the closest approximation to background urban conditions. This structure gives a concise spatial blueprint for prioritising environmental management.

Figure 5. Composite heavy metal contamination risk map of Benin City street-food vending locations. Marker size and colour are proportional to the composite contamination score (sum of normalised CF values), revealing a primary node at New Benin and a secondary node along the 2nd East Circular/Adolor corridor.

4. Discussion

4.1 Source Apportionment: Diffuse Commercial-Cookware versus Vehicular Origins

The PCA-HCA approach consistently resolved two contrasting contamination signals in Benin City roasted plantain. The first, expressed on PC1 and in the Fe-Zn-Cu metal cluster, aligns with the dense commercial and informal-workshop activity that surrounds several vending sites, most strongly at the New Benin market, where metal-working, welding, electrical-repair and auto-parts trades generate metal-rich dusts that can deposit on food during roasting. Co-occurrence of Cu, Zn and Fe is widely reported as a fingerprint of mixed mechanical and commercial metal handling, where Cu derives from wiring and motors, Zn from galvanised materials and lubricants, and Fe from steel fabrication (Bortey-Sam *et al.*, 2015; Imarhiagbe & Obayagbona, 2019; Mfam *et al.*, 2023). In the present data this triad co-varied only weakly (only Zn-Cu reached significance at n = 10), which argues for a diffuse, spatially distributed origin (including the contribution of metallic roasting surfaces common to all vendors) rather than a single dominant industrial discharge.

The second signal, expressed on PC2 and isolated in the Pb branch of the metal dendrogram, aligns spatially with the high-traffic arterial network (2nd East Circular, Adolor, Airport Road). Although Nigeria phased out leaded petrol in the early 2000s, legacy soil Pb accumulated over decades of leaded-fuel combustion continues to be remobilised as resuspended dust, particularly during the dry season when wind-driven suspension is greatest (Chukwu *et al.*, 2019; Orisakwe *et al.*, 2012). Contemporary non-exhaust sources, including brake-wear and tyre-wear particles and aerosols from end-of-life lead-acid batteries, add to traffic-corridor Pb loading at levels measurable in deposited particulates (Adamiec *et al.*, 2016; Liu *et al.*, 2023). The negative, non-significant association of Pb with the Fe-Zn-Cu group confirms that Pb inputs are mechanistically and spatially distinct, a separation with direct implications for source-specific mitigation.

4.2 Geochemical Indices and Pollution Classification

The Igeo and CF classifications identify Cu as the metal of greatest geochemical concern. Copper reached 'moderately polluted' status (Igeo class 2) at New Benin, Airport Road, Ekenwan and Uselu and exceeded the FAO/WHO food limit at all ten sites, indicating that Cu contamination of street-roasted plantain is a city-wide rather than a site-specific phenomenon. A plausible and parsimonious explanation is the contribution of metallic roasting surfaces and utensils used universally by vendors: metallic cookware is a recognised source of toxic-metal transfer to food, with leaching governed by heat, food acidity and contact time (Alabi & Afolabi, 2024). This diffuse cookware contribution, superimposed on localised commercial-workshop inputs, would account for the universal Cu excess together with the additional spike at New Benin (Igeo-Cu = 1.83).

The PLI exceeded unity at every site, ranging from 1.63 (Iyaro) to 2.60 (New Benin). This contrasts with the impression that contamination is confined to a single hotspot: while New Benin clearly carries the heaviest aggregate burden, the city-wide PLI > 1 shows that all vending environments are enriched above background, predominantly through the universal Cu excess. Because the PLI is sensitive to this Cu term, interventions targeting the roasting surface (for example, replacement of reactive metallic grills) would be expected to lower PLI values across most sites, potentially bringing the least-impacted locations close to unity. Iyaro and Agbado, with the lowest PLI and composite scores, are the closest approximations to background and are suitable sentinel sites for longitudinal surveillance.

4.3 Contamination Heterogeneity and the New Benin Zinc Anomaly

The exceptionally high CV for Zn at New Benin (87%), against values generally below 50% elsewhere, is a distinctive finding. High CV in environmental data typically reflects an intermittent or spatially concentrated point source superimposed on a diffuse background (Hakanson, 1980; Qu *et al.*, 2025). At New Benin, episodic Zn input is plausibly driven by periodic release or resuspension of Zn-rich wastes from nearby automobile-mechanic and metal-fabrication activity (Ajeh *et al.*, 2022; Bala *et al.*, 2019), producing intermittent contamination events that intermittently affect vendors operating in the area.

Such fluctuation means that risk assessments based solely on mean concentrations may understate short-term exposure for consumers buying plantain during high-emission episodes (McMullin *et al.*, 2018). The observation reinforces the case for maximum-level, in addition to mean-based, exposure assessment at high-CV sites, consistent with recommendations in the probabilistic risk literature (Koupaie & Eskicioglu, 2015).

4.4 Comparison with Previous Studies

Placing these results alongside earlier Nigerian work clarifies what is, and is not, distinctive about Benin City. The Fe concentrations measured here (6.45–9.13 mg/kg) are comparable to the 6.47–11.73 mg/kg reported for roadside roasted plantain in Lagos by Makanjuola and Adepegba (2016), and the Zn range (2.27–4.68 mg/kg) overlaps their 1.72–4.90 mg/kg. Copper, however, was markedly lower in the present study (0.91–2.67 mg/kg) than in their Lagos samples (3.27–7.57 mg/kg), while Pb was also lower here (up to 0.05 mg/kg versus 0.08–0.26 mg/kg in Lagos). The lower Pb is consistent with the longer interval since leaded-petrol phase-out and with Benin City's lower traffic-emission intensity relative to metropolitan Lagos. Bello *et al.* (2022) similarly reported measurable Fe, Zn, Cu and Pb in roadside roasted plantain and maize around Zaria, with several metals approaching or exceeding permissible limits, echoing the universal Cu and broadly comparable Fe-Zn levels found here. By contrast, Eke-Ejiofor and Maxwell (2019) reported very low heavy metal levels in roasted plantain (bole) from Port Harcourt, illustrating that contamination is strongly site- and source-dependent rather than an inevitable feature of the roasting process. Broader surveys of Nigerian ready-to-eat and roadside foods report the same suite of metals at comparable orders of magnitude and likewise attribute elevations to roadside and commercial activity (Amos-Tautua *et al.*, 2013; Iwegbue *et al.*, 2013; Oyelola *et al.*, 2013; Oyet & Samuel, 2020). The contribution of the present study is to move beyond such concentration reporting to an explicit, spatially resolved source apportionment.

The two-factor structure resolved here, a Fe-Zn-Cu group separate from an independent Pb signal, is itself broadly consistent with source-apportionment work in other urban food and environmental matrices. Kharazi *et al.* (2021) identified analogous Cu-Zn co-variance in food crops from industrial zones in Hamadan, Iran; Bortey-Sam *et al.* (2015) documented Fe-Zn-Cu co-contamination in foodstuffs near mining-industrial sites in Ghana; and Mfam *et al.* (2023) reported Pb-dominant contamination at automobile-workshop sites in Benue State, Nigeria, independent of the Fe-Zn-Cu group. The recurrence of this structure across diverse settings supports a general pattern in which commercial and workshop activity drives Cu-Zn-Fe enrichment while vehicular sources drive Pb, with the two pathways operating largely independently.

4.5 Implications for Source-Specific Mitigation

The two-source model translates directly into targeted action. For the diffuse Fe-Zn-Cu and cookware-driven Cu signal, the most broadly effective measures are replacement of reactive metallic roasting grills with food-grade stainless-steel or ceramic surfaces, relocation of roasting away from dense metal-working and welding clusters (most importantly at New Benin), and the use of certified low-metal charcoal. For the traffic-linked Pb signal along 2nd East Circular, Adolor and Airport Road, priority measures include physical separation of roasting points from traffic lanes, restriction of roadside vending within a defined buffer of high-volume arterials, dust suppression through road watering and vegetation buffers, and attention to legacy roadside soil Pb reservoirs. The composite risk map (Figure 5) functions as a decision-support tool for environmental-health agencies, identifying New Benin and the 2nd East Circular/Adolor corridor as the two priority intervention nodes, followed by Airport Road and Ekenwan. The lowest-priority sites (Iyaro, Agbado) should nonetheless remain under routine monitoring as baseline references against which future change can be tracked.

4.6 Limitations

This study used estimated rather than locally measured geochemical background values, which introduces uncertainty into the Igeo and CF classifications; locally derived backgrounds from uncontaminated reference sites would improve accuracy. Source attribution rests on multivariate inference and land-use association rather than direct receptor modelling (for example, positive matrix factorisation) or isotopic Pb fingerprinting, which would provide definitive confirmation. With ten sampling locations, correlation significance is limited and the co-variation among Fe, Zn and Cu should be read as indicative rather than conclusive. The single dry-season campaign does not capture seasonal dynamics, and only four metals were determined; inclusion of Cd, Cr, Ni and As in future work would enable more comprehensive fingerprinting.

5. Conclusions

This study provides a source-apportioned spatial assessment of heavy metal contamination in street-vended roasted plantain in Benin City, combining geochemical indices with multivariate statistics across ten locations. PCA and HCA consistently resolved two contrasting signals: a diffuse Fe-Zn-Cu group, linked to commercial and informal metal-working activity and to the metallic roasting surfaces used city-wide, and an independent Pb signal associated with high-traffic arterials. Copper exceeded the FAO/WHO permissible limit at every site and the Pollution Load Index exceeded unity everywhere, ranging from 1.63 at Iyaro to a maximum of 2.60 at New Benin, so that multi-metal enrichment above background was a city-wide rather than an isolated condition. Lead, though highest along arterial roads, remained below its food limit throughout.

The resulting composite risk map identifies New Benin and the 2nd East Circular/Adolor corridor as priority intervention nodes and provides a practical basis for the targeted environmental regulation of street-food vending. Future work should incorporate isotopic source tracing, an expanded metal panel, seasonal monitoring and locally derived background values to refine both contamination assessment and source attribution.

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References

Adamiec, E., Jarosz-Krzemińska, E., & Wieszała, R. (2016). Heavy metals from non-exhaust vehicle emissions in urban and motorway road dusts. *Environmental Monitoring and Assessment, 188*(6), 369.

Ajeh, E. A., Modi, F. J., & Omoregie, I. P. (2022). Health risk estimations and geospatial mapping of trace metals in soil samples around automobile mechanic workshops in Benin City, Nigeria. *Toxicology Reports, 9*, 575–587. https://doi.org/10.1016/j.toxrep.2022.03.006

Alabi, O., & Afolabi, A. T. (2024). Cookware as a source of toxic metals: An overview. *Kashmir Journal of Science, 3*(2). https://doi.org/10.63147/krjs.v3i2.46

Alelign, D., Yihune, M., Bekele, M., Oumer, Y., Beyene, K., & Atnafu, K. (2023). Bacteriological quality and antimicrobial resistant patterns of foodborne pathogens isolated from commonly vended street foods in Arba Minch town, Southern Ethiopia. *Infection and Drug Resistance, 16*, 2883–2899.

Amos-Tautua, B. M. W., Inengite, A. K., Abasi, C. Y., & Amirize, G. C. (2013). Evaluation of polycyclic aromatic hydrocarbons and some heavy metals in roasted food snacks in Amassoma, Niger Delta, Nigeria. *African Journal of Environmental Science and Technology, 7*(10), 961–966.

Bala, A., Majebi, O. J., Ebhodaghe, O. F., Ufuoma, U., & Anwuli, E. R. (2019). Levels of heavy metals in soil samples from active automobile workshops in Benin City. *International Journal of Environmental Chemistry, 3*(1), 1–7.

Bello, F., Wada, Y. A., Halilu, F. W., Abolude, D. S., & Abdullahi, S. A. (2022). Roadside roasted plantain and maize in Zaria and environs: Nutritional composition and heavy metal evaluation. *Dutse Journal of Pure and Applied Sciences, 8*(2a), 17–26.

Bortey-Sam, N., Nakayama, S. M. M., Akoto, O., Ikenaka, Y., Fobil, J. N., Baidoo, E., Mizukawa, H., & Ishizuka, M. (2015). Accumulation of heavy metals and metalloid in foodstuffs from agricultural soils around Tarkwa area in Ghana, and associated human health risks. *International Journal of Environmental Research and Public Health, 12*(8), 8811–8827. https://doi.org/10.3390/ijerph120808811

Chukwu, V. N., Anoliefo, G. O., & Ikhajiagbe, B. (2019). Environmental impact of scrap metal industries: Examination of vertical seepage of scrap metal effluents into the aquifer. *NIPES Journal of Science and Technology Research, 1*(2), 12–21.

Eke-Ejiofor, J., & Maxwell, U. S. (2019). Safety and quality assessment of street vended roasted plantain (bole) in Port Harcourt, Rivers State, Nigeria. *International Journal of Biotechnology and Food Science, 7*(1), 9–13.

El Behairy, R. A., El Baroudy, A. A., Ibrahim, M. M., Mohamed, E. S., Rebouh, N. Y., & Shokr, M. S. (2022). Combination of GIS and multivariate analysis to assess the soil heavy metal contamination in some arid zones. *Agronomy, 12*(11), 2871.

FAO/WHO. (2019). General standard for contaminants and toxins in food and feed (Codex Stan 193-1995, rev. 2019). Codex Alimentarius Commission.

Faurat, A., Azhayev, G., Shupshibayev, K., Akhmetov, K., Boribay, E., & Abylkhassanov, T. (2024). Assessment of heavy metal contamination and health risks in the snow cover–soil cover–vegetation system of urban and rural gardens of an industrial city in Kazakhstan. *International Journal of Environmental Research and Public Health, 21*(8), 1002.

Frazzoli, C. (2020). Toxicological risk analysis in data-poor countries: A narrative approach to feed an awareness raising–community empowerment vortex. *Medicina, 56*(11), 629.

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

Imarhiagbe, E., & Obayagbona, N. (2019). Polycyclic aromatic hydrocarbon, physico-chemical properties, and culturable microbial flora of human urine-impacted topsoils at commercial tricycle parks along the Benin–Sapele Expressway, Benin City, Nigeria. *Jordan Journal of Earth and Environmental Sciences, 10*(3), 178–186.

Imathiu, S. (2017). *Street vended foods: Potential for improving food and nutrition security or a risk factor for foodborne diseases in developing countries? Current Research in Nutrition and Food Science, 5*(2), 55–65. https://doi.org/10.12944/CRNFSJ.5.2.01

Iwegbue, C. M. A., Nwozo, S. O., Overah, C. L., Bassey, F. I., & Nwajei, G. E. (2013). Concentrations of selected metals in some ready-to-eat foods consumed in Southern Nigeria: Estimation of dietary intakes and target hazard quotients. *Turkish Journal of Agriculture – Food Science and Technology, 1*(1), 1–7.

Kharazi, A., Leili, M., Khazaei, M., Alikhani, M. Y., & Shokoohi, R. (2021). Human health risk assessment of heavy metals in agricultural soil and food crops in Hamadan, Iran. *Journal of Food Composition and Analysis, 100*, 103890. https://doi.org/10.1016/j.jfca.2021.103890

Koupaie, E. H., & Eskicioglu, C. (2015). Health risk assessment of heavy metals through the consumption of food crops fertilized by biosolids: A probabilistic-based analysis. *Journal of Hazardous Materials, 300*, 855–865. https://doi.org/10.1016/j.jhazmat.2015.08.015

Liu, G., Chen, T., Cui, J., Zhao, Y., Li, Z., Liang, W., Sun, J., Liu, Z., & Xiao, T. (2023). Trace metal(loid) migration from road dust to local vegetables and tree tissues and the bioaccessibility-based health risk: Impacts of vehicle operation-associated emissions. *International Journal of Environmental Research and Public Health, 20*(3), 2520.

Makanjuola, O. M., & Adepegba, A. O. (2016). Determination of heavy metals in roasted plantain sold along major roads in Lagos, South-West Nigeria. *International Journal of Science and Technology, 2*(1), 1–8.

McMullin, T. S., Bamber, A. M., Bon, D., Vigil, D. I., & Van Dyke, M. (2018). Exposures and health risks from volatile organic compounds in communities located near oil and gas exploration and production activities in Colorado (USA). *International Journal of Environmental Research and Public Health, 15*(7), 1500.

Mfam, A. N., Aguoru, C. U., Ogbonna, I. O., Okoh, T., Olasan, J. O., & Mfam, N. N. (2023). Heavy metals contamination in soils at automobile workshops in Benue State, Nigeria. *International Journal of Recent Research in Life Sciences, 10*, 9–18.

Müller, G. (1969). Index of geoaccumulation in sediments of the Rhine River. *GeoJournal, 2*, 108–118.

National Population Commission (NPC). (2009). 2006 population and housing census of the Federal Republic of Nigeria: Priority tables, Volume IV — Population distribution by age and sex (state and local government area). National Population Commission of Nigeria.

Ogunwale, T. O., Oyekunle, J. A. O., Ogunfowokan, A. O., Oluwalana, A. I., Ogar, P. A., & Salami, K. D. (2021). Seasonal speciation study of heavy metals content in well water of some chicken farms in Osun State, Southwestern Nigeria. *Chemistry Africa, 4*, 645–658.

Olayiwola, A. M., & Igbavboa, O. E. (2014). Land use dynamics and expansion of the built-up area in Benin City, Nigeria. *Mediterranean Journal of Social Sciences, 5*(20), 2351–2360.

Olufunso, A., & Dennis, K. (2024). Nutritional assessment and sub-acute toxicity study in Wistar rats fed with a compounded diet of roasted plantain and fish sold in Otuoke, Nigeria. *European Journal of Nutrition & Food Safety, 16*(10), 213–226.

Oluwadamilare, K. Y., Adejoke, D. O., Oluwaseun, H. A., & Adejoke, B. A. (2023). Heavy metals in street-roasted food and home-oven-roasted foods. *Journal of Science and Technology (Ghana), 41*(2), 50–62. https://doi.org/10.4314/just.v41i2.5

Onakpa, M. M., Njan, A. A., & Kalu, O. C. (2018). A review of heavy metal contamination of food crops in Nigeria. *Annals of Global Health, 84*(3), 488. https://doi.org/10.29024/aogh.2314

Opeolu, B. O., Adebayo, K., Okuneye, P. A., & Badru, F. A. (2010). Physicochemical and microbial assessment of roadside food and water samples in Lagos and environs. *International Journal of Biological and Chemical Sciences, 4*(2), 318–326.

Orisakwe, O. E., Nduka, J. K., Amadi, C. N., Dike, D. O., & Bede, O. (2012). Heavy metals health risk assessment for population via consumption of food crops and fruits in Owerri, South Eastern Nigeria. *Chemistry Central Journal, 6*, 77. https://doi.org/10.1186/1752-153X-6-77

Oviasogie, A. C. (2020). Neighbourhood spatial pattern and noise disturbance in Benin City, Nigeria. *Journal of Engineering Research and Reports, 12*(2), 37–46.

Oyelola, O. T., Afolabi, M. I., Ajiboshin, I. O., & Banjoko, I. O. (2013). Heavy metal and microbial contents of roadside roasted corn and plantain in Alimosho LGA of Lagos State, Nigeria. *International Journal of Research in Medical and Health Sciences, 3*, 28–32.

Oyet, G. I., & Samuel, C. B. (2020). Safety assessment of the presence of heavy metals and organic pollutants in vended street foods from selected locations in Lagos State, Nigeria. *European Journal of Nutrition and Food Safety, 12*(6), 109–120.

Qu, L., Peng, J., Cong, P., & Huang, Y. (2025). Spatiotemporal evolution and integrated risk assessment of potentially toxic element pollution in coastal waters: A case study of Bohai Bay, China. *Toxics, 13*(11), 880.

Smoliński, A., Rompalski, P., Cybulski, K., Chećko, J., & Howaniec, N. (2014). Chemometric study of trace elements in hard coals of the Upper Silesian Coal Basin, Poland. *The Scientific World Journal, 2014*, 234204.

Tomlinson, D. L., Wilson, J. G., Harris, C. R., & Jeffrey, D. W. (1980). Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgoländer Meeresuntersuchungen, 33*(1), 566–575. https://doi.org/10.1007/BF02414780

Uraku, A. J., Chukwu, I., Uraku, O. H., Edwin, N., Ezeali, C., & Ogoh, N. V. (2021). Assessment of some heavy metal levels and related health hazards in two staple foods grown in mining communities of Ebonyi State. *Journal of Pharmaceutical Research International, 33*, 358–366.