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Heavy metal and pesticide toxicity in agricultural soils across a farming intensity gradient in Central Zambia

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Routine pesticide applications are an under-recognized pathway for heavy metal accumulation in agricultural soils, particularly in sub-Saharan Africa where synthetic pesticide use is expanding rapidly but systematic monitoring remains limited. This study investigated the co-occurrence of heavy metals and pesticides in soils across farming landscapes of Central Province, Zambia, focusing on Chibombo and Mkushi Districts. Four metals (Cd, Pb, Cu, Zn) and twelve pesticides; acetamiprid, acifluorfen, chlorpyrifos, clodinafop propargyl, lambda cyhalothrin, cypermethrin, emamectin benzoate, fomesafen, haloxyfop methyl, lufenuron, profenofos, glyphosate, and its metabolite AMPA, were assessed in commercial, emergent, and smallholder farming systems using pollution indices (enrichment factor and ecological hazard index) and correlation analysis. Results showed significant differences in the accumulation of Cu, Cd, and Zn across farming systems, with commercial farms exhibiting higher Cd and Cu concentrations than emergent and smallholder systems, and heavy metals being significantly enriched in topsoils (0-20 cm) compared to deeper layers. Smallholder farms had high insecticide residues, especially chlorpyrifos (1494-5961 μg/kg), emergent farms showed elevated insecticide and herbicide levels, notably cypermethrin and fomesafen, while commercial farms were dominated by herbicides including acifluorfen, fomesafen, glyphosate, and AMPA. Correlation analysis revealed significant associations between metals and certain pesticides, with chlorpyrifos and profenofos residues showing consistent negative correlations with all metals except Cu. Comparative analysis against international soil quality standards indicated heavy metals remained below WHO limits except for Cu and Cd in some commercial farms. These findings underscore significant ecological and food safety risks, highlighting the urgent need for systematic monitoring and integration into policy frameworks.

KEYWORDS
chlorpyrifos, ecological risk assessment, farming systems, glyphosate, heavy metals, pesticide residues, soil contamination, sub-Saharan Africa

1 Introduction

Modern agriculture has become increasingly dependent on agrochemicals such as fertilizers, and pesticides to sustain crop yields and meet the demands of a growing global population (1). While these inputs have undeniably boosted productivity, they also represent a significant source of environmental contaminants, particularly heavy metals (2, 3). Pesticides often contain trace elements such as cadmium (Cd), lead (Pb), copper (Cu), and zinc (Zn), either as impurities in raw materials or as intentional additives to improve product effectiveness (4, 5). With repeated application, these metals accumulate in agricultural soils, creating long-term ecological and public health challenges (6–8). Unlike organic pollutants, heavy metals are non-biodegradable and persist in the soil matrix, where they alter soil chemistry, reduce fertility, and disrupt microbial communities essential for nutrient cycling (9). Their persistence also facilitates bioaccumulation in crops, leading to contamination of the food chain and posing serious health risks to consumers (10, 11).

Research across different regions has documented the link between pesticide use and heavy metal accumulation. In Asia, studies have shown that intensive pesticide application contributes to elevated Cd and Pb levels in rice paddies, with measurable impacts on food safety (12). In Europe, long-term monitoring has revealed correlations between farming intensity and soil contamination, highlighting the need for stricter regulation of agrochemical composition (13). While Asia and Europe provide growing bodies of evidence, comparable data from African agricultural systems remain scarce.

In sub-Saharan Africa, where agriculture is the backbone of livelihoods, the contribution of pesticides to heavy metal contamination remains under-researched. The problem is exacerbated by weak or poorly enforced regulatory frameworks governing pesticide composition and application, coupled with limited farmer awareness of hidden risks (14). Excessive or imbalanced application accelerates soil degradation, yet the cumulative effects of heavy metals are not immediately visible, making the issue less prioritized compared to more obvious challenges such as pest outbreaks or declining yields, which motivate the application of pesticides regardless of the risks (6, 15, 16). Critically, existing studies often treat heavy metals and pesticide residues separately, overlooking their potential interactions. This creates uncertainty for policymakers and farmers in Zambia, who lack context-specific data to guide sustainable soil management and agrochemical regulation. The research gap therefore centers on the need for integrated, region-specific studies that investigate heavy metal accumulation alongside pesticide residues across gradients of farming intensity.

This study addresses this need by investigating heavy metal and pesticide accumulation in agricultural soils of Central Province, Zambia. Here, we (i) quantify concentrations of heavy metals (Cd, Pb, Cu, Zn) and twelve pesticides (acetamiprid, acifluorfen, chlorpyrifos, clodinafop-propargyl, lambda-cyhalothrin, cypermethrin, emamectin benzoate, fomesafen, haloxyfop-methyl, lufenuron, profenofos, glyphosate, and its metabolite aminomethylphosphonic acid) (ii) analyze their distribution across farming landscapes; and (iii) assess how pesticide residues and heavy metals influence persistence and toxicity.

2 Materials and methods

2.1 Description of study area, farming systems and sampling strategy

2.1.1 Study area and farming systems

The study was conducted in Chibombo and Mkushi Districts of Zambia's Central Province (Figure 1), both situated in agroecological region IIa. Mkushi is dominated by luvisols with localized ferralsols, while Chibombo primarily contains acrisols with cambisols occurring in valley areas (17). Agroecological region IIa receives approximately 800–1000 mm of annual rainfall. Three farming systems (commercial, emergent, and smallholder) are present in both districts. However, Mkushi is predominantly characterized by commercial farming, while Chibombo is largely dominated by smallholder systems (for a detailed description of the study area and farming systems, see Supplementary Material 1).

2.1.2 Study design

The study employed a two-stage nested research design in which location (districts) was treated as a fixed factor, while farming systems were considered as a random factor nested within locations (Figure 2). Each farming system had 3 replications.

2.1.3 Sampling procedure

Soil sampling was conducted at nine sites per district, giving a total of 18 sites. Site selection was based on the dominant farming systems (commercial, emergent, and smallholder) in each district. Within each farm, three sampling points were identified within soya bean fields, and at each point three sub-points were chosen within a 10m radius (Figure 3). At every sub-point, soils were collected at

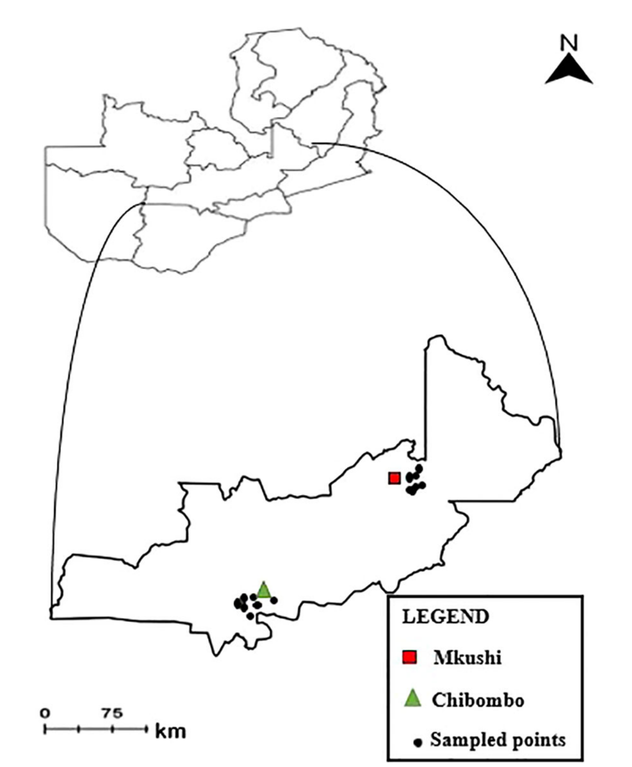

FIGURE 1
Soil sampling locations (Chibombo; latitude -14.6569° S and longitude 28.0706° E & Mkushi; latitude -13.6202° S and longitude 29.3939° E). Map adapted from United Nations Geospatial Information Section. (2020). Modified by Author, 2026.

three depths: 0–20 cm, 20–40 cm, and 40–60 cm. Sub-samples from each depth were composited into a 1-kg sample. This procedure yielded nine samples per farm (three per soil depth). Sampling was carried out during the 2024/2025 cropping season, between 15 March and 15 April, resulting in a total of 162 samples. All samples were transported to the Soil Chemistry Laboratory at the University of Zambia for pre-treatment. Samples were air-dried at ambient temperature and sieved through a 20-mesh (equivalent to aperture size 0.85 mm/850 microns) sieve to remove gravel, stones, roots, and other debris. For pesticide analysis, ~20 g of soil from the 0–20 cm depth at each sampling point were stored at 4 °C and shipped to Wageningen University. The remaining portion (~700 g per sample, from all depths) was sent to Zambia Agricultural Research Institute (ZARI) for heavy metal analysis.

2.2 Sample analysis

2.2.1 Soil heavy metal analysis

Soil samples were air-dried at room temperature, ground using a mortar and pestle, and sieved through a 2 mm sieve (18). Approximately 0.5 g of soil was digested with a mixed acid solution of HCl, HNO_3, HF, and $HClO_4$ (3:2:1:1, v/v; 10 mL total volume) in Teflon beakers on a hot plate at 180 °C until near dryness (19). Residues were re-dissolved in 25 mL of 2% HNO_3 for analysis. The bioavailable fraction was extracted using the DTPA method: 10 g of soil was shaken with 20 mL of 0.005 M DTPA, 0.1 M triethanolamine, and 0.01 M $CaCl_2$ (pH 7.3) for 2 h, centrifuged at 4,000 rpm for 15 min, and filtered through 0.45 μm membranes (20). Heavy metal concentrations (Cd, Pb, Cu, Zn) were quantified using ICP-MS (Perkin Elmer NexION 300X; Thermo iCAP 6300) following USEPA Method 6020A (21). Calibration curves were prepared with multi-element standards (0.1–10 mg L^{-1}), and indium and yttrium (10 μg L^{-1}) were used as internal standards. Method validation yielded recovery rates of 93.5-104.2%, RSD<5%, LOD 1.1–12.3 ng L^{-1}, and LOQ 3.5-38.9 ng L^{-1}. All glassware and containers were pre-treated in 20% HNO_3 for 24h and rinsed with distilled and deionized water (22). Certified reference materials (GBW 07603 bush leaf; GBW 07408 yellow soil) were analyzed for quality control, with deviations from certified values consistently<10%. Soil pH was determined using deionized water at a 1:5 soil-to-water ratio with a pH meter (PHS-3E).

2.2.2 Pesticide analysis

Pesticide residues were extracted using a modified QuEChERS method and analyzed by liquid chromatography-tandem mass

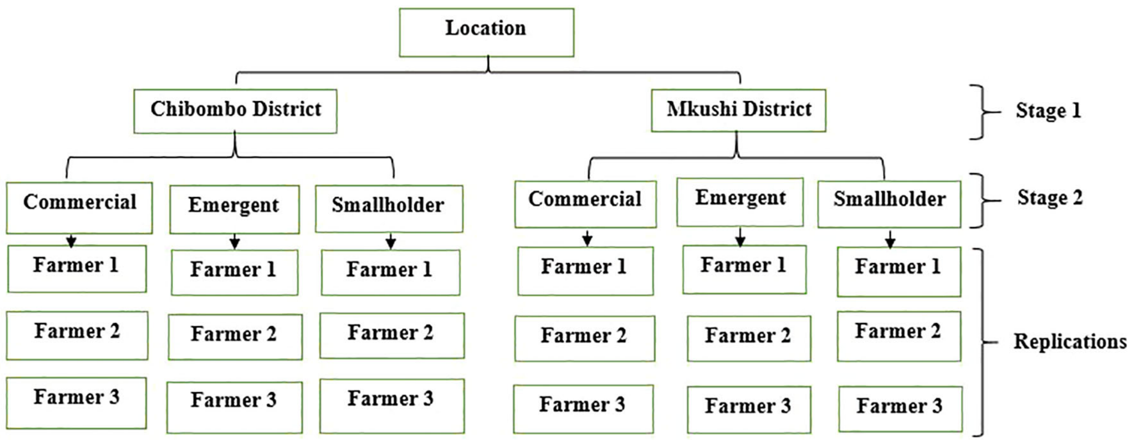

FIGURE 2
Research design.

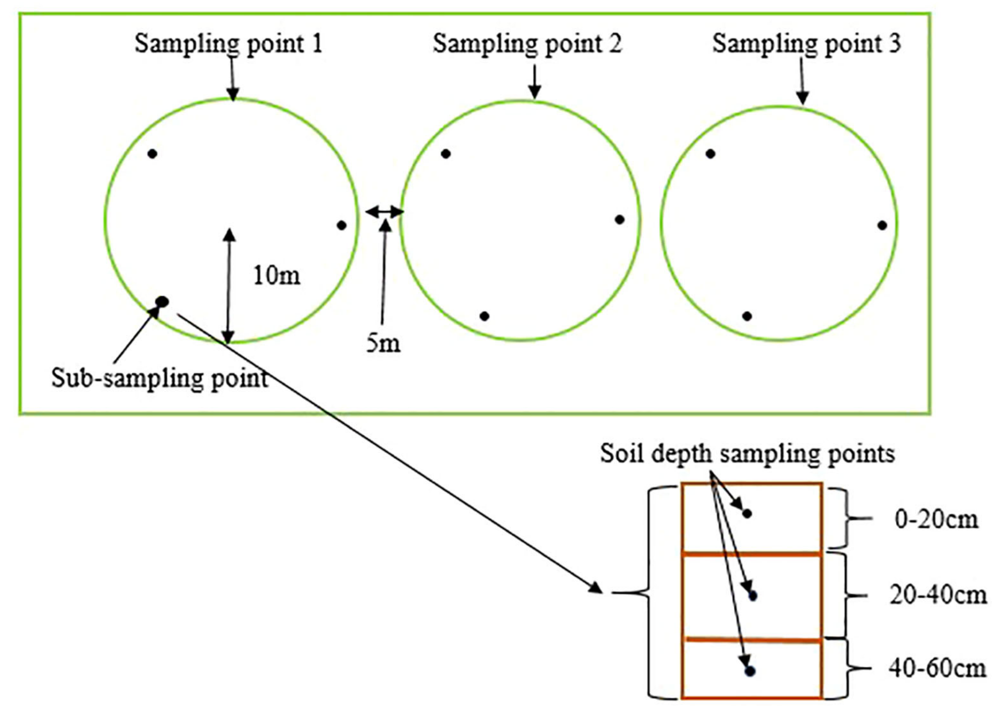

FIGURE 3
Farmer field sampling layout.

spectrometry (LC-MS/MS) and gas chromatography-tandem mass spectrometry (GC-MS/MS). (see Supplementary Materials 2, 3, for a methodology on pesticide analysis procedure, instrumental and apparatus details).

2.2.3 Pollution index calculations

The enrichment factor (EF), first proposed by Zoller et al. (23), is a key indicator for assessing the extent of human disturbance on heavy metal sources in soils and sediments. It is widely used to evaluate the enrichment status of heavy metals and is calculated using the following equation adopted from Hakanson. (1980) (24).

$$EF = \frac{(C_j/C_m)}{(C_j/C_m)} \frac{Sample}{background} \quad (1)$$

Where; EF is the enrichment factor, C_j is the quantified value of element j in the soil and $C_m$is the quantified value of the selected reference element. Reference elements are typically those with stable geochemical properties and minimal susceptibility to external interference, such as Ti, Al, Mn and Fe (25–27). In our study, Fe was used as a reference element. The background values used to calculate the pollution indices were Cu (100 mg/kg), Cd (2.01 mg/kg), Pb (56 mg/kg), and Zn (185 mg/kg). These regional reference values are cited from Herselman et al. (28).

The Potential Ecological Risk Index (PERI) was applied to analyze the data. This widely used method integrates heavy metal interactions, toxicity, ecological risk assessment, chemistry, and ecological sensitivity. The comprehensive ecological risk index (RI) is calculated using the following equations adopted from Hakanson (1980) (24).

$$E_r^i = T_r^i \cdot C_f^i = T_r^i \cdot C_s^i / C_n^i \quad (2)$$

$$RI = \sum E_r^i = \sum T_r^i \cdot C_f^i = \sum T_r^i \cdot C_s^i / C_n^i \quad (3)$$

Where; E_r^i is the potential ecological hazard index of heavy metal i, T_r^i is the toxicity coefficient of heavy metal i. The toxicity coefficients applied were; Zn (1), Pb (5), Cu (5) and Cd (30). C_f^i is the enrichment factor of heavy metal i, C_s^i is the measured value of heavy metal i, and C_n^i is the background value of heavy metal i. The standardized classification of potential ecological risk assessment (PERA) were adopted from He et al. (9) as shown in Table 1.

2.3 Statistical analysis

Initial data analysis employed descriptive statistics to summarize concentrations of heavy metals and pesticide residues across all

TABLE 1 Standardized classification of potential ecological risk indice.

E_r^i Grade	Pollution grade	RI grade	Comprehensive ecological risk grade
$E_r^i < 40$	Slight (low)	RI< 135	Slight (low)
$40 \le E_r^i < 80$	Mid (medium)	135 ≤ RI< 265	Mid (medium)
$80 \le E_r^i < 160$	Strong (heavy)	265 ≤ RI< 525	Strong (heavy)
$160 \le E_r^i < 320$	Stronger (heavier)	525 ≥ RI	Stronger (serious)
$320 \ge E_r^i$	Strongest (serious)		

sampling sites (for pesticide statistics, see Siyunda et al., submitted). The nested analysis of variance (ANOVA) was used to test differences in heavy metal concentrations across soil depths, farming systems, and districts at a significance level of $\alpha < 0.05$. Where significant variation was detected, the Tukey's HSD post-hoc test was used to identified specific group differences. Pearson correlation coefficients were calculated to assess relationships among heavy metal concentrations, pesticide residues, and soil pH.

3 Results

3.1 Heavy metal concentrations in agricultural soils

3.1.1 Heavy metal concentrations across location and farming systems

The results show the concentrations of Cu, Cd, Pb, and Zn (Table 2). Unlike Pb and Zn whose average score were below the WHO permissible limit, Cu and Cd had some commercial farms that indicated values above the WHO permissible limits (For descriptive statistics of heavy metals, see Supplementary Material 4). Source of heavy metal permissible limits is WHO, (29) cited in Alengebawy et al. (13).

3.1.2 Pesticide concentrations across location and farming systems

Pesticide residues were detected across all farming systems with notable variation in concentration levels. In smallholder farms, the highest mean values were observed for chlorpyrifos (2796.98 µg/kg), followed by cypermethrin (205.64 µg/kg), and AMPA (81.69 µg/kg). Emergent farms recorded elevated cypermethrin (391.23 µg/kg), chlorpyrifos (1554.52 µg/kg), and fomesafen (90.09 µg/kg). Commercial farms showed high herbicide residues, including glyphosate (175.88 µg/kg), AMPA (440.37 µg/kg), acifluorfen (266.95 µg/kg), and fomesafen (264.47 µg/kg), with comparatively lower insecticide levels. Statistical analysis indicated significant differences across farming systems for acetamiprid ($p = 0.037$), chlorpyrifos ($p = 0.019$), cypermethrin ($p = 0.047$), and profenofos ($p = 0.039$). (For detailed descriptive statistics of pesticides, see Supplementary Material 5).

3.2 Spatial variation: differences across farming landscapes

3.2.1 Influence of farming practices versus location on soil contamination patterns

Soil pH, Pb, and location effects for all parameters were non-significant ($P>0.05$) (Table 3). Significant variations by farming system was observed for Cu ($P = 0.048$), Cd ($P = 0.020$), and Zn ($P = 0.000$).

Cu concentrations increased in commercial farming systems, with Chibombo recording significantly higher ($p < 0.05$) values than Mkushi (Figure 4). Cd levels were also highest in commercial systems, with Chibombo significantly greater than Mkushi. Pb concentrations remained relatively similar across farming systems and locations, with no significant differences ($p > 0.05$) observed. Zn concentrations were elevated in commercial systems, with Chibombo significantly higher ($p < 0.05$) than Mkushi.

3.2.2 Patterns of heavy metal enrichment across farming systems and soil profiles

Significant variation by farming system was observed for Cu ($P = 0.006$) and Zn ($P = 0.005$). Soil depth effects were significant for Cd ($P = 0.000$), Pb ($P = 0.000$), and Zn ($P = 0.000$). Non-significant results were recorded for the remaining parameters (Table 4).

Significant effects of farming systems were observed for Cu and Zn, with commercial systems showing higher enrichment at the 0–20 cm soil depth compared to emergent and smallholder systems. Smallholder systems consistently recorded the lowest Zn enrichment across all depths. For Pb, enrichment was significantly higher at 0–20 cm compared to 20–40 cm, and 20–40 cm was significantly higher than 40–60 cm. Cd enrichment showed no significant difference between 0–20 cm and 20–40 cm, but both depths were significantly higher than 40–60 cm. Zn enrichment was significantly greater at 0–20 cm compared to the subsoil depths (20–40 cm and 40–60 cm) (Figure 5).

3.3 Correlations among soil pH, heavy metal accumulation, and pesticide residues

Soil pH showed weak negative correlations with Cu, Cd, Pb, and Zn, except Haloxyfop-R-Methyl, which was moderately positive (Table 5). Strong positive associations existed among heavy metals,

TABLE 2 Average concentration of heavy metals across location and farming systems at 0-20cm soil depth.

	Chibombo			Mkushi			
Heavy metals	SH (mg/kg)	EF (mg/kg)	CF (mg/kg)	SH (mg/kg)	EF (mg/kg)	CF (mg/kg)	WHO permissible limits (mg/kg)
Cu	4.23	6.79	32.22	3.11	5.30	3.60	36
Cd	0.26	0.54	0.77	0.30	0.47	0.50	0.8
Pb	7.31	10.97	10.72	6.38	11.12	10.69	85
Zn	8.37	29.30	36.92	7.48	30.34	36.82	50

SH, smallholder farming system; EF, emergent farming system; CF, commercial farming system.

TABLE 3 Statistical significance of heavy metals by location and farming system.

Parameter	Location (*P-value*)	Farming system (*P-value*)
pH	1.000	0.075
Cu	0.310	**0.048**
Cd	0.582	**0.020**
Pb	0.895	0.101
Zn	0.999	**0.000**

Bold figures indicate significance across farming systems.

especially Cu-Cd and Cd-Pb. Cu and Cd correlated significantly with herbicides like acifluorfen, clodinafop, fomesafen, and AMPA. In contrast, chlorpyrifos and profenofos correlated negatively with metals. Emamectin benzoate and lufenuron displayed a very strong positive correlation, highlighting close pesticide-pesticide associations in soil chemistry.

3.4 Pollution index

3.4.1 Enrichment factor

Cu and Cd showed similar enrichment factor (EF) trends, with no significant differences ($P > 0.05$) between Chibombo and Mkushi overall. Within farming systems, however, significant differences ($P < 0.05$) were observed between locations. Smallholder systems in Chibombo differed significantly from those in Mkushi, and this pattern was consistent across all farming systems for both Cu and Cd. Comparable trends were noted for Pb enrichment among smallholder systems and Zn enrichment among emergent systems (Figure 6).

3.4.2 Potential ecological hazard index (E_r^i) and PERI (RI) values

All potential ecological hazard indices (E_r^i) for Cu, Cd, Pb, and Zn remained below the threshold ($E_r^i < 40$) across farming systems and locations. Within commercial farming systems, Chibombo recorded significantly higher index values for Cu and Cd compared to Mkushi (Figure 7).

Commercial farming systems in Chibombo recorded significantly higher RI values compared to those in Mkushi. No significant variations ($P > 0.05$) were observed between locations within smallholder and emergent farming systems. All values remained below the threshold (RI< 135) (Figure 8).

4 Discussion

The findings reveal a clear distinction in the co-occurrence of heavy metals and pesticides contamination across smallholder, emergent, and commercial farming systems. These differences are not merely quantitative but reflect broader dynamics of farming practices and soil depth that shape contamination distribution. By situating these results within global research, several critical themes emerge; heavy metal-pesticide associations, implications for soil health, and risks to food safety.

4.1 Heavy metal concentrations vs WHO standards

The results point to a clear distinction between metals that exceed permissible limits and those that remain within safe thresholds, with important implications for soil management and food

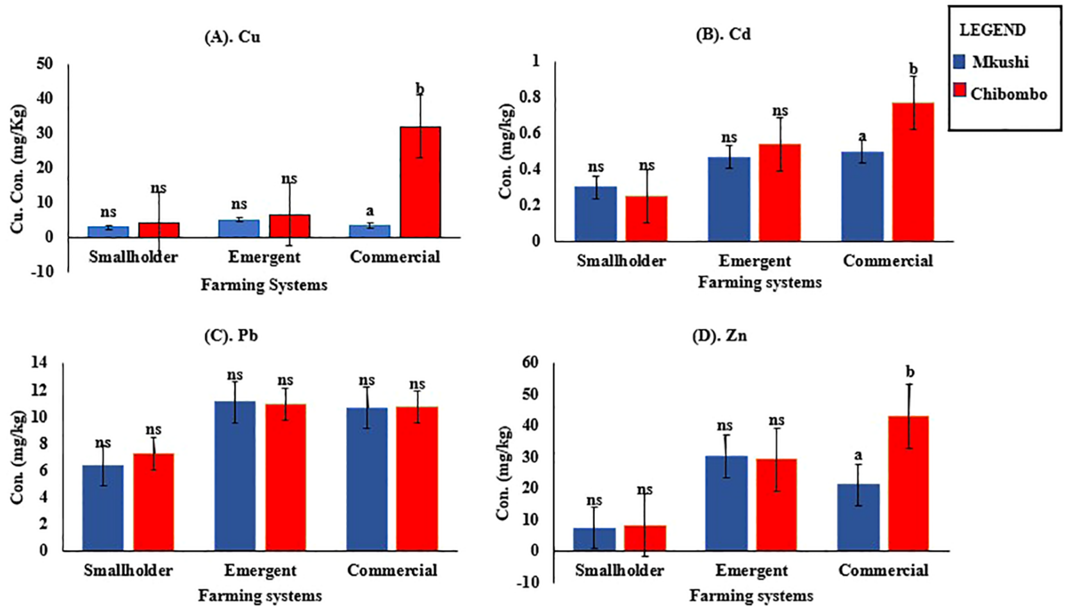

FIGURE 4
Variation in heavy metals between farming systems and locations. Different letters indicate significant differences within farming systems. ns indicates no significant difference (compared at a significance level of 5%).

TABLE 4 **Statistical significance of heavy metals by farming system and soil depth.**

Parameter	Farming systems (*P-value*)	Soil depth (*P-value*)
Cu	**0.006**	0.294
Cd	0.165	**0.000**
Pb	0.814	**0.000**
Zn	**0.005**	**0.000**

Bold figures indicate significance across farming systems and soil depth.

safety. In commercial farms, Cu and Cd occasionally surpassed the WHO permissible limits for agricultural soils. The exceedance signals potential risks, as both Cu and Cd can accumulate in crops grown in contaminated soils, posing hazards to human health through dietary exposure. The fact that these exceedances were observed specifically in commercial systems highlights the role of intensive farming practices, such as heavy fertilizer use, pesticide application, or industrial inputs, in driving contamination beyond safe thresholds. In contrast, Pb and Zn remained below WHO limits on average, showing no evidence of dangerous accumulation across farming systems. This stability suggested that Pb and Zn are less influenced by current agricultural practices, either because their inputs are minimal or because they are more tightly bound in soil matrices, reducing mobility and bioavailability.

The findings of the present study align with previous research highlighting the role of anthropogenic activities in heavy metal accumulation. For instance, Chrastný et al. (30) examined the impact of mining activities near Olkusz town in Upper Silesia, South Poland, and reported significant enrichment of Cd (200 mg/kg), Pb (25 mg/kg), and Zn (20 mg/kg) in agricultural and forest soils. Similarly, Ratiu et al. (31) investigated heavy metal concentrations around the Tisza River and its tributaries, attributing elevated levels of Cd (1.3–2.1 mg/kg), Pb (38–3630 mg/kg), Cu (54–4850 mg/kg), and Zn (200–770 mg/kg) to human activities. These concentrations exceeded permissible limits, underscoring their toxic potential. In contrast, Saadia et al. (32), who analyzed 52 soil samples from cotton fields, found near-background values for most metals (Cu, Co, Pb, and Cr), with only Ni and Cd showing slight enrichment linked to agricultural practices. A comparative assessment of these studies suggests that the intensity of anthropogenic activities strongly influences the degree of heavy metal accumulation in soils. More intensive operations such as mining, fertilizer application, pesticide use, and irrigation, tend to result in higher concentrations, whereas less intensive agricultural practices may only cause minor enrichment.

The WHO thresholds provide critical benchmarks for assessing soil safety. Exceedances of Cu and Cd in commercial farms suggest that these systems may be approaching, or even crossing, the boundary between productive agriculture and environmental risk. Similar concerns have been reported in non-industrial farming regions, where overall contamination is modest but Cu and Cd demand closer management (8, 33, 34). While Pb and Zn remain within acceptable ranges, elevated Cu and Cd highlight the need for stricter monitoring in commercial systems to prevent long-term accumulation. This is particularly important because surface soils, being biologically active and directly linked to crop uptake, can translate localized exceedances into food chain risks. Evidence from China (35, 36) shows Cd levels exceeding environmental standards,

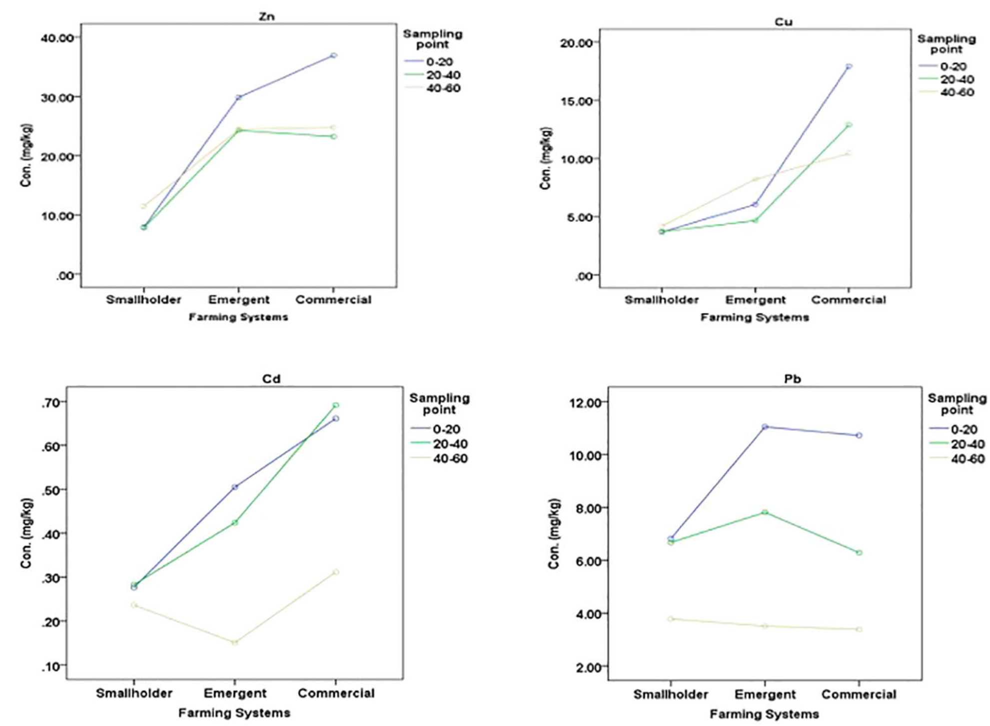

FIGURE 5
Variation in heavy metal accumulation between farming systems at different soil depths.

TABLE 5 **Correlation matrix of Soil pH, heavy metals and pesticide residues in agricultural soils.**

	pH	Cu	Cd	Pb	Zn	Acet	Acif	Clod	Chl	Cyp	Ema	Prof	Luf	Hal	Fom	Cyh	Gly	AMPA
pH	1																	
Cu	-0.27	1																
Cd	-0.35	0.82**	1															
Pb	-0.30	0.51*	0.79**	1														
Zn	-0.44	0.41	0.66**	0.66**	1													
Acet	0.26	0.37	0.13	-0.12	-0.19	1												
Acif	-0.23	0.95**	0.71**	0.46	0.32	0.45	1											
Clod	-0.18	0.93**	0.66**	0.42	0.25	0.48*	0.99**	1										
Chl	0.17	-0.28	-0.49*	-0.51*	-0.57*	0.37	-0.19	-0.12	1									
Cyp	0.13	-0.11	-0.01	0.11	-0.06	0.21	-0.07	-0.06	0.10	1								
Ema	-0.25	0.34	0.36	0.04	0.28	-0.01	0.09	0.03	-0.20	-0.05	1							
Prof	0.19	-0.28	-0.59**	-0.58*	-0.61**	0.37	-0.15	-0.08	0.89**	0.17	-0.23	1						
Luf	-0.12	0.18	0.25	-0.02	0.26	-0.02	-0.06	-0.12	-0.16	-0.05	0.96**	-0.19	1					
Hal	0.50*	0.10	-0.04	-0.26	-0.36	0.37	0.06	0.13	0.60**	0.01	0.13	0.44	0.20	1				
Fom	-0.16	0.91**	0.70**	0.45	0.29	0.42	0.97**	0.97**	-0.22	-0.01	0.05	-0.18	-0.10	0.07	1			
Cyh	-0.32	0.95**	0.79**	0.49*	0.38	0.42	0.92**	0.89**	-0.25	0.02	0.39	-0.19	0.24	0.05	0.88**	1		
Gly	-0.29	0.05	0.24	0.24	0.33	-0.13	0.07	0.04	-0.29	-0.15	0.05	-0.28	0.04	-0.33	0.05	0.05	1	
AMPA	-0.45	0.80**	0.69**	0.45	0.45	0.30	0.82**	0.79**	-0.24	-0.20	0.27	-0.17	0.14	-0.08	0.77**	0.83**	0.52*	1

*significant at 0.05, **significant at 0.01; Cu, Copper; Cd, Cadmium; Pb, Lead; Zn, Zinc; Acet, Acetamiprid; Acif, Acifluorfen-sodium; Clod, Clodinafop-propargyl; Chl, Chlorpyriphos; Cyp, Cypermethrin; Ema, Emamectin benzoate; Prof, Profenofos; Luf, Lufenuron; Hal, Haloxyfop-R-Methyl; Fom, Fomesafen; Cyh, Cyhalothrin Lambda; Gly- Glyphosate, AMPA.

with documented inhibition of microbial growth, respiration, and enzymatic activity. European studies (37, 38) further confirm Cd's isotopic variability and synergistic toxicity when combined with salinity. Cu, though essential as a micronutrient, becomes toxic when concentrations surpass optimal levels. Its availability is strongly influenced by soil pH and organic matter, with accumulation often linked to Cu-based pesticides. Natural concentrations typically range between 5–30 mg/kg, yet excessive Cu disrupts microbial activity, damages cell membranes, and inhibits enzymes such as urease (39–41).

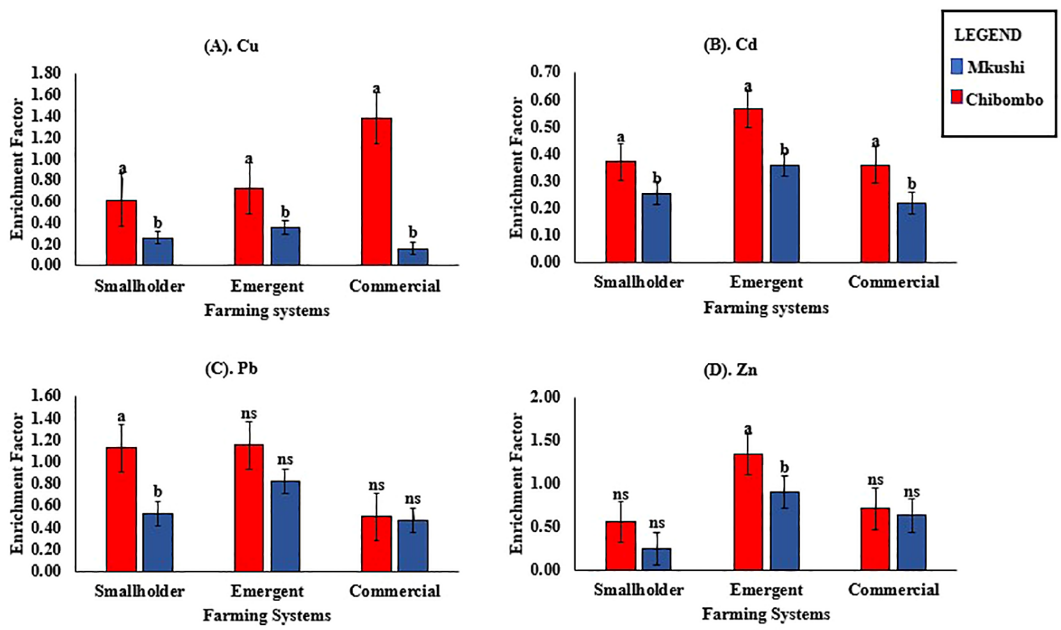

FIGURE 6
Spatial variation in heavy metal enrichment factors between farming systems and locations. Different letters indicate significant differences within farming systems. ns indicates no significant difference (compared at a significance level of 5%).

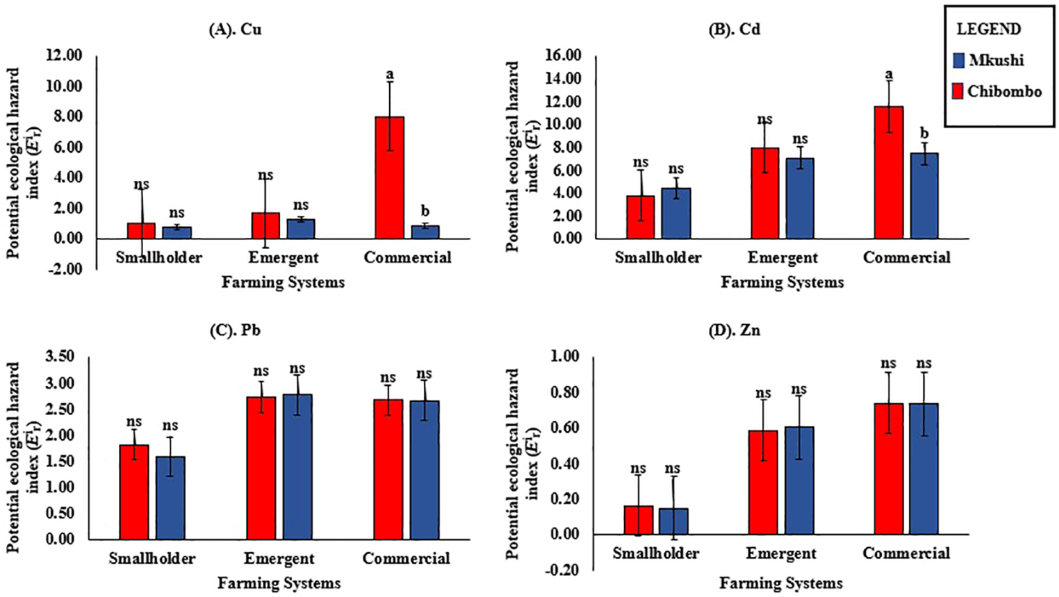

FIGURE 7
Ecological risk assessment of heavy metals (Cu, Cd, Pb, Zn) across farming systems in Chibombo and Mkushi. **(a, b)** are compared according to a farming system, different letters within the same farming system indicate significant differences. ns: no significant difference (compared at a significance level of 5%).

4.2 Pesticides concentrations vs WHO/FAO standards

The results point to a clear distinction between pesticides that exceed internationally recognized thresholds and those that remain within acceptable ranges, with important implications for soil safety and food security. In smallholder systems, residues of organophosphate insecticides such as chlorpyrifos and profenofos surpass WHO/FAO benchmarks, reflecting heavy reliance on broad-spectrum, low-cost chemicals. These exceedances signal potential risks, as organophosphates are known to accumulate in soils and crops, increasing hazards to both ecological integrity and human health through dietary exposure. In emergent or mixed farming systems, the pattern shifts toward diversified pesticide use, with pyrethroids such as cypermethrin and selective herbicides like fomesafen becoming more prominent. While diversification indicates a transition in management practices, the elevated concentrations of these compounds still exceed Codex reference values for several food commodities, suggesting that transitional farms remain vulnerable to unsafe accumulation. Commercial farms present a markedly different profile, characterized by lower insecticide residues but intensified herbicide use. Glyphosate and its metabolite AMPA stand out, with concentrations surpassing Codex limits for cereals and pulses. The widespread detection of glyphosate residues in soils mirrors global trends in large-scale agriculture, where chemical weed control dominates. The uneven contamination profiles observed across commercial farms highlight variability in management practices, with some adopting integrated pest management while others remain heavily dependent on chemical inputs.

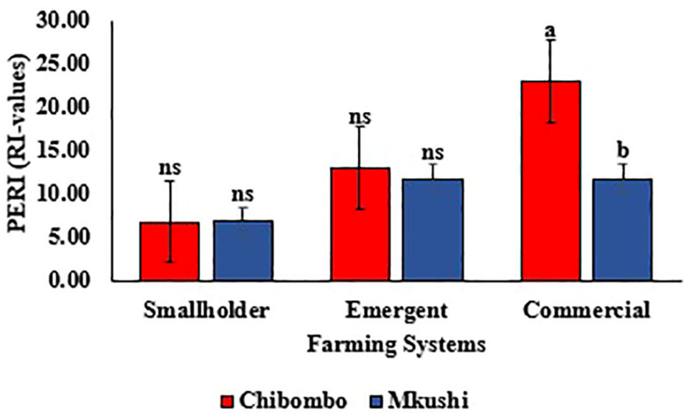

FIGURE 8
Potential ecological risk index across farming systems in Chibombo and Mkushi. **(a, b)** are compared according to a farming system, different letters within the same farming system indicate significant differences. **ns**: no significant difference (compared at a significance level of 5%).

WHO/FAO thresholds serve as critical benchmarks for evaluating agricultural safety. Exceedances of insecticides in smallholder and emergent systems, alongside herbicide intensification in commercial systems, indicate that different farming systems are approaching or crossing boundaries between productive agriculture and environmental risk. From an environmental and health perspective, the persistence of chlorpyrifos and cypermethrin in smallholder and emergent systems is concerning due to their toxicity (42–44), while the heavy reliance on herbicides in commercial farms raises issues of ecological impact and potential resistance development (45). This underscores the need for stricter monitoring, farmer education, and promotion of safer alternatives to ensure long-term sustainability.

4.3 Spatial variation across farming systems

The interpretation of our findings highlights clear differences among farming systems, with commercial practices driving higher metal enrichment. When comparing farming systems, commercial farms consistently recorded higher concentrations of Cu, Cd, and Zn than other farming systems. This suggests that farming intensity and management practices contribute more strongly to surface soil contamination, possibly due to greater reliance on chemical inputs or more intensive cultivation. It is also critical to note which metals showed significant versus non-significant variation. Cu, Cd, and Zn varied significantly across farming systems and locations, underscoring their sensitivity to agricultural practices (46). In contrast, Pb remained relatively stable, with no significant differences observed between systems or locations. This stability suggests that Pb contamination is less influenced by farming practices and may be more tied to background levels or non-agricultural sources.

The accumulation of pesticide residues exhibits clear spatial variation across farming systems, shaped by differences in land size, management intensity, and pest pressures. In smallholder farms, residues are dominated by insecticides, particularly organophosphates. This reflects the challenges faced by resource-constrained farmers who cultivate small parcels of land and encounter higher insect-pest pressure than weed infestations. Reliance on broad-spectrum insecticides in these systems leads to localized contamination, with residues concentrated in soils subjected to repeated applications. In emergent or mixed farming systems, residue profiles become more diverse. Pyrethroids and selective herbicides appear alongside insecticides, reflecting medium-scale practices where farmers adopt multiple products (often in combination) to manage varied pest and weed pressures. Residue levels in these systems are moderate but inconsistent, suggesting uneven adherence to application protocols and variability in handling practices. In commercial farming systems, the profile shifts toward herbicide intensification. Glyphosate and its metabolite AMPA dominate, accompanied by variable levels of acifluorfen and fomesafen. This pattern reflects large-scale reliance on chemical weed control, where extensive arable lands favour herbicide-based strategies over insecticide use. Spatial variation here is marked by widespread herbicide residues, with contamination levels influenced by crop type, management intensity, and the degree of integration of pest management practices.

In our study, spatial variation across farming systems highlights distinct contamination profiles; insecticide dominance and low heavy metal accumulation in smallholder soils, diversified pesticide residues in emergent landscapes, and herbicide intensification and higher heavy metal enrichment in commercial farms. These differences emphasize the need for system-specific monitoring and management strategies to address localized risks while ensuring broader environmental and food safety.

4.4 Soil profile effects

The enrichment profiles of Pb, Cd, and Zn reveal a clear stratification across soil depths, underscoring the tendency of these metals to concentrate in surface horizons. Pb and Zn both exhibit strong surface retention, reflecting limited downward mobility and strong binding to organic matter and fine particles typically abundant in topsoil. Their enrichment diminishes progressively with depth, highlighting their persistence in upper layers where agricultural inputs and biological activity are most intense. Cd shows a slightly different behavior, with comparable accumulation in the upper and mid-depth layers. Suggesting moderate mobility compared to Pb and Zn. Cd did not penetrate deeply, its presence beyond the surface horizon indicates a capacity for partial downward migration, likely influenced by soil chemistry and its weaker binding affinity relative to Pb and Zn. Together, these depth-related patterns emphasize that Pb and Zn are largely surface-bound contaminants, while Cd demonstrates intermediate mobility. This stratification highlights the importance of monitoring surface soils for contamination risks, while also recognizing Cd's potential to affect subsurface layers.

The enrichment pattern observed in the soils point to a strong influence of the farming practices and surface exposure, with the topsoil (0-20cm) acting as the primary zone of accumulation. Metals such as Cu and Zn are more concentrated in commercial farming systems, which reflects the intensity of the input use (fertilizers, pesticides, and soil amendments) that tend to leave residues that accumulate in the biologically active surface layer. In contrast, smallholder systems, which rely less on external input, show consistently lower enrichment, suggesting a more restrained impact on soil chemistry. Significant differences in Cu, Cd and Zn across farming systems at soil depth 0–20 are consistent with Rahmani (47), who linked Cd accumulation on top soils to phosphate fertilizers and Zn enrichment to repeated manure, fertilizer, and pesticide use. Gimeno-García et al. (48) further emphasized that chemical input intensity, rather than geographic variation, drives heavy metal contamination. In contrast, Pb, and soil pH showed no significant differences, aligning with long-term monitoring studies that report relative stability unless extreme inputs are applied (9, 11, 49–51). Depth gradients reinforce this pattern, with topsoil enrichment reflecting direct agrochemical application and limited leaching (52, 53).

From an environmental and agronomic perspective, this has significant implications. The surface soil is the zone of root activity and microbial processes, meaning that metals concentrated here are more likely to be taken up by crops and enter the food chain. Commercial systems, while productive, may therefore pose greater risks of heavy metal accumulation in edible plants, raising concerns for food safety. Smallholder systems, though less enriched, may be more sustainable in terms of long-term soil health. The findings reinforce the need for careful monitoring of surface soils, as they are the most dynamic and sensitive to farming practices, while deeper layers serve more as background reservoirs.

4.5 Correlations between metals, soil pH, and pesticides

The strong positive correlations among Cu, Cd, Pb, and Zn observed in this study suggest that these metals share common pathways of accumulation and mobility in agricultural soils. Their co-occurrence points to overlapping sources such as fertilizers, pesticides, and irrigation practices, as well as similar geochemical behaviors that favour joint retention in the soil matrix. The particularly close associations between Cu and Cd, and between Cd and Pb, indicate that these metals may be influenced by comparable environmental drivers, reinforcing the idea of linked contamination processes. Cd's consistent clustering with multiple metals highlights its central role in shaping contamination profiles, while Zn, though positively associated with Cd and Pb, showed weaker alignment with Cu, suggesting that it may be partly governed by distinct soil interactions or input sources. These findings mirror those of Ahamad et al. (54), who reported strong associations among As-Mn and As-Cr, and Xinfa et al. (55), who observed significant relationships between Pb-As, Ni-Cr, and Cu-Cr, supporting the conclusion that heavy metals often share similar entry pathways.

Our findings are also consistent with Liu et al. (56), who reported that herbicides and insecticides contained traces of heavy metals at varying levels, with insecticides showing higher concentrations than chemical fertilizers but lower than organic fertilizers. This highlights the role of agrochemicals as a major source of metal contamination. The human health implications are evident, as Nityasani et al. (5) found elevated levels of Pb, Cd, and Cr^{6+} in the urine of farmers with long-term exposure to pesticide spraying compared to the general population. In contrast, Saadia et al. (32) reported non-significant correlations between heavy metals and pesticides such as imidacloprid, emamectin benzoate, and acetamiprid, suggesting that associations may vary depending on pesticide type, farming practices, and environmental conditions.

The correlations between pesticides and metals reveal overlapping contamination pathways, with Cu and Cd showing strong positive associations with herbicides such as acifluorfen, clodinafop, fomesafen, and the glyphosate metabolite (AMPA). These repeated linkages suggest that pesticide applications may reinforce metal accumulation through shared sources, co-application practices, or soil retention mechanisms. Cyhalothrin-lambda further aligns with Cu, underscoring coupled contamination dynamics. In contrast, chlorpyrifos and profenofos, though strongly correlated with each other, exhibited negative relationships with Cd, Pb, and Zn, and no meaningful association with Cu, indicating distinct mechanisms that diverge from metal enrichment. This dual pattern highlights the complexity of soil contamination, while some pesticides amplify heavy metal presence, others act independently or inversely. The co-occurrence of pesticides and heavy metals may also be linked to blended pesticide formulations commonly sold in Zambia, which enhance pest control but simultaneously increase cumulative contamination risks. Heavy metals can enter soils either as pesticide impurities (56) or as stabilizing agents within formulations (5). Similar associations have been documented in Asia (57–59) and the Middle East (60). Soil pH further influenced these dynamics, with negative correlations suggesting that acidification exacerbates contamination by increasing bioavailability. Although contamination from pesticides and heavy metals is well established, their co-occurrence may produce either synergistic (enhanced toxicity) or antagonistic (reduced toxicity) effects (13). Wang et al. (61) investigated Cd and insecticides in earthworms, finding that synergistic interactions were more prevalent than antagonistic ones, underscoring the importance of considering combined effects.

Taken together, these associations emphasize that soil contamination in farming systems is not driven by metals or pesticides in isolation. Instead, the evidence points to a coupled dynamic where specific agrochemicals are closely linked with heavy metal enrichment. This interconnected behavior underscores the need for integrated monitoring approaches that consider both pesticide residues and heavy metals simultaneously, ensuring comprehensive risk assessment and management of agrochemical impacts.

4.6 Pollution indices and risk assessment

The EF analysis revealed that Cu and Cd followed similar overall trends, with no significant differences between Chibombo and Mkushi at the broader scale. However, within farming systems, notable location-based variations emerged. Smallholder farms in Chibombo consistently recorded higher EF values than those in Mkushi, a pattern observed across all farming systems for both Cu and Cd. Comparable differences were also evident for Pb enrichment in smallholder systems and Zn enrichment in emergent systems, indicating that specific combinations of farming system and location drive distinct enrichment behaviors. These results highlight that broad comparisons between locations may mask important variations, and that the interaction between farming system type and location plays a critical role in shaping EF outcomes. Similar localized enrichment patterns have been reported in Zambia, where EF values for Cu and Pb varied significantly across mining-influenced soils and river sediments, underscoring the importance of site-specific monitoring (62).

Despite these differences, E^{ir} for Cu, Cd, Pb, and Zn remained below the critical threshold of 40 across all systems and locations, suggesting that individual metals did not pose immediate ecological risks under the studied conditions. Similarly, the cumulative ecological risk index (PERI, RI-values) remained below the threshold of 135, reinforcing that overall risk levels were within acceptable limits. Within commercial farming systems, however, Chibombo consistently recorded higher $E^{i}r$ and RI-values for Cu and Cd compared to Mkushi, highlighting localized elevations in contamination intensity. Comparable findings in North Western and Copperbelt Zambia have shown that while overall ecological risks remain low, localized hotspots of Cu, Pb, and Zn enrichment can occur near agricultural and mining activity, warranting targeted monitoring and pollution control (62).

5 Conclusion and recommendations

Routine pesticide applications are an under-recognized source of heavy metal accumulation in agricultural soils, especially in sub-Saharan Africa where synthetic pesticide use is expanding but monitoring remains limited. This study in Zambia's Central Province (Chibombo and Mkushi Districts) assessed four metals (Cd, Pb, Cu, Zn) and twelve pesticides across commercial, emergent, and smallholder farming systems. Results showed significant differences, with commercial farms exhibiting higher Cd and Cu concentrations, and heavy metals enriched in topsoils compared to deeper layers. Correlation analysis revealed associations between metals and pesticides, with chlorpyrifos residues negatively correlated with most metals except Cu. While pesticide residues at some sites exceeded international thresholds, heavy metals generally remained below WHO limits except for Cu and Cd in some commercial farms. These findings highlight ecological and food safety risks requiring systematic monitoring and policy integration.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

AS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. DL: Supervision, Writing – review & editing. NM: Formal analysis, Supervision, Validation, Writing – review & editing. JY: Supervision, Validation, Writing – review & editing. AG: Investigation, Writing – review & editing. HT: Investigation, Writing – review & editing. SS: Writing – review & editing. RQ: Writing – review & editing. MS: Writing – review & editing. LM: Investigation, Writing – review & editing. XY: Writing – review & editing. RO: Methodology, Writing – review & editing. LF: Writing – review & editing. VN: Methodology, Writing – review & editing. AD: Supervision, Validation, Writing – review & editing. EM: Funding acquisition, Project administration, Supervision, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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