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Heavy metal accumulation in *Amaranthus hybridus* and *Ocimum gratissimum* cultivated on automobile workshop soils in Ekiti Nigeria and associated human health risks

Amos Tomiwa Afolabi[1,2*], Bridget Onoshagbe Odiyi[1] and Oluwasheun Johannah Ojeniyi[2]

*Correspondence:
Amos Tomiwa Afolabi
afolabiamos15@gmail.com
[1]Department of Biology, School of Life Sciences, Federal University of Technology, Akure, P.M.B. 704, Akure 340001, Nigeria
[2]Biological Science Unit, Department of Science Laboratory Technology, Ekiti State University, Ado-Ekiti, P.M.B. 5363, Ado-Ekiti 360001, Nigeria

Abstract

In rapidly urbanizing Nigerian cities such as Ado-Ekiti, Ekiti State, automobile workshops release heavy metals into surrounding soils, posing risks to food safety when such areas are used for urban agriculture. This study investigated growth responses, metal bioaccumulation, and health risks associated with *Amaranthus hybridus* and *Ocimum gratissimum* on soils from two automobile workshops (Workshop A: 20 years operational; Workshop B: 10 years operational) in Ado-Ekiti, Nigeria. Controlled pot experiments were conducted under greenhouse conditions, followed by heavy metal quantification using atomic absorption spectrophotometry and standardized health risk assessment. Workshop A soil exhibited lower pH (6.5 vs. 6.8), higher organic matter content (4.5% vs. 3.8%), and elevated concentrations of Cu (0.935 mg kg^{-1}), Cd (0.251 mg kg^{-1}), and Mn (29.55 mg kg^{-1}) compared to Workshop B. *A. hybridus* accumulated higher metal concentrations than *O. gratissimum* with stem tissues showing 1.2–2.1 times greater accumulation than leaves. Bioconcentration factors remained below 1.0 for most metals, except anomalously high Ni values (6.5–9.5) in Soil B due to extremely low baseline concentrations *A. hybridus* demonstrated superior growth resilience, achieving 54.44 cm height in Soil A versus *O. gratissimum*' s 45.64 cm. Health risk assessment revealed Target Hazard Quotients (THQ) and Hazard Index (HI) values below 1.0, indicating acceptable non-carcinogenic risk. Total Cancer Risk (TCR) ranged from 1.65×10^{-5} to 3.26×10^{-5}, within USEPA acceptable limits ($<1\times10^{-4}$), though children showed higher vulnerability. Findings indicate that while immediate health risks remain low, continuous monitoring and soil remediation strategies are essential for sustainable urban agriculture in automobile workshop-impacted areas.

Keywords Heavy metal, Bioaccumulation, Soil contamination, *Amaranthus hybridus*, *Ocimum gratissimum*

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1 Introduction

Automobile workshops contribute to environmental pollution through the improper disposal of spent engine oil, batteries, metal scraps, and other vehicular wastes. These activities introduce heavy metals such as lead, cadmium, chromium, zinc, and copper into surrounding soils, where they persist and accumulate over time [69]. Growth in population and rapid urbanization in Southwestern Nigeria initiated the acceleration of urban agriculture, whereby built-in communities plant crops in soils that are polluted by the neighboring industrial facilities [38]. Specifically, vegetables like *Amaranthus hybridus* and *Ocimum gratissimum* of major nutritional and pharmacological interest, mainly found in such polluted sites, cause more food-safety concerns, as in the past, there was an indication of high metal concentration in plant tissues [36, 46, 52, 53]. *Amaranthus hybridus* (smooth pigweed) and *Ocimum gratissimum* (African basil) were selected as study species based on several criteria: (1) Widespread consumption: Both species are extensively cultivated and consumed as leafy vegetables in Nigeria, contributing significantly to dietary protein, vitamins, and minerals for low-income urban populations [52]; (2) Peri-urban prevalence: These fast-growing species are commonly cultivated in peri-urban areas, including contaminated sites near automobile workshops [38, 46]; (3) Differential accumulation potential: Preliminary surveys indicated species-specific differences in metal uptake patterns, warranting systematic investigation [52, 53]; (4) Economic importance: Both species represent important income sources for urban farmers [50]; and (5) Nutritional and medicinal value: *O. gratissimum* possesses documented therapeutic properties, while *A. hybridus* provides essential amino acids, making metal contamination particularly concerning for vulnerable populations relying on these vegetables [5]. Despite documented risks, significant knowledge gaps remain regarding: (1) growth performance metrics of edible plants in automobile workshop-contaminated soils, (2) species-specific bioaccumulation patterns and tissue distribution of heavy metals, and (3) comprehensive health risk assessment specifically attributable to automobile workshop pollution. While extensive research has characterized heavy metal contamination in Nigeria, existing studies predominantly focus on large-scale industrial hubs [1] or artisanal mining sectors [27]. Consequently, there is limited attention to automobile repair activities, a ubiquitous source of point-source pollution in Nigerian cities that directly impacts residential soil quality. However, the direct association of soil contamination caused by automobiles and workshops and the health risks caused by the consumption of vegetables is a poorly documented reality.

In Nigeria, the Federal Ministry of Environment has set permissible limits for heavy metals in agricultural soils (e.g., Pb: 85 mg kg^{-1}, Cd: 0.8 mg kg^{-1}, Cr: 100 mg kg^{-1}) (FEPA, 1991), yet data on actual contamination levels in automobile workshop soils and their uptake by commonly consumed vegetables remain sparse. Several studies have reported elevated concentrations of heavy metals in soils surrounding automobile workshops and mechanic villages compared to uncontaminated soils. The accumulation of these metals alters soil physicochemical properties and increases the likelihood of heavy metal uptake by crops cultivated on such soils [21]. Excessive long-term exposure to such staple vegetables through daily food consumption requires extensive health-risk analysis that can be used to formulate health policies and protection strategies. Additionally, the relationship between socioeconomic factors and soil contamination highlights the general urban-planning issues and lack of a proper resource distribution, especially in Nigeria, where

the environment management policies and recovery solutions are limited. The physiological impacts of heavy metal exposure on the plants are complex, especially regarding amino acid metabolizing processes, thus urgently compelling a scrupulous questioning of the implications involved in urban food contamination [42]. The urban environment with its heavy industry and large traffic load further increases the load on the environment because of increased deposition of heavy metals in the soils [9]. Combining the efforts to respond to this messy issue, both short-term response to public-health mitigation and long-term development of sustainable urban agricultural operations should be given [81].

Despite documented risks in Nigerian urban agricultural settings, significant knowledge gaps remain regarding holistic measures of growth- performance in soils polluted with heavy metals and elaborate health-risk assessment peculiar to automobile-works pollution. This study addresses critical knowledge gaps at the intersection of urban environmental health and food security in rapidly urbanizing Nigerian cities. The findings will: (1) provide baseline data on automobile workshop impacts on soil-crop systems, (2) inform urban planning policies regarding spatial separation between industrial activities and agricultural land use, (3) guide food safety recommendations for vegetables grown in contaminated urban environments, (4) contribute to evidence-based risk assessment frameworks for low- and middle-income countries where urban agriculture is expanding, and (5) support development of targeted soil remediation and crop selection strategies for contaminated sites in Nigeria. This study aims to: (1) assess soil physicochemical properties and heavy metal concentrations in automobile workshop soils of varying operational duration in Ado-Ekiti, Nigeria, (2) quantify metal bioaccumulation in *A. hybridus* and *O. gratissimum* under controlled greenhouse conditions, (3) evaluate growth responses and physiological impacts on these commonly consumed vegetables, and (4) conduct standardized non-carcinogenic and carcinogenic health risk assessment for adult and child populations in Nigeria.

2 Materials and methods

2.1 Study site and experimental setup

Soil samples were collected from two automobile workshops located within Ado-Ekiti, Ekiti State, southwestern Nigeria. The approximate geographical coordinates of the study area are 7°15′N latitude and 5°12′E longitude. Workshop A has been operational for approximately 20 years, while Workshop B has been operational for about 10 years, representing different durations of exposure to contamination. These sites were selected based on long-term automobile repair activities involving disposal of spent engine oil, battery residues, and metal scraps, which are recognized sources of heavy metal contamination in urban soils. Soil samples were collected from unpaved working areas where direct contact with automotive fluids and metal particles occurs during repair activities. No petroleum was visibly observed in the collected soil samples; however, the presence of hydrocarbons cannot be entirely excluded. The workshops handle an average of 15–25 vehicles daily, primarily involving oil changes, battery replacements, and general mechanical repairs. Although a reference soil from a non-industrial area was initially assessed to establish background soil characteristics, experimental cultivation and subsequent analyses focused solely on soils obtained from the two automobile workshops due to the study's emphasis on contamination effects. This controlled environment

minimized external variables such as direct sunlight, wind, and weather fluctuations that could affect experimental reproducibility [60]. The total study duration, from soil collection to plant harvest, was approximately 10 weeks, comprising pre-experiment soil characterization (2 weeks), pot establishment and germination (1 week), and a five-week growth period post-thinning.

2.2 Plant materials

Seeds of *Amaranthus hybridus* and *Ocimum gratissimum* were obtained from the Seed Bank Department, Ondo State Ministry of Agriculture, Akure, Nigeria and species authentication was performed at the university herbarium. Proper authentication ensures that observed variations in growth performance and metal uptake can be accurately attributed to the target species [26]. Prior to sowing, seeds were pre-soaked in distilled water for 24 h to enhance germination uniformity. After germination (approximately 7 days), seedlings were acclimatized under screen-house conditions for one week before thinning to five plants per pot, allowing physiological adjustment to the experimental soil conditions.

2.3 Soil collection and preparation

At each automobile workshop, five soil subsamples were collected at a depth of 0–10 cm using a stainless-steel auger. The subsamples were composited to obtain a representative sample for each site, a procedure commonly adopted in soil contamination studies to minimize spatial variability. The collected soils were air-dried at room temperature, gently crushed, and passed through a 2 mm sieve to remove debris and stones before laboratory analyses. Processed samples were stored in clean polyethylene bags to prevent contamination prior to physicochemical and heavy metal analyses [23].

2.4 Experimental design

A completely randomized design (CRD) was employed with the two soil samples and two plant species, replicated five times (n = 20 experimental units). Each experimental pot (30 cm diameter × 33 cm depth) contained 10 kg of the respective soil. Seeds were sown at a 1 cm depth and thinned to five plants per pot post-germination to minimize competition. Soil moisture was maintained at 60–70% field capacity through regular watering, monitored using gravimetric techniques [79].

2.5 Soil physicochemical analysis (pre-experiment characterization)

Prior to pot experiment establishment, soil physicochemical properties were analyzed to characterize baseline conditions. Soil pH was measured using a 1:2.5 soil-to-water suspension with a calibrated pH meter (Hanna HI9813-6) [15]. Organic carbon was determined by the Walkley-Black method, with organic matter calculated using a conversion factor of 1.724 [25]. Cation exchange capacity (CEC) was evaluated using the ammonium acetate saturation method at pH 7.0, and soil texture was determined by the hydrometer method following Bouyoucos procedures [44].

2.6 Heavy metal analysis

2.6.1 Sample preparation and digestion

Soil samples (1 g) were digested with 15 ml aqua regia (HNO_3:HCl, 3:1 v/v) at 80 °C for 2 h [40]. Plant tissues (leaves and stems) were oven-dried at 60 °C for 48 h, ground to fine powder, and digested using tri-acid mixture (HNO_3:H_2SO_4:$HClO_4$, 5:1:1 v/v/v) under similar heating conditions until clear solutions were obtained. Aqua regia digestion (HCl: HNO_3, 3:1 v/v) was employed following ISO 11466:1995 and USEPA Method 3050B protocols [32, 67]. This method extracts pseudo-total heavy metal concentrations, representing the environmentally mobile and potentially bioavailable fraction rather than total metal content. While complete dissolution (requiring hydrofluoric acid) would yield higher values, aqua regia digestion is widely accepted for environmental risk assessment as it targets the metals most relevant to plant uptake and human health exposure [40]. To ensure the accuracy of the analytical procedure, the WEPAL (Wageningen Evaluating Programmes for Analytical Laboratories) International Soil-analytical Exchange (ISE) sample 921 was used as a Certified Reference Material (CRM) [70]. The measured recovery rates for the aqua regia extractable elements were Cu 94.2%, Cd 96.8%, Cr 91.5%, Ni 93.7%, Mn 95.1%, and Pb 97.3%. These results confirm method reliability within the 90–110% acceptable range.

2.6.2 Metal quantification

Digested samples were filtered, diluted to 50 ml with deionized water, and analyzed for Cu, Cd, Cr, Ni, Mn, and Pb using Flame Atomic Absorption Spectrophotometry (FAAS, Buck Scientific 210 VGP). Instrument calibration was performed using certified standards with linearity coefficients (R^2) > 0.99 to ensure analytical accuracy [56].

2.6.3 Quality assurance and quality control (QA/QC)

Quality assurance and quality control (QA/QC) procedures were strictly followed to ensure the reliability and accuracy of heavy metal analyses. All glassware and digestion vessels were soaked in 10% nitric acid and rinsed with deionized water prior to use. Analytical blanks were included with each batch of samples to monitor potential contamination. Calibration of the Atomic Absorption Spectrophotometer (AAS) was performed using certified standard solutions, and calibration curves with correlation coefficients (R^2) greater than 0.99 were accepted.

Limits of detection (LOD) and limits of quantification (LOQ) for each metal were determined based on repeated measurements of blank samples. Recovery tests were conducted by spiking selected samples with known concentrations of metals, yielding recovery rates within the acceptable range of 90–110%. All measurements were carried out in triplicate, and mean values were reported to enhance analytical precision.

2.7 Bio-concentration factor (BCF)

The Bio-Concentration Factor (BCF) is fundamental to understanding the accumulation of heavy metals in plants relative to their soil sources. The BCF can be mathematically expressed as:

$$\mathrm{BCF} = \frac{C_v}{C_s} \tag{1}$$

where;

BCF = Bio-concentration factor (dimensionless).

Cv = Concentration of heavy metal in edible vegetable parts (mg kg^{-1}).

Cs = Concentration of heavy metal in soil (mg kg^{-1}).

2.8 Plant growth parameters and leaf chlorophyll content

Growth parameters were monitored weekly from 2weeks after planting (WAP) to six weeks post-planting. Plant height was measured from the soil surface to the apical bud using a measuring ruler. Leaf count was recorded, and leaf area was determined using a LI-3000 C meter (LI-COR, USA). At harvest, fresh biomass was weighed immediately, followed by dry weight determination after oven-drying at 70 °C for 48 h. Chlorophyll content was extracted using 80% acetone and quantified spectrophotometrically at 645 nm and 663 nm wavelengths [39].

2.8.1 Plant harvesting and sample processing

Plants were harvested at physiological maturity when vegetative growth plateaued and before flowering initiation. Harvesting was conducted in the morning (08:00–10:00 h) to minimize diurnal physiological variation. Entire plants were carefully uprooted, and adhering soil particles were removed by gentle washing with deionized water. Plants were separated into leaves and stems using stainless steel scissors.

Fresh weight was immediately recorded using an analytical balance (± 0.01 g precision). Tissue samples were then placed in clean paper bags and oven-dried at 60 °C for 48 h until constant weight was achieved (verified by weighing at 6-hour intervals). Dried samples were ground to a fine powder (< 0.5 mm particle size) using an agate mortar and pestle to prevent metal contamination from grinding equipment. Powdered samples were stored in clean, labeled polyethylene vials at room temperature in a desiccator until chemical analysis.

2.9 Health risk assessment

Health risk assessment was conducted using USEPA-approved models to evaluate potential risks from consuming vegetables grown in contaminated soils [29].

2.9.1 Estimated daily intake (EDI)

The major route of exposure for plants is the ingestion route, and this is calculated using the formula by Gebeyehu and Bayissa [29].

$$\mathrm{EDI} = \frac{\mathrm{E_f} \times \mathrm{E_d} \times \mathrm{F_{ir}} \times \mathrm{C_m} \times \mathrm{C_f} \times 0.001}{\mathrm{B}_w \times \mathrm{T_a}} \quad (2)$$

where E_f is exposure frequency (365/days/year), E_d is exposure period (60 years for an adult and 10 years for children), F_{ir} is average vegetable consumption (240/person/day for an adult and 120/person/day for children according to [72]), C_m is metal concentration, C_f is the concentration conversion factor for fresh vegetables (0.085), B_w is the average body weight for the adult population (70 kg for adults and 30 kg for children) and T_a is average exposure period (E_d 365 day/year) 365days ×60years which is 21900days. An adult body weight of 70 kg was adopted following WHO [72] standard assumptions,

consistent with health risk assessment frameworks applied in comparable Nigerian studies [7].

2.9.2 Non-carcinogenic risk assessment

The non-carcinogenic health risk was calculated using the target hazard quotient and hazard index, thus:

2.9.2.1 Target hazard quotient (THQ) The purpose of this calculation is to assess the non-carcinogenic health risk that eating leafy vegetables contaminated with heavy metals poses to humans. Using the following formula, it was determined as the ratio of an oral reference dosage of each metal to estimated daily metal consumption [66]:

$$THQ = \frac{EDI}{RfD} \tag{3}$$

EDI is the average daily metal consumption in mg/day/kg body weight, and RfD is the oral reference dosage values also in mg/kg/day, for each heavy metal of concern. The RfD values of Cu, Cd, Cr, Ni, Mn, and Pb are 0.037, 0.001, 0.003, 0.02, 0.14, and 0.0035 mg/kg/day, respectively [29]. THQ values < 1 are considered to have non-carcinogenic consequences, whereas values > 1 indicate a higher probability of non-carcinogenic effects [7]; U.S. EPA, 2001.

2.9.2.2 Hazard index (HI) This is calculated as the sum of all THQs estimated for specific heavy metals, and it is expressed as;

$$HI = \sum_{n=1}^{i} THQ_n;\ i = 1, 2, 3, ...n, \tag{4}$$

where HI is the sum of all the hazard quotients of the heavy metals. If HI < 1, there appears to be no discernible health effect. An HI > 1, on the other hand, implies the probability of a negative health outcome. HI > 1 has been associated with serious chronic health impacts (Alsafran et al., 2021).

2.9.3 Carcinogenic risk assessment

The estimated Cancer Risk (CR) to human health posed by each suspected carcinogenic metal was determined. We then calculated the total cancer risk (TCR) from metal ingestion, which may enhance carcinogenic effects based on the synergistic effect of exposure to all suspected carcinogenic metals.

$$\mathrm{CR} = \mathrm{EDI} \times \mathrm{C_{SF}} \tag{5}$$

$$TCR = \sum_{n=1}^{i} CR_n;\ i = 1, 2, 3, ...n, \tag{6}$$

where CR = cancer risk over a lifetime by individual heavy metal ingestion, EDI = estimated daily metal intake of the population in mg/day/kg body weight, C_{SF} = oral cancer slope factor in (mg/kg/day), and n is the number of heavy metals considered for cancer risk calculation. Cd, Cr, Ni, and Pb's CSF values are 0.38, 0.5, 1.7, and 0.0085 mg/kg/day, respectively. The acceptable carcinogenic risk ranges from 10^{-4} to 10^{-6} (USEPA, 2014).

2.10 Statistical analysis

Before analysis, data were tested for normality using the Shapiro-Wilk test and for homogeneity of variance using Levene's test to confirm the assumptions of parametric analysis [33]. Data analysis was then performed using SPSS version 20. Treatment differences were evaluated using one-way ANOVA followed by Duncan's Multiple Range Test (DMRT) for post hoc comparisons. Statistical significance was set at $p < 0.05$. Results are presented as mean ± standard error of the mean (SEM). Pearson correlation analysis was performed to assess relationships between soil and plant metal concentrations.

3 Results

3.1 Soil physicochemical properties and heavy metal concentration

The physicochemical properties and heavy metal concentrations of soils collected from the two automobile workshops are presented in Table 1. Workshop A (Soil A) has been operational for approximately 20 years, while Workshop B (Soil B) has been operational for approximately 10 years, reflecting different durations of heavy metal input into the soil. Soil A exhibited a slightly acidic pH (6.5 ± 0.1), which was significantly lower than that of Soil B (6.8 ± 0.1; $p < 0.05$). The average pH of agricultural soils in the study area ranges from 6.8 to 7.2 (slightly acidic to neutral). The measured pH of Soil A (6.5 ± 0.1) is notably lower than the local agricultural soil average, while Soil B (6.8 ± 0.1) falls within the typical range. The acidic condition of Soil A may enhance the mobility and bioavailability of heavy metals. Soil B was near neutral, indicating a comparatively shorter contamination history. One of the most acidic values was observed in Soil A with a pH of 6.5 ± 0.1 (Table 1), proving that battery acids and motor oils can reduce the pH of the soil and promote the mobility of heavy metals in it. Soil B (6.8 ± 0.1) was a near-neutral soil, indicating a shorter period of contamination. Organic matter content was significantly higher in Soil A (4.5 ± 0.2%) than in Soil B (3.8 ± 0.2%; $p < 0.05$). Similarly, cation exchange capacity (CEC) was higher in Soil A (18 ± 0.9 meq 100 g^{-1}) compared to Soil B (15 ± 0.8 meq 100 g^{-1}), reflecting greater metal retention potential in Soil A. Heavy metal concentrations varied between the two workshop soils (Table 1). Soil A exhibited higher concentrations of manganese (Mn: 29.55 ± 0.050 mg kg^{-1}), copper (Cu: 0.935 ± 0.003 mg kg^{-1}), and cadmium (Cd: 0.251 ± 0.001 mg kg^{-1}) compared to Soil B (Mn: 15.40 ± 0.040 mg kg^{-1}, Cu: 0.708 ± 0.002 mg kg^{-1}, Cd: 0.036 ± 0.001 mg kg^{-1}). Conversely, chromium (Cr) concentration was higher in Soil B (1.456 ± 0.003 mg kg^{-1}) than in Soil A (0.603 ± 0.002 mg kg^{-1}). Lead (Pb) and nickel (Ni) concentrations were higher in Soil A (0.311 ± 0.002 and 0.183 ± 0.002 mg kg^{-1}, respectively) compared to Soil B (0.061 ± 0.001

Table 1 Physicochemical properties and pseudo-total heavy metal concentrations (mg kg^{-1}) of soil samples from two automobile workshops

Elements	Soil A	Soil B
Organic matter (%)	4.5 ± 0.2	3.8 ± 0.2
CEC (meq 100 g^{-1})	18 ± 0.9	15 ± 0.8
pH	6.5 ± 0.1	6.8 ± 0.1
Texture	Sandy loam	Loamy sand
Cd	0.251 ± 0.001	0.036 ± 0.001
Cr	0.603 ± 0.002	1.456 ± 0.003
Cu	0.935 ± 0.003	0.708 ± 0.002
Mn	29.55 ± 0.050	15.40 ± 0.040
Ni	0.183 ± 0.002	0.004 ± 0.001
Pb	0.311 ± 0.002	0.061 ± 0.001

Table 2 Heavy metal concentrations (mg kg^{-1}) in the edible parts of *A. hybridus* and *O. gratissimum*

Soil	Samples	Heavy metals					
		Cu	Cd	Cr	Ni	Mn	Pb
SOIL A	A L	0.099 ± 0.002	0.011 ± 0.001	0.030 ± 0.000	0.022 ± 0.002	0.039 ± 0.001	0.019 ± 0.001
	A S	0.111 ± 0.001	0.020 ± 0.000	0.033 ± 0.001	0.042 ± 0.001	0.062 ± 0.002	0.046 ± 0.001
	O L	0.078 ± 0.001	0.010 ± 0.000	0.029 ± 0.002	0.031 ± 0.001	0.053 ± 0.001	0.020 ± 0.001
	O S	0.066 ± 0.004	0.015 ± 0.001	0.041 ± 0.001	0.027 ± 0.001	0.068 ± 0.002	0.029 ± 0.001
SOIL B	A L	0.085 ± 0.003	0.014 ± 0.001	0.028 ± 0.001	0.026 ± 0.002	0.042 ± 0.001	0.025 ± 0.002
	A S	0.120 ± 0.002	0.018 ± 0.001	0.034 ± 0.002	0.038 ± 0.002	0.058 ± 0.002	0.031 ± 0.001
	O L	0.090 ± 0.002	0.012 ± 0.001	0.027 ± 0.001	0.030 ± 0.001	0.047 ± 0.001	0.022 ± 0.002
	O S	0.075 ± 0.003	0.017 ± 0.001	0.039 ± 0.002	0.029 ± 0.002	0.060 ± 0.002	0.027 ± 0.001

BDL Below detection level, *ALAmaranthus hybridus* leaves, *AS Amaranthus hybridus* stem, *OLOcimum gratissimum* leaves, *OSOcimum gratissimum* stem

Values are mean ± SEM (n=5)

Table 3 Pearson correlation coefficients between soil and plant metal concentrations

Metal	A. hybridus (*r*)	O. gratissimum (*r*)	Significance
Cd	0.82	0.74	$P < 0.01$
Cr	0.45	0.39	$P < 0.05$
Cu	0.76	0.68	$P < 0.01$
Mn	0.79	0.72	$P < 0.01$
Ni	0.71	0.63	$P < 0.01$
Pb	0.84	0.77	$P < 0.01$

r = Pearson correlation coefficient; $n = 10$ (5 replicates × 2 tissues)

and 0.004 ± 0.001 mg kg^{-1}, respectively). Of the metals analyzed, only manganese (Mn) recorded concentrations that were relatively elevated compared to typical background levels in Nigerian agricultural soils, while all other metals remained comparatively low. These concentration patterns reflect differences in workshop operational duration and specific repair activities conducted at each site.

3.2 Heavy metal concentration and bioconcentration in edible parts (stem and leaves) of *A. hybridus* and *O. gratissimum*

There is a correlation between the concentration of heavy metals in plant tissues (mg kg^{-1}) and contamination in the underlying soil, as indicated in Tables 2 and 3. The highest loads of copper (Cu; 0.935 ppm) and cadmium (Cd; 0.251 ppm) were found in soil A, which recorded an acidic pH and had a greater share of organic content. In comparison, the concentration of metals in Soil B was lower. These trends confirm the influence of the properties of the soil, namely pH and organic matter, on metal bioavailability; in Soil A, an acidic pH and high quality of organic matter foster better plant uptake [37]. Heavy metal concentrations in the edible parts of *Amaranthus hybridus* and *Ocimum gratissimum* which are shown in Table 2. Metal concentrations varied significantly among plant species, tissues, and soil types ($p < 0.05$). In both soils, stem tissues accumulated higher metal concentrations than leaves. *A. hybridus* generally exhibited higher concentrations of Cd, Pb, and Ni than *O. gratissimum*. Bioconcentration factor (BCF) values (Table 4) were generally below unity, indicating limited bioaccumulation. However, unusually high BCF values for Ni in Soil B resulted from the extremely low soil Ni concentration (0.004 mg kg^{-1}), which is likely close to the analytical detection limit. These elevated BCF values therefore represent a mathematical artefact rather than enhanced biological accumulation. The accumulation of metal differed in various species and tissues of plants,

Table 4 Bioconcentration factor (BCF) of selected heavy metals in leaves and stems of *A. hybridus* and *O. gratissimum* cultivated on soils from automobile workshops A and B

Metals	SOIL A				SOIL B			
	AL	AS	OL	OS	AL	AS	OL	OS
Cd	0.044	0.080	0.040	0.060	0.389	0.500	0.333	0.325
Cr	0.050	0.055	0.048	0.068	0.019	0.023	0.019	0.027
Cu	0.106	0.119	0.083	0.071	0.120	0.170	0.127	0.106
Mn	0.001	0.002	0.002	0.002	0.003	0.004	0.003	0.004
Ni	0.120	0.230	0.169	0.148	6.500	9.500	7.500	7.250
Pb	0.061	0.148	0.064	0.093	0.410	0.443	0.360	0.443

BCF values are calculated as the ratio of plant tissue to pseudo-total soil metal concentration

Values represent dimensionless ratios

BDL Below detection level, *AL* Amaranthus hybridus leaves, *AS* Amaranthus hybridus stem, *OL* Ocimum gratissimum leaves, *OS* Ocimum gratissimum stem

therefore, demonstrating the multilateral dynamics between soil chemistry, plant physiology, and external conditions, including the availability of nutrients, that altogether can affect the accumulation of heavy metals [59, 77]. Pearson correlation analysis revealed significant positive relationships between soil and plant metal concentrations for all metals examined (Table 3). Cadmium (Cd) and lead showed the strongest correlations (r = 0.82 and 0.84 for *A. hybridus*, respectively), while Chromium (Cr) exhibited the weakest association (r = 0.45).

3.3 Plant growth parameters and leaf chlorophyll content

During a five-week observation period, *A. hybridus* consistently exceeded *O. gratissimum* in height across both soil types. By the 6th WAP, *A. hybridus* averaged 54.44 cm in Soil A and 53.76 cm in Soil B, whereas *O. gratissimum* recorded 45.64 cm and 42.28 cm, respectively. Plant height differed significantly between species ($p < 0.05$), with *A. hybridus* consistently taller than *O. gratissimum* across both soils during the six-week growth period (Table 5). Although Soil A contained higher organic matter, growth variability and reduced chlorophyll content indicate that metal stress limited the positive effects of nutrient availability.

In terms of leaf production, *A. hybridus* produced more leaves than *O. gratissimum*, with significant leaf counts observed in Soil A. Observations on leaf area reversed this trend, with *O. gratissimum* exhibiting larger leaf areas, suggesting that moderate soil contamination may negatively influence leaf development more severely than heavier contamination. Measurements of the chlorophyll content showed that chlorophyll levels in Soil B were high, and the amount of chlorophyll maintained in Soil A was reduced as a result of metal stress. The results summarized in Table 5 prove the significance of heavy metal stress and plant physiological factor relationships and show how chlorophyll alleviates heavy metal-induced oxidative stress.

3.4 Health risk assessment

3.4.1 Estimated daily intake (EDI)

Estimated daily intake (EDI) values for all metals were higher in children than in adults due to lower body weight assumptions (Table 5). Cadmium and lead contributed most to dietary exposure; however, all EDI values remained below their respective reference doses, indicating no immediate health concern [2, 35]. As opposed to Soil B, the EDI of chromium (Cr) and manganese (Mn) were both increased by Soil A, although, in

Table 5 Growth parameters and leaf chlorophyll content of *A. hybridus* and *O. gratissimum* cultivated on soils from automobile workshops A and B

Growth parameters	Weeks after planting	Amaranthus hybridus		Ocimum gratissimum	
		SOIL A	SOIL B	SOIL A	SOIL B
Plant height (cm)	2	21.93 ± 2.97^{b}	18.63 ± 1.69^{b}	14.14 ± 3.47^{a}	13.46 ± 2.47^{a}
	3	28.16 ± 6.78^{a}	24.47 ± 4.53^{a}	21.84 ± 4.96^{a}	19.30 ± 6.48^{a}
	4	40.30 ± 13.27^{a}	37.17 ± 7.59^{a}	33.10 ± 6.95^{a}	29.80 ± 5.36^{a}
	5	45.30 ± 15.67^{a}	44.87 ± 8.88^{a}	38.35 ± 6.86^{a}	33.11 ± 4.83^{a}
	6	54.44 ± 19.37^{a}	53.76 ± 8.81^{a}	45.64 ± 8.30^{a}	42.28 ± 5.63^{a}
Number of leaves	2	11.67 ± 3.18^{a}	8.67 ± 2.19^{a}	8.33 ± 0.88^{a}	6.67 ± 0.67^{a}
	3	20.33 ± 5.21^{a}	13.00 ± 2.08^{a}	10.67 ± 1.67^{a}	9.33 ± 1.33^{a}
	4	27.00 ± 6.35^{a}	18.33 ± 2.60^{a}	13.67 ± 0.67^{b}	10.67 ± 0.67^{a}
	5	29.00 ± 6.66^{a}	16.33 ± 3.71^{a}	15.00 ± 0.58^{b}	12.00 ± 1.15^{ab}
	6	33.33 ± 7.06^{a}	22.67 ± 4.33^{a}	16.00 ± 1.15^{a}	14.00 ± 1.15^{a}
Leaf area (cm^2)	2	3.40 ± 1.04^{a}	2.39 ± 0.69^{a}	2.53 ± 1.14^{a}	2.58 ± 0.63^{a}
	3	4.27 ± 1.76^{a}	3.52 ± 0.67^{a}	4.90 ± 1.94^{a}	4.55 ± 1.68^{a}
	4	4.34 ± 1.84^{a}	3.71 ± 0.74^{a}	7.44 ± 1.69^{a}	6.76 ± 2.14^{a}
	5	4.44 ± 1.88^{a}	3.80 ± 0.94^{a}	7.82 ± 1.54^{b}	7.35 ± 1.96^{b}
	6	4.45 ± 1.67^{a}	4.01 ± 0.82^{a}	9.67 ± 2.49^{b}	8.62 ± 1.84^{ab}
Biomass	Fresh weight (g)	2.49 ± 0.01^{b}	2.46 ± 0.00^{a}	2.49 ± 0.01^{b}	2.38 ± 0.01^{a}
	Dry weight (g)	0.50 ± 0.58^{a}	0.43 ± 0.01^{a}	0.54 ± 0.00^{b}	0.40 ± 0.01^{a}
Leaf chlorophyll	a (mg/g)	1.94 ± 0.01^{a}	5.89 ± 0.01^{b}	1.76 ± 0.00^{a}	3.65 ± 0.01^{b}
	b (mg/g)	10.47 ± 0.01^{b}	7.91 ± 0.01^{a}	9.87 ± 0.01^{b}	8.23 ± 0.01^{a}

Each value is a mean ± standard error of five replicates. Means followed by the same letter along the column are not significantly different (P > 0.05) using Duncan's Multiple Range Test

both cases, the increase was associated with both the elevated soil concentrations [2, 13] and a higher bioavailability [2]. Such different trends in bioaccumulation of metals indicate the inherent character of the soils and variations in metal speciation, but further methodical studies need to be carried out to explain these differences in detail. Specifically, cadmium and lead have the most severe levels of health hazard, as shown by the pronounced higher bioaccumulation factors (BCFs) in the Soil B, a measure indicative of increased mobility and uptake, thus, the increased risk of chronic health outcomes outcomes [62]. All together, these data, summarized in Table 6, represent the urgency of the necessity to maintain the surveillance and risk-assessment of heavy metals intake through contaminated plants in agricultural systems [14, 34].

3.4.2 Non-carcinogenic risk assessment

The target hazard quotient (THQ) model has provided very useful information on the possible health risk posed by the consumption of the crops of *Amaranthus hybridus* and *Ocimum gratissimum*, which were cultivated in the polluted soils. The results indicate that the risk profiles differ markedly by heavy metal and by crop component. Copper (Cu) exhibited a low-risk profile: THQ values for *O. gratissimum* stems from Soil A ranged from 6.06×10^{-4} for children to 2.46×10^{-4} for adults, whereas those for *A. hybridus* stems from Soil B were 1.10×10^{-3} for children and 1.62×10^{-3} for adults. The research findings concur with the established essentiality of Cu under low exposure levels [65]. All THQ and HI values were below the USEPA threshold of 1 (Table 7), indicating low non-carcinogenic risk for both adults and children. Although Cd and Pb showed relatively higher THQ contributions, particularly among children, the cumulative hazard index (HI) values (0.008–0.017) remained within acceptable limits. Cadmium (Cd), well-known for its renal effects, especially in children, is a concern at the elevated THQ levels

Table 6 Estimated daily intake (EDI) of selected heavy metals in the edible parts of *A. hybridus* and *O. gratissimum* harvested from Soil A and Soil B

Metals	Children				Adult			
	A. hybridus		*O. gratissimum*		*A. hybridus*		*O. gratissimum*	
	leaves	stem	leaves	stem	leaves	stem	leaves	stem
Soil A								
Cd	3.74×10^{-6}	6.80×10^{-6}	3.40×10^{-6}	5.10×10^{-6}	3.21×10^{-6}	5.83×10^{-6}	2.91×10^{-6}	4.37×10^{-6}
Cr	1.02×10^{-5}	1.12×10^{-5}	9.86×10^{-6}	1.39×10^{-5}	8.74×10^{-6}	9.62×10^{-6}	8.45×10^{-6}	1.19×10^{-5}
Cu	3.37×10^{-5}	3.77×10^{-5}	2.65×10^{-5}	2.24×10^{-5}	2.89×10^{-5}	3.23×10^{-5}	2.27×10^{-5}	1.92×10^{-5}
Mn	1.33×10^{-5}	2.11×10^{-5}	1.80×10^{-5}	2.31×10^{-5}	1.14×10^{-5}	1.81×10^{-5}	1.54×10^{-5}	1.98×10^{-5}
Ni	7.48×10^{-6}	1.43×10^{-5}	1.05×10^{-5}	9.18×10^{-6}	6.41×10^{-6}	1.22×10^{-5}	9.03×10^{-6}	7.87×10^{-6}
Pb	6.46×10^{-6}	1.56×10^{-5}	6.80×10^{-6}	9.86×10^{-6}	5.54×10^{-6}	1.34×10^{-5}	5.83×10^{-6}	8.45×10^{-6}
Soil B								
Cd	4.76×10^{-6}	6.12×10^{-6}	4.08×10^{-6}	5.78×10^{-6}	4.08×10^{-6}	5.25×10^{-6}	3.50×10^{-6}	4.95×10^{-6}
Cr	9.52×10^{-6}	1.16×10^{-5}	9.18×10^{-6}	1.33×10^{-5}	8.16×10^{-6}	9.91×10^{-6}	7.87×10^{-6}	1.14×10^{-5}
Cu	2.89×10^{-5}	4.08×10^{-5}	3.06×10^{-5}	2.55×10^{-5}	2.48×10^{-5}	3.50×10^{-5}	2.62×10^{-5}	2.19×10^{-5}
Mn	1.43×10^{-5}	1.97×10^{-5}	1.60×10^{-5}	2.04×10^{-5}	1.22×10^{-5}	1.69×10^{-5}	1.37×10^{-5}	1.75×10^{-5}
Ni	8.84×10^{-6}	1.29×10^{-5}	1.02×10^{-5}	9.86×10^{-6}	7.58×10^{-6}	1.11×10^{-5}	8.74×10^{-6}	8.45×10^{-6}
Pb	8.50×10^{-6}	1.05×10^{-5}	7.48×10^{-6}	9.18×10^{-6}	7.29×10^{-6}	9.03×10^{-6}	6.41×10^{-6}	7.87×10^{-6}

Table 7 Target hazard quotient (THQ) and hazard index (HI) of selected heavy metals from Plant Parts in Soil A and B respectively

Metals	Child				Adult			
	A. hybridus		*O. gratissimum*		*A. hybridus*		*O. gratissimum*	
	leaves	stem	leaves	stem	leaves	Stem	leaves	stem
Soil A								
Cd	3.74×10^{-3}	6.80×10^{-3}	3.40×10^{-3}	5.10×10^{-3}	3.21×10^{-3}	5.83×10^{-3}	2.91×10^{-3}	4.37×10^{-3}
Cr	3.40×10^{-3}	3.74×10^{-3}	3.29×10^{-3}	4.65×10^{-3}	2.91×10^{-3}	3.21×10^{-3}	2.82×10^{-3}	3.98×10^{-3}
Cu	9.10×10^{-4}	1.02×10^{-3}	7.17×10^{-4}	6.06×10^{-4}	7.80×10^{-4}	8.74×10^{-4}	6.14×10^{-4}	5.20×10^{-4}
Mn	9.47×10^{-5}	1.51×10^{-4}	1.29×10^{-4}	1.65×10^{-4}	8.12×10^{-5}	1.29×10^{-4}	1.10×10^{-4}	1.42×10^{-4}
Ni	3.74×10^{-4}	7.14×10^{-4}	5.27×10^{-4}	4.59×10^{-4}	3.21×10^{-4}	6.12×10^{-4}	4.52×10^{-4}	3.93×10^{-4}
Pb	1.85×10^{-3}	4.47×10^{-3}	1.94×10^{-3}	2.82×10^{-3}	1.58×10^{-3}	3.83×10^{-3}	1.67×10^{-3}	2.42×10^{-3}
HI	$\mathbf{1.04\times10^{-2}}$	$\mathbf{1.69\times10^{-2}}$	$\mathbf{1.00\times10^{-2}}$	$\mathbf{1.38\times10^{-2}}$	$\mathbf{8.88\times10^{-3}}$	$\mathbf{1.45\times10^{-2}}$	$\mathbf{8.57\times10^{-3}}$	$\mathbf{1.18\times10^{-2}}$
Soil B								
Cd	4.76×10^{-3}	6.12×10^{-3}	4.08×10^{-3}	5.78×10^{-3}	4.08×10^{-3}	5.25×10^{-3}	3.51×10^{-3}	4.95×10^{-3}
Cr	3.17×10^{-3}	3.85×10^{-3}	3.06×10^{-3}	4.42×10^{-3}	2.72×10^{-3}	3.30×10^{-3}	2.62×10^{-3}	3.79×10^{-3}
Cu	7.81×10^{-4}	1.10×10^{-3}	8.27×10^{-4}	6.89×10^{-4}	6.69×10^{-4}	9.45×10^{-4}	7.09×10^{-4}	5.91×10^{-4}
Mn	1.02×10^{-4}	1.41×10^{-4}	1.14×10^{-4}	1.46×10^{-4}	8.74×10^{-5}	1.21×10^{-4}	9.78×10^{-5}	1.25×10^{-4}
Ni	4.42×10^{-4}	6.46×10^{-4}	5.10×10^{-4}	4.93×10^{-4}	3.79×10^{-4}	5.54×10^{-4}	4.37×10^{-4}	4.23×10^{-4}
Pb	2.43×10^{-3}	3.01×10^{-3}	2.14×10^{-3}	2.62×10^{-3}	2.08×10^{-3}	2.58×10^{-3}	1.83×10^{-3}	2.25×10^{-3}
HI	$\mathbf{1.17\times10^{-2}}$	$\mathbf{1.49\times10^{-2}}$	$\mathbf{1.07\times10^{-2}}$	$\mathbf{1.42\times10^{-2}}$	$\mathbf{1.00\times10^{-2}}$	$\mathbf{1.28\times10^{-2}}$	$\mathbf{9.21\times10^{-3}}$	$\mathbf{1.21\times10^{-2}}$

HI Hazard index

[73]. Although the sum of THQ for Cd is not above the risk threshold, the high values should still be discussed.

Chromium (Cr) exhibited modest total hazard quotients (THQs) in this study, with maximum values of 4.65×10^{-3} for children and 3.98×10^{-3} for adults associated with *O. gratissimum* stems harvested from Soil A. Despite such THQs, there is a high chance that the toxicity potential of Cr may arise due to its ability to convert to Chromium VI, which is proven to be more toxic. On the other hand, Nickel (Ni) and Manganese (Mn) demonstrated lower THQs, with.

Table 8 Carcinogenic risk (CR) and Total carcinogenic risk (TCR) of selected heavy metals in the edible parts of *A. hybridus* and *O. gratissimum* harvested from Soil A and Soil B

Metal	Children				Adult			
	A. hybridus		*O. gratissimum*		*A. hybridus*		*O. gratissimum*	
	Leaves	stem	leaves	stem	leaves	stem	leaves	stem
Soil A								
Cd	1.42×10^{-6}	2.58×10^{-6}	1.29×10^{-6}	1.94×10^{-6}	1.22×10^{-6}	2.21×10^{-6}	1.11×10^{-6}	1.66×10^{-6}
Cr	5.10×10^{-6}	5.61×10^{-6}	4.93×10^{-6}	6.97×10^{-6}	4.37×10^{-6}	4.81×10^{-6}	4.23×10^{-6}	5.97×10^{-6}
Cu	–		–	–	–	–	–	–
Mn	–	–	–	–	–	–	–	–
Ni	1.27×10^{-5}	2.43×10^{-5}	1.79×10^{-5}	1.56×10^{-5}	1.09×10^{-5}	2.08×10^{-5}	1.54×10^{-5}	1.34×10^{-5}
Pb	5.49×10^{-8}	1.33×10^{-7}	5.78×10^{-8}	8.38×10^{-8}	4.71×10^{-8}	1.14×10^{-7}	4.95×10^{-8}	7.18×10^{-8}
TCR	$\mathbf{1.93\times10^{-5}}$	$\mathbf{3.26\times10^{-5}}$	$\mathbf{2.42\times10^{-5}}$	$\mathbf{2.46\times10^{-5}}$	$\mathbf{1.65\times10^{-5}}$	$\mathbf{2.79\times10^{-5}}$	$\mathbf{2.07\times10^{-5}}$	$\mathbf{2.11\times10^{-5}}$
Soil B								
Cd	1.81×10^{-6}	2.33×10^{-6}	1.55×10^{-6}	2.20×10^{-6}	1.55×10^{-6}	1.99×10^{-6}	1.33×10^{-6}	1.88×10^{-6}
Cr	4.76×10^{-6}	5.78×10^{-6}	4.59×10^{-6}	6.63×10^{-6}	4.08×10^{-6}	4.95×10^{-6}	3.93×10^{-6}	5.68×10^{-6}
Cu	–		–	–	–	–	–	–
Mn	–	–	–	–	–	–	–	-–
Ni	1.50×10^{-5}	2.20×10^{-5}	1.73×10^{-5}	1.68×10^{-5}	1.29×10^{-5}	1.88×10^{-5}	1.49×10^{-5}	1.44×10^{-5}
Pb	7.23×10^{-8}	8.96×10^{-8}	6.36×10^{-8}	7.80×10^{-8}	6.19×10^{-8}	7.68×10^{-8}	5.45×10^{-8}	6.69×10^{-8}
TCR	$\mathbf{2.17\times10^{-5}}$	$\mathbf{3.02\times10^{-5}}$	$\mathbf{2.35\times10^{-5}}$	$\mathbf{2.57\times10^{-5}}$	$\mathbf{1.86\times10^{-5}}$	$\mathbf{2.59\times10^{-5}}$	$\mathbf{2.02\times10^{-5}}$	$\mathbf{2.20\times10^{-5}}$

TCR Total carcinogenic risk

all values being below the limit of 1 in all modes of exposure, so the non-cancer hazard to health would be insignificant. However, in vulnerable groups, Ni can be the cause of an allergic reaction through long-term direct exposure [71]. Lead (Pb) yielded the highest THQs, reaching 4.47×10^{-3} for children and 4.04×10^{-3} for adults (Table 7). Consuming *A. hybridus* stems from Soil A reflects elevated neurotoxicity concerns, particularly for children. The harmful impacts of Pb on neurodevelopment highlight the extreme significance of measuring exposure and the necessary remedial measures.

The cumulative hazard index (HI) ranged from 8.57×10^{-3} (adults consuming *O. gratissimum* leaves, Soil A) to 1.69×10^{-2} (*A. hybridus* stems, Soil A children). Although these values of HI are significantly lower than the critical 1 threshold and show that there is a low level of overall non-carcinogenic risk, values close to 0.01–0.02 should be given special attention, in particular, regarding the possible synergies of exposures to several metals at the same time. It can be concluded that in the current analysis, the values of both Cu and Ni indicate the presence of a very low level of risk as compared to the results of the other two metals, Cd and Pb, where THQs are significantly higher, indicating the necessity to pay more attention to non-carcinogenic risks, especially among children.

3.4.3 Carcinogenic risk assessment

The carcinogenic risk (CR) was analyzed, and the results, as shown in Table 8, said that cadmium (Cd) had the highest CR of stems of *Amaranthus hybridus* in Soil A, with the value of 2.58×10^{-6} in children and 2.21×10^{-6} in adults. The major driver of this risk is the high values of estimated daily intake (EDI) (6.80×10^{-6} mg/kg/day) and cancer slope factor (CSF) of 0.38 mg/kg/day [45]. Conversely, chromium (Cr) CR similarly peaked in the stems of *Ocimum gratissimum* from Soil A, though the variability in soil metal content is noted, with lower values in Soil B. Nickel (Ni) displayed a significantly higher CR in *A. hybridus*, nearly reaching the risk threshold of 1×10^{-4}, suggesting a major carcinogenic concern, especially for children [28]. The smaller CR of lead (Pb) does not mean

that the metal does not contribute to the cumulative risk load of exposure to heavy metals [10].

The total carcinogenic risk (TCR) values (Table 8), which were determined by summing up the CRs of the said metals, varied between 1.65×10^{-5} and 3.26×10^{-5}. Notably, the TCR for *A. hybridus* stems from Soil A which significantly surpassed that of Soil B, indicating higher contamination levels, consistent with findings in similar studies [54]. Every value of TCR was under the level of acceptable risk when it comes to federal guidelines promoted by USEPA, which is 1×10^{-4}, but close to potential hazards, especially those that are related to a pediatric population, illustrating the necessity to conduct further monitoring and risk mitigation measures [61].

4 Discussion

4.1 Soil physicochemical properties and heavy metal concentration

Bioavailability of heavy metals in soil is strongly influenced by soil physicochemical properties, which in turn regulate plant uptake and potential entry into the food chain. In the present study, Soil A exhibited a slightly acidic pH (6.5 ± 0.1), which favors increased solubility and mobility of metals such as cadmium (Cd), lead (Pb), and nickel (Ni), thereby enhancing their availability to plant roots [19, 59]. These conditions are particularly relevant in urban agricultural settings, including Nigerian cities, where cultivation often occurs on marginal or contaminated land due to limited space [49]. The higher organic matter content measured in Soil A (4.5 ± 0.2%) may have contributed to enhanced retention of metals through complexation processes, thereby influencing their availability over time. While organic matter can temporarily reduce metal mobility, its capacity to retain metals within the soil matrix may sustain long-term exposure potential under continuous cultivation [63, 76].

Cation exchange capacity (CEC) further modulated metal behavior in the studied soils. The higher CEC recorded in Soil A (18 ± 0.9 meq 100 g^{-1}) compared with Soil B indicates a greater capacity to retain exchangeable metal ions, which may enhance their availability for plant uptake under favorable conditions. This interaction between CEC and metal mobility highlights the importance of soil management strategies aimed at mitigating metal exposure [16, 20, 30, 49]. The effects of accumulation of heavy metals go beyond the health of plants to human health and sustainability of the environment: the presence of heavy metals in food crops is extremely dangerous as they can have severe impacts on human health, not to mention the threat of kidney diseases, neurotoxicity, and the risk of getting cancer due to long-term exposure. Li et al., [41], Yao, [78]. Contaminated sites associate with urban agriculture need urgent remediation in order to preserve the purity of food and the health of the population because the issue of pollution by heavy metals is a complex process and depends on farming activities, the use of wastewater to irrigate land, and the close presence of industry [3, 20, 30]. The remediation that will serve as effective health soil management or rather good urban planning should entail the establishment of additional food production systems through sound planning [22, 80].

It should be noted that the aqua regia digestion method employed in this study extracts pseudo-total rather than complete total heavy metal content. While this approach aligns with standard environmental assessment protocols (ISO 11466:1995), it may underestimate absolute soil metal concentrations compared to complete acid digestion methods. However, pseudo-total extraction is more relevant for bioavailability and

risk assessment purposes, as it represents the environmentally mobile fraction accessible to plant roots [40, 74, 75]. Our measured values reflect bioavailable metals rather than geochemically bound fractions. Additionally, soil samples were sieved to a 2 mm fraction following standard agricultural soil protocols. While finer fractions (< 0.2 mm) would provide more precise total metal quantification, the 2 mm fraction better represents field conditions and agronomic relevance for pot experiments simulating actual cultivation practices [60]. Comparisons with literature values should consider methodological differences. Studies reporting higher concentrations may have employed complete acid digestion or finer particle fractions, while our pseudo-total values specifically represent environmentally relevant, bioavailable metal pools.

The higher metal concentrations in Soil A compared to Soil B are primarily attributable to the longer operational history of Workshop A (20 years vs. 10 years). Prolonged and repeated exposure to automotive waste streams, including spent engine oil, battery acid, brake fluid, and corroded metal parts, leads to cumulative metal deposition over time. Battery acid contributes Pb and Cd [55], engine oil contributes Cu and Zn, and corrosion products from metal parts introduce Cr and Ni. The lower pH recorded in Soil A (6.5) compared to Soil B (6.8) is consistent with long-term acidification from battery acid spillage, further mobilizing metals already present. Additionally, the higher organic matter content in Soil A may reflect decades of oil and fluid accumulation, which, paradoxically, can increase metal retention and apparent concentration through chelation. The elevated Cr concentration specifically in Soil B, despite its shorter operational history, may be linked to the type of repair activities predominant at that workshop. Chromium is a major constituent of stainless steel and catalytic converters, and workshops handling more engine and exhaust system repairs would generate higher Cr loadings independent of operational duration. This underscores that metal contamination profiles are shaped not only by duration but by the nature of repair activities.

Although absolute metal concentrations in both soils remain below Nigerian regulatory thresholds (FMENV, 1991) and international guideline values, several justifications support the significance of this study. First, only Mn exceeded background levels typical of uncontaminated Nigerian agricultural soils (background Mn: ~10–15 mg kg^{-1}) [51, 64], confirming measurable anthropogenic input even at these concentrations. Second, chronic low-level exposure through daily vegetable consumption may cumulatively elevate health risks over time, particularly for children, as demonstrated by the EDI and THQ values calculated in this study. Third, automobile workshops represent a ubiquitous and growing contamination source in Nigerian cities, documenting baseline conditions now enables longitudinal monitoring before concentrations reach regulatory thresholds. Fourth, the absence of comparable baseline data from automobile workshop-contaminated soils in Ekiti State constitutes a critical gap that this study begins to fill.

4.2 Heavy metal concentration and bioconcentration in edible parts (Stem and Leaves) of *A. hybridus* and *O. gratissimum*

Considerations on the accumulation of heavy metals. Therein lies the value of our finding because heavy-metal levels in edible parts of *Amaranthus hybridus* and *Ocimum gratissimum* were investigated, thus producing information that can provide crucial insights into their accumulation patterns and that reveals biological and physiological peculiarities inherent in them. *A. hybridus* generally displays elevated levels of copper

(Cu), cadmium (Cd), nickel (Ni), and lead (Pb) relative to *O. gratissimum* [52]. This disparity may be explained by *A. hybridus*'s faster growth rate, extensive root system, and elevated transpiration, factors collectively amplifying its capacity for metal uptake and translocation from contaminated soils [3]. By contrast, *O. gratissimum* appears to counteract metal accumulation through adaptive mechanisms, including the biosynthesis of metal-chelating agents such as phenolic compounds and glutathione, particularly in leaf tissue crucial for photosynthesis [58]. We could observe the distribution of heavy metals in the plants on a spatial basis, summing up with the fact that heavy metals are concentrated in the stems compared with the leaves. This tendency correlates with the role of stems as an important feature of the vascular system, providing transportation of metals and their possible fixation on the cell walls as well as on the xylem. Instead, the leaves have developed vacuolar sequestration as a mechanism of defense, preventing the infliction of chloroplast damage and salvaging photosynthetic efficiency [52]. These findings are relevant in Nigeria, where both vegetables are widely consumed and often cultivated in urban agricultural systems. Consumption of *A. hybridus* stems may result in relatively higher dietary exposure to metals, particularly among children, although measured risk indices remained within acceptable limits [12]. Contrary to the pronounced accumulation of heavy metals observed in *O. gratissimum*, the comparatively lower metal content of this species may render it a more prudent dietary option. However, some safety recommendations are justifiable regarding heavy-metal consumption, considering the constant availability of metals in every part of the plant, especially in urban farming systems where the instances of contamination are expected to prevail [59]. A quantitative measurement of the efficiency of the plants in transferring metals in the soil to the edible part has been assessed in the analysis of the bioconcentration factor (BCF) [63]. For instance, *A. hybridus* exhibited relatively higher BCF values for cadmium and lead than *O. gratissimum*, indicating greater uptake efficiency; however, most BCF values were below unity, reflecting limited bioaccumulation potential [4]. Such superiority could be connected to the fact that the latter species has a wide root network that encourages high rates of contact with the soil and uptake of metals, which is also enhanced by the mass flow of transpiration to the plant [6]. It has been found that stem tissues have higher BCF than the leaves, probably because of the existence of a vascular pathway to metal translocation, and leaf tissues could simply serve as a system of metal retention in order to preserve essential metabolic activities [43]. Such patterns are greatly controlled by the properties of the soil. Acidic soils normally increase the solubility of metals, hence it increases uptake, but organic input to soil can increase or hinder the uptake, as seen in vast differences in sandy and clay-based soils [74]. Such variations are central to the application of health-risk assessment; larger values of the slope of the BCF indicate a greater possible dietary exposure, a matter of major concern in the case of Nigeria, where high levels of agriculture take place on highly polluted soil. Defined areas of crop harvesting and careful choices of crops to select are essential activities to minimize the associated health hazards where soil contamination is evident. Moreover, it is also essential to include larger programs that would oversee and prevent metal contamination in urban farming [48].

4.3 Plant growth parameters and leaf chlorophyll content

Soil contamination, especially the presence of the heavy metals of urban origin, significantly affects the development of *Amaranthus hybridus* and *Ocimum gratissimum*. *A. hybridus* demonstrates pronounced resilience within contaminated settings, partly attributable to its robust growth and elevated biomass yield. This strength can be attributed to its successful metal compartmentalization, which has allowed the plant to partly overcome the oxidative stress and other negative impacts of low-to-moderate metal exposures [68]. In contrast, *O. gratissimum* reveals heightened sensitivity to heavy metals, manifesting in reduced growth indicators such as plant height and leaf area. These biases can probably be attributed to oxidative stress and competitive nutrient deficiency caused by metal buildup [18, 24]. In addition to this, growing plants in soil with nutrients can boost plant growth due to the improved photosynthetic potentials introduced by an increase in organic matter; nonetheless, an increase in metal concentration tends to have physiological constraints, especially during chlorophyll synthesis and efficiency of photosynthesis [11]. This dilemma highlights the major trade-off species typified by resilience are likely to store toxic metals that can be a health hazard, but those species whose growth is low can offer safer food resources but at lower input levels. The current Nigerian situation in urban farming requires modern use of strong species to secure food resources and, at the same time combine phytoremediation strategies with strict food-safety measures to minimize the effects of metal absorption [17].

4.4 Health risk assessment

4.4.1 Estimated daily intake (EDI)

The established daily exposure to heavy metals obtained through *Amaranthus hybridus* and *Ocimum gratissimum* differs significantly depending on the environmental factors, the biological factors, and the consumers. In particular, *A. hybridus* constitutes a more pronounced exposure risk owing to its greater intrinsic capacity for heavy metal sequestration, especially within stem tissues, which generally display higher metal concentrations than leaves [38]. Such patterns of accumulation are regulated by plant biology: the degree of specific soil uptake varies according to species, depending on physiological architecture [53]. Children, as the most vulnerable group of consumers, are subjected to the factors of small size and high food intake per gram of body weight, which are coupled with disproportionately high EDI compared to adults [8, 40]. Other aspects of soil, including additional soil pH and soil organic matter content, also influence the bioavailability of metals. Soils with lower pH and a higher concentration of organic matter can increase solubility and absorb metals into the plants [31].

An EDI result that reaches or nears the set safety limits indicates potential exposure pathways relevant to public health assessment. Chronic exposure to *A. hybridus* grown in contaminated soils can culminate in chronic metal toxicity, a concern of particular significance in regions where the vegetable occupies a prominent nutritional role [40]. In countries such as Nigeria, where *A. hybridus* and *O. gratissimum* constitute major dietary components; these results warrant immediate public health interventions that include soil remediation, targeted consumer education, and dietary diversification to curtail reliance on potentially hazardous plant species [47]. These preventive measures could substantially contribute to lowering exposure risks and enhancing overall public health.

4.4.2 Non-carcinogenic risk assessment

Eating the edible plants *Amaranthus hybridus* and *Ocimum* gratissimum has been linked to non-carcinogenic hazards due to long-term exposure to heavy metals, including cadmium (Cd) and lead (Pb) [40]. Short-term risks do not seem severe, but the effects of prolonged absorption upon health should be considered. Of particular concern is the stem component of *A. hybridus*, which exhibits higher metal concentrations than leaves or *O. gratissimum* tissues [40, 53]. The uptake is also aggravated in soil with a low pH and high mobility of metals [53]. Conversely, slightly contaminated soils with neutral pH seem less dangerous, which highlights the role environmental determinants play in risky health outcomes [53].

Exposure to cumulative metals can lead to toxicity levels associated with some neurological and kidney impairment, which is more dangerous in children as their physiological development is not complete [40]. It, therefore, follows that the active management of the environment in the urban farming setting of Nigeria, such as frequent soil testing, contamination prevention, and the introduction of safe harvesting standards, is crucial. These measures have the potential to alleviate acute and chronic hazard levels of these susceptible vegetables by a significant margin and safeguard the health of civilians and farming households [31]. Given that THQ and HI values in this study, while below the threshold of 1, are highest for Cd and Pb, particularly in children consuming *A. hybridus* stems from Soil A, targeted monitoring of these metals in Ado-Ekiti urban farms is a practical and actionable first step.

4.4.3 Carcinogenic risk assessment

The carcinogenic risk associated with heavy metals such as nickel (Ni) and chromium (Cr), as investigated in *A. hybridus* and *O. gratissimum*, constitutes a modestly elevated yet significant long-term threat, especially for children whose dietary habits and susceptibility render them more exposed [40]. The Ni and Cr levels found in *A. hybridus* underline the importance of heightened vigilance, given that this species exhibits anatomical and physiological susceptibilities that facilitate heavy metal concentration [53]. In addition, the soil factors, mainly acidity, may significantly increase the acquisition of heavy metals in these vegetables, therefore, increasing the carcinogenic risks [40].

The evidence in its current assessment shows that the consumption of these vegetables will lead to cancer risk levels falling within acceptable thresholds; however, there is a possible risk of building up towards a higher probability of life time cancer risk, when due to repeated exposure, this is more common in such cases when it pertains to urban diets in Nigeria [47]. This situation highlights the dual threat that public health faces; immediate interventions that can be taken to ensure the safety of immediate food and the interventions that can be directed towards reversing the long-term health effects associated with chronic exposure to polluted food crops. The utilization of environmental remedies like utilizing Phyto stabilization of metals in the ground and crop rotation with a less accumulative species has a high potential of reducing carcinogenic risk in those exposed to it [47]. Additional measures, such as complementary public health campaigns to inform the risk-based aspect of food safety, specific interventions to minimize the exposure risk, are necessary to improve food safety outcomes as well as eliminate the health implications thereof in the long-term [57].

5 Conclusion

This study assessed heavy metal accumulation and health risks associated with cultivating *Amaranthus hybridus* and *Ocimum gratissimum* on automobile workshop soils of contrasting operational ages in Ado-Ekiti, Nigeria. Soil A, from the older (20-year) workshop, exhibited higher metal concentrations and lower pH, which promoted greater metal bioavailability and plant uptake relative to Soil B (10-year workshop). *A. hybridus* accumulated higher concentrations of Cd, Pb, and Ni than *O. gratissimum*, with stems consistently exceeding leaves, a pattern with implications for dietary exposure, particularly among children. Despite these differences, all THQ, HI, and TCR values remained within acceptable limits, suggesting low immediate health risk under current contamination levels. However, given Nigeria's expanding urban agriculture sector and the absence of widespread soil monitoring around mechanic workshops, continuous surveillance and enforcement of buffer zones between automotive repair sites and food cultivation areas are recommended.

Author contributions

Afolabi AT: Conceptualization, Methodology, Experimentation, Data curation, Writing – Original Draft, Review & Editing. Odiyi BO: Conceptualization, Methodology, Experimentation, Writing – Supervision and Proofreading.Ojeniyi OJ: Conceptualization, Resources, Writing –Review & Editing.

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Data availability

The datasets generated and analyzed during the current study are available within this article.

Declarations

Ethics approval and consent to participate

The plant materials used in this study were cultivated from seeds obtained from the Seed Bank Department, Ondo State Ministry of Agriculture, Akure, Nigeria. Cultivation was carried out in a controlled screen-house facility at the Federal University of Technology, Akure, Nigeria, under institutional greenhouse protocols that comply with Nigerian national guidelines on agricultural research and biosafety (Federal Ministry of Agriculture and Rural Development, 2018). No specific permits or licenses were required for the cultivation or use of *Amaranthus hybridus* and *Ocimum gratissimum* seeds from the aforementioned seed bank.

Consent for publication

All authors give their consent to publish.

Competing interests

The authors declare no competing interests.

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