



OPEN ACCESS

EDITED BY

Qingli Dong,
University of Shanghai for Science and
Technology, China

REVIEWED BY

Adefarati Oloruntoba,
University of Calgary, Canada
Patsiri Sriwieng,
Thammasat University, Thailand

*CORRESPONDENCE

Sylvester Chibueze Izah
✉ chivestizah@gmail.com

RECEIVED 13 October 2025

REVISED 30 December 2025

ACCEPTED 05 January 2026

PUBLISHED 17 February 2026

CITATION

Jack TJ and Izah SC (2026) Trace metal
contamination and health risk assessment of
edible land snails (*Achatina achatina*) in
Yenagoa Metropolis, Nigeria.
Front. Sustain. Food Syst. 10:1724347.
doi: 10.3389/fsufs.2026.1724347

COPYRIGHT

© 2026 Jack and Izah. This is an open-access
article distributed under the terms of the
[Creative Commons Attribution License
\(CC BY\)](https://creativecommons.org/licenses/by/4.0/). The use, distribution or reproduction
in other forums is permitted, provided the
original author(s) and the copyright owner(s)
are credited and that the original publication
in this journal is cited, in accordance with
accepted academic practice. No use,
distribution or reproduction is permitted
which does not comply with these terms.

Trace metal contamination and health risk assessment of edible land snails (*Achatina achatina*) in Yenagoa Metropolis, Nigeria

Tarvie Jacob Jack¹ and Sylvester Chibueze Izah^{2*}

¹Department of Medical Social Work, Faculty of Health Sciences, Bayelsa Medical University, Yenagoa, Bayelsa, Nigeria, ²Department of Community Medicine, Faculty of Clinical Sciences, Bayelsa Medical University, Yenagoa, Bayelsa, Nigeria

Background: Trace metal contamination of edible land snails is an emerging public health concern due to their strong bioaccumulation capacity in polluted environments. This study assessed trace metal concentrations, dietary exposure, and associated health risks of *Achatina achatina* consumed in Yenagoa Metropolis, Nigeria, to evaluate food safety and ecological implications.

Methods: Sixty *A. achatina* samples were collected from 12 locations across Yenagoa Metropolis. Concentrations of cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn) were quantified using Atomic Absorption Spectrophotometry. Spatial patterns and potential contamination sources were explored using descriptive statistics, Pearson correlation, Principal Component Analysis (PCA), and hierarchical cluster analysis. Human health risks were evaluated through Estimated Daily Intake (EDI), Hazard Quotient (HQ), Hazard Index (HI), and carcinogenic risk assessment.

Results: Trace metal concentrations (mg/kg dry weight) ranged as follows: Cd (1.274–6.839), Co (0.928–7.004), Cr (0.066–3.102), Cu (28.871–64.589), Fe (121.675–507.840), Mn (65.516–146.889), Ni (0.537–7.410), Pb (2.456–8.881), and Zn (68.759–102.069), with significant spatial variability ($p < 0.05$). Cd, Pb, and Ni exceeded permissible limits at several sites, reflecting anthropogenic inputs such as vehicular emissions, waste combustion, and crude oil-related activities. PCA and cluster analysis analyses revealed strong associations among Co, Cr, Fe, Ni, and Pb, suggesting common pollution sources. The HI exceeded unity at all locations, indicating potential non-carcinogenic risk, while carcinogenic risks for Cd, Cr, Ni, and total lifetime cancer risk surpassed USEPA acceptable thresholds.

Conclusion: The findings demonstrate that consumption of *A. achatina* from Yenagoa may pose significant non-carcinogenic and carcinogenic health risks. Continuous monitoring, improved pollution control, and public awareness are essential to safeguard consumer health.

KEYWORDS

Achatina achatina, bioaccumulation, carcinogenic risk, environmental contamination, health risk assessment, multivariate analysis, trace metals

Introduction

The edible African giant snail, *Achatina achatina*, is one of the largest terrestrial gastropods, widely distributed across tropical regions of West and Central Africa, including Nigeria, Ghana, Cameroon, Côte d'Ivoire, etc. Other commonly consumed species include *Achatina fulica* and *Archachatina marginata*, each differing in shell morphology, ecological preference,

and reproductive capacity. These snails thrive in humid forest zones, farmlands, and peri-urban areas where decaying vegetation provides abundant food sources. Due to their nutritional value and economic importance, edible giant snails are increasingly harvested and traded across sub-Saharan Africa as a sustainable protein source.

The assessment of trace element exposure through the consumption of the *A. achatina* has become an important environmental and public health concern in Nigeria and other parts of sub-Saharan Africa. The species serves as a valuable source of animal protein and income for many households; however, its tendency to bioaccumulate trace metals from soil, vegetation, and water sources makes it a potential vector for toxic element transfer to humans. Trace metals have been reported in Nigerian environmental matrices including air, water and soil (Oloruntoba et al., 2024; Uzoekwe et al., 2021). Trace metals can adversely affect the environment and the human health (Jota Baptista et al., 2022). Environmental contamination from agricultural runoff, vehicular emissions, petroleum exploration, and waste disposal in urban centers such as Yenagoa Metropolis increases the likelihood of snail exposure to heavy metals (Eneji et al., 2016; Ikimi and Addy, 2024; Joseph et al., 2021; Iwegbue et al., 2008). The consumption of contaminated snail meat may therefore constitute a significant route for trace metal ingestion and potential health risk to consumers.

The bioaccumulation of trace elements in *A. achatina* depends largely on the environmental conditions of their habitat, including soil pH, organic matter content, and proximity to pollution sources. Snails collected from industrial or roadside environments often exhibit higher metal concentrations compared to those from less impacted areas (Samuel et al., 2018). Hence, assessing the concentration and distribution of trace metals in edible snail tissues provides valuable information on the environmental quality of their habitats and potential exposure pathways to humans.

Multivariate statistical techniques such as Principal Component Analysis (PCA) and Cluster Analysis, and Pearson correlation are vital analytical tools that can be used to identify the source of the metals (Izah et al., 2023, 2024a). PCA is vital in determining major contributing sources [such as anthropogenic (industrial and vehicular) or natural (geogenic and dietary)] by reducing data complexity and identifying dominant factors influencing metal accumulation. CA can be useful in grouping metals with similar distribution patterns, indicating common sources or pathways, while Pearson correlation assesses the degree of association between metals, suggesting whether they originate from shared or distinct contamination processes. Integrating these techniques enhances the interpretation of environmental data and supports evidence-based source apportionment (Izah et al., 2021; Aigberua et al., 2021).

Furthermore, health risk assessment (HRA) is crucial for evaluating the potential toxicological implications of trace element exposure. Typically, HRA employs quantitative models such as Estimated Daily Intake (EDI), Hazard Quotient (THQ), Hazard Index (HI), and Carcinogenic Risk to determine whether observed concentrations pose non-carcinogenic or carcinogenic risks to human consumers (Izah et al., 2024b, 2022, 2021; Aigberua et al., 2021; Izah and Aigberua, 2020). Therefore, estimating these indices aids in differentiating essential and toxic metal contributions, evaluate exposure safety thresholds, and identify priority areas for public health intervention (Ogamba et al., 2021; Uzoekwe et al., 2021). This probabilistic approach is particularly useful in accounting for variability and uncertainty in consumption patterns and exposure pathways (Izah et al., 2024b).

Trace metal concentrations have been reported in various species of edible snails across the world, highlighting their usefulness as bioindicators of environmental contamination (Abdullahi et al., 2021; N'guessan and Kouassi, 2024). In Nigeria, studies on *A. achatina*, *A. marginata*, and *A. fulica* from different ecological zones have revealed varying levels of trace metal accumulation. For instance, *A. marginata* from contaminated regions in Rivers and Akwa Ibom States showed elevated levels of cadmium (Onuoha et al., 2016; Joseph et al., 2021), while *A. achatina* collected from cement factory vicinities and agricultural areas exhibited higher concentrations of trace metals (Ugbaja et al., 2020; Nnamonu et al., 2021). Similarly, *A. fulica* from Okolobiri, Bayelsa State, contained considerable levels of toxic metals linked to petroleum pollution (Ikimi and Addy, 2024). Other investigations in Abia, Rivers, and Akwa Ibom States have demonstrated that both wild and market-sold snails can pose potential health risks due to heavy metal contamination (Kalu et al., 2024; Eze and Ohanele, 2021; Eneji et al., 2016).

Although several studies have examined environmental contamination and food-related exposure pathways in the Niger Delta, only a limited number have conducted comprehensive health-risk assessments focused specifically on human exposure through *A. achatina* consumption. In Yenagoa Metropolis, *A. achatina* is widely harvested, traded, and consumed, forming a routine component of local diets. Market observations and community-level consumption patterns indicate that the species is both readily available and frequently eaten, making it a meaningful pathway for human exposure assessment.

Despite this high consumption rate, there remains a paucity of location-specific data on the concentrations, sources, and potential health implications of trace metals in these edible snails. Previous studies within Bayelsa State (particularly in Ogbia local government area) have reported elevated levels of heavy metals and petroleum-related pollutants in *A. achatina* (Chokor and Ogonegbu, 2023). This stress the sensitivity of *A. achatina* to environmental contamination. Yet, these findings have not been adequately extended to Yenagoa metropolis, the capital of Bayelsa State, currently experiencing increasing ecological pressure from rapid urbanization, etc. Given the species' dietary significance, ecological abundance, and documented capacity to accumulate pollutants, assessing trace-metal levels and associated health risks among consumers in Yenagoa metropolis is essential.

This study therefore, aims to determine trace element exposure and health risk through the consumption of *A. achatina* in Yenagoa Metropolis, Nigeria. It further seeks to identify and apportion possible sources of contamination using multivariate statistical techniques, including Principal Component Analysis (PCA), Cluster Analysis, and Pearson correlation. The findings are expected to enhance understanding of the contamination dynamics of trace metals, their health implications, and the need for effective monitoring and regulatory interventions to safeguard public health.

Methodology

Study area

The research was carried out in Yenagoa Metropolis, the administrative capital of Bayelsa State, Nigeria. Located within the Niger Delta region, Yenagoa experiences a humid tropical climate,

substantial annual rainfall, and a high population density. Rapid urbanization is evident in the city, characterized by increasing vehicular traffic, roadside trading, and the widespread consumption of snail-based delicacies. The *A. achatina*, is commonly sold in open markets, and along roadways including street, making it a suitable bioindicator for assessing potential trace metal contamination in the urban environment.

Sample collection

Achatina achatina in Bayelsa State particularly in Yenagoa metropolis is sourced from forested bush areas, peri-urban farmlands, and riparian habitats where the species naturally thrives. Snails are also commonly collected from urban gardens, compost heaps, and refuse sites, and a substantial portion enters the food chain through local markets supplied by rural harvesters and small-scale traders. In addition, small backyard and emerging commercial snail farms contribute to the overall supply available for household consumption and market sale. However, because vendors often obtain snails from multiple collectors and mixed ecological sources, it is difficult to ascertain the precise origin of each batch sold in markets.

Samples of *A. achatina* were collected from 12 predetermined sites across Yenagoa: Agudama (SnA), Igbogene (SnB), Akenfa (SnC), Swali (SnD), Kpansia (SnE), Etegwe (SnF), Opolo (SnG), Okaka (SnH), Ekeki (SnI), Bossy Water (SnJ), Okutukutu (SnK), and Yenezuie-gene (SnL). A total of 60 samples were obtained, with five specimens from each location. Five specimens were sampled at location to ensure representativeness and reduce bias. Samples SnA–SnH were obtained from markets, while SnI–SnL were collected from roadside vendors. Each batch contained samples purchased from the same or different vendors to ensure representativeness.

Sample preparation and analysis

Preparation and analysis of *A. achatina* tissues followed established protocols (Aigberua et al., 2018, 2021; Izah et al.,

2022, 2024b; Odubo and Izah, 2025). Soft tissues were carefully separated from shells, oven-dried at 60 °C to constant weight, and homogenized into fine powder using a ceramic mortar and pestle. This samples were further sieved through a 2.00 mm mesh to obtain uniform powder. Approximately 2 g of each homogenized sample was weighed into a digestion vessel and treated with a mixture of 10 mL concentrated nitric acid (HNO₃) and 4 mL perchloric acid (HClO₄) on a hot plate inside a fume hood. The mixture was gently heated until dense white fumes appeared. When residual carbon remained, 1–2 mL of additional HNO₃ was added, and digestion continued until complete mineralization. After cooling, 10 mL of distilled water was added, and the solution was filtered into a 20 mL volumetric flask using 110 mm filter paper and brought to volume with distilled water. Trace metals (Cd, Pb, Cu, Cr, Mn, Zn, Co, Ni, and Fe) were quantified using Flame Atomic Absorption Spectrophotometry (FAAS, GBC SavantAA, Australia). Calibration curves were prepared from certified standard solutions. Metal concentrations in the digests were expressed in mg/kg dry weight. Operational parameters for FAAS are summarized in Table 1.

Quality control and recovery assessment

Comprehensive quality assurance and quality control (QA/QC) measures were implemented throughout the analysis. All glassware and volumetric equipment were acid-washed and rinsed with deionized water prior to use. Procedural blanks, reagent blanks, and duplicate samples were included in every batch to ensure accuracy and precision.

The LOD, LOQ and Spike recovery was calculated using the formula:

$$LOD = 3 \times \frac{SD \text{ of blank}}{\text{slope of calibration curve}}$$

$$LOQ = 10 \times \frac{SD \text{ of blank}}{\text{slope of calibration curve}}$$

TABLE 1 Operational conditions for FAAS analysis of *Achatina achatina* tissues.

Elements	Width of the slit, nm	Wavelength, nm	Current lamp, mA	Flame composition	
				Gas (acetylene, L/min)	Air (L/min)
Lead	1.0	217.0	5.0	1.7	10.0
Chromium	0.2	357.9	6.0	2.5	10.0
Manganese	0.2	280.1	5.0	1.7	10.0
Copper	0.5	324.7	3.0	1.7	10.0
Zinc	0.5	213.9	0.5	1.7	10.0
Iron	0.2	248.3	7.0	1.7	10.0
Cadmium	0.5	228.8	3.0	1.7	10.0
Nickel	0.5	232.0	4.0	1.7	10.0
Cobalt	0.5	240.7	4.0	1.7	10.0

$$\text{Recovery (\%)} = \frac{\text{Post-spike concentration} - \text{Pre-spike concentration}}{\text{Spike added}} \times 100$$

The pre-spike and post-spike concentrations were measured in 10 replicate analyses per metal. The limits of detection (LOD) and limits of quantification (LOQ) were determined based on blank measurements, following established procedures (Aigberua et al., 2018, 2021; Izah et al., 2022, 2024b). Recovery rates for all metals ranged between 90.98 and 98.18%, confirming the reliability of the digestion and FAAS method. Spike levels were chosen based on expected sample concentrations, with nitrate salts used as standards to ensure solubility and stability in the acidic matrix. Detailed recovery and detection limits for trace elements in the samples are presented in Table 2.

Health risk assessment

The health risk assessment for metal exposure through *A. achatina* consumption was conducted based on the United States Environmental Protection Agency (USEPA) methodology. The assessment involved the estimation of EDI, HQ, HI and carcinogenic risk model.

Non-carcinogenic risk (hazard quotients and hazard index)

Estimated daily intake (EDI)

The EDI was calculated following the USEPA method [United States Environmental Protection Agency (USEPA), 2025a]:

$$\text{EDI} = \frac{\text{SnmC} \times \text{SnIR} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}}$$

Where: SnmC = concentration of each metal in *A. achatina* (mg/kg), SnIR = ingestion rate (0.10274 kg/day) (Gabriel et al., 2025), and BW = average adult body weight (70 kg) (Gabriel et al., 2025; Falae et al., 2025), EF = 365 days [United States

Environmental Protection Agency (USEPA), 2025a], 56.35 years (average Nigerian life expectancy) (Macrotrends, 2025).

Non-carcinogenic risk was estimated using the Hazard Quotient (HQ) and Hazard index (HI) based on the USEPA model [United States Environmental Protection Agency (USEPA), 2011; Falae et al., 2025]:

$$\text{Hazard Quotient} = \frac{\text{EDI}}{\text{RfD}}$$

Where RfD (mg/kg/day): Cd (0.001) and Mn (0.14) based on IRIS [United States Environmental Protection Agency (USEPA), 2020], Pb (1.5), Cu (0.04), Cr (1.5), Zn (0.3), Fe (0.7), Co (0.0004), (Aigberua et al., 2018; Iwegbue et al., 2013).

Hazard index

The Hazard Index (HI) was determined as $\text{HI} = \sum \text{THQ}$.

An HI > 1 implies potential health concern [United States Environmental Protection Agency (USEPA), 2011; Falae et al., 2025; Ogamba et al., 2021; Uzoekwe et al., 2021; Izah et al., 2022].

Carcinogenic risk

Carcinogenic risk was estimated following United States Environmental Protection Agency (USEPA) (2025b, 2011), Falae et al. (2025), Onuoha et al. (2016) and Gabriel et al. (2025) using:

$$\text{Carcinogenic risk} = \text{EDI} \times \text{CSF}$$

Where: CSF = oral cancer slope factor (mg/kg/day)—Cd (0.38), Pb (0.0085) [United States Environmental Protection Agency (USEPA), 2012; Falae et al., 2025], Cr (0.5), Ni (1.7). Acceptable carcinogenic risk values range between 10^{-6} and 10^{-4} (Vesković and Onjia, 2025; Ogamba et al., 2021; Uzoekwe et al., 2021).

Statistical analysis

Data were statistically analyzed using SPSS software. Results were expressed as mean ± standard error. Furthermore, the 95% confidence

TABLE 2 LOD, LOQ, spike standards, pre- and post-spike concentrations, and recovery (%) for trace metals in the snail samples

Element	Working solutions range (mg/l)	LOD (mg/kg)	LOQ (mg/kg)	Spike Standard (mg/kg)	Pre-spike (mg/kg)	Post-spike (mg/kg)	Recovery (%) (mean ± SD, n = 10)	RSD
Pb	0.5–5	3.49×10^{-7}	1.06×10^{-6}	1.0	2.417	3.370	95.34 ± 1.2	3.75
Cr	0.5–5	4.29×10^{-6}	1.30×10^{-5}	2.0	5.839	7.672	91.65 ± 1.5	4.33
Cu	0.5–5	7.73×10^{-6}	2.34×10^{-5}	2.0	3.251	5.212	98.11 ± 1.0	4.30
Mn	1–10	1.26×10^{-5}	3.83×10^{-5}	2.0	5.693	7.656	98.18 ± 1.1	4.79
Zn	1–10	2.20×10^{-5}	6.68×10^{-5}	2.0	4.148	6.127	97.85 ± 1.0	4.40
Fe	10–100	4.27×10^{-7}	1.29×10^{-6}	10.0	50.329	59.965	96.56 ± 1.5	4.00
Cd	0.5–2	1.47×10^{-5}	4.47×10^{-5}	0.5	0.372	0.847	90.98 ± 2.0	4.22
Ni	0.5–5	2.00×10^{-7}	6.05×10^{-7}	0.5	0.813	1.301	96.11 ± 1.3	0.00
Co	1–10	1.58×10^{-5}	4.79×10^{-5}	0.5	0.729	1.214	96.84 ± 1.2	3.48

intervals (CI) and coefficients of variation (CV) of the measured values were also determined and reported. One-way analysis of variance (ANOVA) was used to determine significant differences ($p < 0.05$), followed by the Waller–Duncan multiple range test to identify sources of variation. Pearson correlation analysis was applied to assess inter-metal relationships, while PCA was used to identify latent contamination sources. Hierarchical Cluster Analysis was also employed to classify metals and sampling locations based on similarities.

Furthermore, the dry weight data was converted to wet weight formula previously presented by United States Environmental Protection Agency (USEPA) (2024).

$$\text{Concentration of wet weight} = \text{Concentration of dry weight} \times (1 - \text{Moisture content}).$$

Where moisture content = 71.65% based on the study of Chukwudebe (2024), on *A. achatina* in the Enugu State, Nigeria.

Results and discussion

Concentration of trace metals in *Achatina achatina* sold in Yenagoa Metropolis

The dry weight and wet weight concentration of trace metals in *A. achatina* sold in Yenagoa Metropolis, Nigeria are presented in Tables 3, 4, respectively. Furthermore, supplementary material 1 show the mean, class interval and CV values for the wet weight for each of the metals across the locations. Cadmium (Cd) concentrations (dry weight) in the sampled *A. achatina* ranged from 1.270 ± 0.180 mg/kg (SnB) to 6.840 ± 0.940 mg/kg (SnH), showing significant spatial variation ($p < 0.05$). When expressed on a wet weight basis, mean concentrations ranged from 0.361 to 1.939 mg/kg WW, with corresponding 95% CI of 0.218–2.683 mg/kg WW and coefficient of variation (CV%) ranging from 9.200 to 31.900%. The relatively wide 95% CI and high CV in certain locations, particularly SnH, SnI, and SnJ, indicate substantial variability in Cd exposure within these sites, suggesting localized contamination hotspots. These elevated levels are likely driven by Cd-rich particulates from vehicular emissions, roadside dust, and waste combustion, whereas lower Cd concentrations in SnB and SnD reflect reduced exposure, consistent with less contaminated environments.

The measured Cd concentrations exceed the FAO limit of 0.03 mg/kg (Hassan, 2022) and surpass the WHO guideline of 3 mg/kg in some locations (Joseph et al., 2021), highlighting potential health risks associated with chronic dietary intake of these snails. Mechanistically, Cd accumulation in *A. achatina* is attributable to its high metal-binding capacity, slow depuration rate, and frequent contact with contaminated soil and litter, particularly in areas receiving battery disposal, pigments, and other Cd-containing household or industrial wastes.

Comparison with previous studies shows that the Cd values recorded here fall within or exceed those reported by Joseph et al. (2021) (0.260–5.382 mg/kg) in *A. marginata*, and are higher than the 0.000–1.250 mg/kg reported by Gabriel et al. (2025) in *A. fulica*. The concentrations also span the ranges documented by Eneji et al. (2016) (0.420–2.800 mg/kg), Awharitoma et al. (2016)

(0.070–0.350 mg/kg), Iwegbue et al. (2008) (0.190–3.280 mg/kg), and Onuoha et al. (2016) (0.500–0.650 mg/kg). Conversely, the values are lower than the extremely high Cd concentrations reported in *A. fulica* from Okolobiri and Odi (0.010–53.750 mg/kg) (Ikimi and Addy, 2024) and ready-to-eat snails from Abia State (32.670–58.440 mg/kg) (Kalu et al., 2024). These variations reflect differences in local contamination sources, soil metal mobility, species-specific bioaccumulation efficiency, and proximity to anthropogenic pollution hotspots.

Cobalt (Co) concentrations (dry weight) varied significantly across sites ($p < 0.05$), with mean values ranging from 0.923 mg/kg (SnL) to 7.004 mg/kg (SnA). When converted to wet weight (WW), the means ranged from 0.263 to 1.986 mg/kg WW, with 95% CI of 0.195–2.452 mg/kg WW, and CV ranging from 5.900 to 29.200%. The relatively narrow 95% CI observed at some sites (e.g., SnH, SnL) indicates consistent Co levels among sampled snails, suggesting stable environmental conditions or uniform accumulation patterns. Conversely, the wider CI at sites such as SnA, SnC, and SnD reflects greater variability, likely resulting from heterogeneous sources of contamination or differences in snail feeding behavior. Similarly, CV values highlight the relative variability of Co concentrations within sites, with higher CVs indicating more variable accumulation possibly due to localized anthropogenic inputs or uneven eugenic distribution.

Elevated Co levels in SnA, SnC, and SnD may be driven by eugenic Co enrichment or anthropogenic contributions, including vehicular emissions, industrial residues, or solid-waste leachates. Lower concentrations in SnH and SnL suggest limited contamination or naturally lower Co content in these environments. Biologically, Co is an essential element involved in vitamin B12 structure, and snails accumulate it through soil ingestion and feeding on decomposing plant material. However, at higher concentrations, Co can be toxic, suggesting increased environmental loading and the potential for trophic transfer.

Compared with literature, Co concentrations in this study exceed the 0.03–0.070 mg/kg reported by Awharitoma et al. (2016) in Edo State, and are higher than or overlap with the 0.710–4.456 mg/kg reported by Iwegbue et al. (2008) across southern states (Delta, Edo, Bayelsa, Rivers, and Anambra). These patterns indicate stronger anthropogenic influence in Yenagoa and underscore the combined effects of soil mineral composition, waste deposition, and the snail's physiological preference for essential metal uptake in determining site-specific Co accumulation.

Chromium (Cr) concentrations in snails exhibited significant spatial variation across sampling sites. Dry weight Cr levels ranged from 0.066 mg/kg (SnL) to 3.102 mg/kg (SnA), while the corresponding wet weight (WW) concentrations ranged from 0.019 to 0.879 mg/kg, with 95% CI of 0.013–0.999 mg/kg and CV between 5.5 and 23.6%. The relatively narrow 95% CI in some sites (e.g., SnK, SnL) suggests consistent measurements and limited intra-site variability, whereas broader CIs in sites like SnA and SnC reflect higher heterogeneity in Cr accumulation, likely due to variable exposure sources or differences in snail feeding behavior.

The CV values provide further insight into data reliability and dispersion. Lower CVs (5.5–10%) indicate more uniform Cr distribution among snails at those sites, suggesting stable environmental exposure. In contrast, higher CVs (above 20%) indicate significant variability among individual snails, which could stem from localized contamination events, such as contact with Cr-contaminated

TABLE 3 Dry weight concentration of trace metals in *Achatina achatina* sold in Yenagoa metropolis, Nigeria.

Locations	Cd (mg/kg)	Co (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Zinc, Zn (mg/kg)
SnA	2.453 ± 0.102ab	7.004 ± 0.194e	3.102 ± 0.152f	35.961 ± 1.345ab	463.992 ± 9.688e	111.066 ± 10.040bcd	4.105 ± 0.286d	8.130 ± 0.616e	72.336 ± 3.782ab
SnB	1.274 ± 0.181a	3.410 ± 0.172d	1.352 ± 0.066d	39.333 ± 1.395abcd	138.562 ± 8.838ab	69.298 ± 6.227a	5.881 ± 0.150 fg	4.658 ± 0.268bcd	91.136 ± 4.289cde
SnC	2.713 ± 0.126ab	6.349 ± 0.827e	2.521 ± 0.072e	50.007 ± 2.232de	317.642 ± 8.526c	118.895 ± 7.862cde	6.483 ± 0.439 g	8.881 ± 0.643e	102.069 ± 3.427e
SnD	1.340 ± 0.066a	3.766 ± 0.421d	1.331 ± 0.088d	37.396 ± 1.589abc	151.640 ± 20.043ab	86.400 ± 9.881ab	7.410 ± 0.339 h	5.115 ± 0.589d	75.185 ± 4.591abc
SnE	2.715 ± 0.266ab	2.811 ± 0.122bcd	1.170 ± 0.053 cd	39.567 ± 5.353abcd	359.996 ± 21.975 cd	133.915 ± 4.102de	5.479 ± 0.384ef	8.379 ± 0.448e	96.966 ± 5.344de
SnF	2.208 ± 0.131ab	1.897 ± 0.144ab	0.956 ± 0.100bc	47.762 ± 2.646cde	130.827 ± 6.433ab	85.285 ± 8.360ab	3.970 ± 0.198d	5.509 ± 0.557d	84.153 ± 2.017abcd
SnG	2.863 ± 0.132b	1.620 ± 0.043a	0.811 ± 0.030b	52.408 ± 3.983ef	122.289 ± 13.615a	114.520 ± 4.760bcd	4.658 ± 0.246de	3.267 ± 0.241ab	84.990 ± 5.496abcde
SnH	6.839 ± 0.943d	1.492 ± 0.153a	0.954 ± 0.054bc	61.905 ± 4.472 fg	121.675 ± 7.191a	146.889 ± 2.323a	1.611 ± 0.121b	2.456 ± 0.108a	88.738 ± 1.014bcde
SnI	6.232 ± 0.805d	2.005 ± 0.127abc	0.893 ± 0.022bc	37.591 ± 1.049abc	507.840 ± 23.824e	65.516 ± 4.421e	1.874 ± 0.100b	4.430 ± 0.302bcd	84.770 ± 5.173abcde
SnJ	5.623 ± 0.356 cd	1.192 ± 0.059a	1.324 ± 0.134d	45.412 ± 2.038bcde	381.846 ± 31.578d	93.740 ± 5.810abc	0.537 ± 0.026a	4.818 ± 0.315 cd	90.042 ± 7.147cde
SnK	2.895 ± 0.192b	3.124 ± 0.394 cd	0.352 ± 0.030a	28.871 ± 3.326a	181.485 ± 9.440b	124.350 ± 21.637cde	1.442 ± 0.059b	4.663 ± 0.439bcd	68.759 ± 3.536a
SnL	4.456 ± 0.484c	0.928 ± 0.086a	0.066 ± 0.007a	64.589 ± 4.703a	146.272 ± 7.263ab	135.581 ± 5.192de	2.773 ± 0.132c	3.486 ± 0.228abc	82.433 ± 8.450abcd

Data are expressed as mean ± standard error (n = 5); Different letters along the column indicate significant variations (p < 0.05) according to Waller-Duncan Test statistics; Agudama (SnA), Igbogene (SnB), Akemia (SnC), Swali (SnD), Kpansia (SnE), Elegwe (SnF), Opolo (SnG), Okaka (SnH), Ekeki (SnI), Bossy Water (SnJ), Okutukutu (SnK), and Yenezue-gene (SnL).

TABLE 4 Summary wet weight concentration (mg/kg WW) of trace metals in *Achatina achatina* sold in Yenagoa metropolis, Nigeria.

Metal	Mean (mg/kg WW)	95% CI (mg/kg WW)	CV (%)
Cd	0.361–1.939	0.218–2.683	9.2–31.9
Co	0.263–1.986	0.195–2.452	5.9–29.2
Cr	0.019–0.879	0.013–0.999	5.5–23.6
Cu	8.190–18.320	5.567–22.026	7.9–30.3
Fe	34.523–143.981	23.922–162.705	4.677–29.593
Mn	18.573–41.631	14.243–44.913	3.537–38.888
Ni	0.152–1.838	0.132–2.182	5.701–21.1
Pb	0.696–2.518	0.610–3.021	9.769–25.793
Zn	19.491–28.934	16.706–31.623	2.556–24.196

soils, exposure to metal-rich dust, or the roasting of snails on metallic surfaces. These high-CV sites warrant closer attention, as variability may mask peak exposures that could affect human consumers.

Site-specific trends showed elevated Cr levels in SnA and SnC, while SnK and SnL exhibited comparatively low concentrations. This spatial variation aligns with environmental exposure pathways: areas with industrial or anthropogenic influence tend to elevate Cr bioavailability, whereas less impacted sites reflect minimal contamination. Mechanistically, Cr uptake in snails is influenced by soil pH, redox potential, and the chemical form of chromium [Cr(III) vs. Cr(VI)], with organic-rich acidic soils enhancing metal bioavailability and uptake.

When compared with international standards, the wet weight concentrations generally fall within the FAO limit of 1.0 mg/kg (Hassan, 2022), but dry weight values at SnA slightly exceed this threshold. All measured concentrations surpass the WHO limit of 0.05 mg/kg (Joseph et al., 2021), suggesting potential health implications depending on consumption patterns. Comparisons with prior studies reveal that the observed Cr concentrations align with ranges reported by Samuel et al. (2018), Joseph et al. (2021), and Gabriel et al. (2025), yet they are considerably higher than the minimal levels reported by Iwegbue et al. (2008) and Onuoha et al. (2016), and substantially lower than extreme values reported by Eneji et al. (2016) and Hassan (2022). These differences underscore the influence of local industrial activities, soil geochemistry, and snail foraging behavior on Cr accumulation.

Copper concentrations in *A. achatina* displayed notable spatial variation. On a dry weight basis, Cu ranged from 28.871 mg/kg (SnK) to 64.589 mg/kg (SnL), with all values exceeding the recommended limit of 20 mg/kg for mollusks (Iwegbue et al., 2008). On a wet weight (WW) basis, Cu ranged from 8.190 to 18.320 mg/kg, with 95% CI spanning 5.567–22.026 mg/kg, and CVs ranging from 7.900 to 30.300%, reflecting moderate to high variability among samples.

The higher Cu levels observed at SnL suggest localized sources of contamination, potentially from leaching of copper from metallic utensils, roofing sheets, proximity to mechanic workshops, or waste dumps. Conversely, the lower Cu levels at SnK indicate limited exposure to Cu-enriched substrates, consistent with its comparatively lower mean and narrower CI. The relatively wide CI in wet weight measurements highlights variability within the sampled population, suggesting uneven Cu distribution in snail tissues, likely due to

differences in foraging microhabitats or local environmental inputs. The CV values, particularly those exceeding 20%, indicate substantial heterogeneity in Cu accumulation among individual snails, emphasizing that risk is not uniform across the population.

Compared with earlier studies, the present Cu concentrations fall between previously reported extremes. Kalu et al. (2024) reported extremely high Cu levels (242.61–362.10 mg/kg) in Abia State snails, while Awharitoma et al. (2016) observed much lower values (1.47–7.48 mg/kg) in *A. marginata* from Edo State. Other reports, such as Iwegbue et al. (2008) (0.04–0.13 mg/kg) and Hassan (2022) (145.17–145.18 mg/kg), further illustrate the wide variability across regions. The present values are lower than those reported for *A. fulica* from Okolobiri and Odi (1.19–198.32 mg/kg; Ikimi and Addy, 2024) but align more closely with *A. achatina* from Abia, Ebonyi, and Enugu States (7.879–12.817 mg/kg) (Samuel et al., 2018). These differences likely reflect variations in soil Cu content, snail feeding behavior, environmental contamination patterns, and localized anthropogenic inputs.

Mechanistically, Cu accumulation in *A. achatina* is influenced by soil adsorption capacity, organic matter content, and bioavailability of Cu ions. Their habit of consuming decomposing vegetation and soil facilitates ingestion of Cu, while contact with Cu-containing materials increases dermal and oral uptake. The elevated DW values exceeding regulatory limits, despite WW values remaining within recommended levels, signal potential dietary overexposure, as DW reflects the total metal load independent of moisture content.

Iron (Fe) concentrations in the sampled snails exhibited considerable variability across sites, as reflected in both dry and wet weight measures. On a dry weight basis, Fe ranged from 121.675 mg/kg (SnH) to 507.840 mg/kg (SnI), with significant differences between sites ($p < 0.05$). Correspondingly, the wet weight concentrations ranged from 34.523 to 143.981 mg/kg WW, with 95% CI spanning 23.922–162.705 mg/kg WW. The CV for Fe ranged from 4.677 to 29.590%, indicating moderate to high variability depending on the site.

Sites SnA and SnI displayed the highest Fe levels, likely attributable to eugenic enrichment from iron-rich soils, red lateritic deposits, or contamination during processing via metallic knives or grinding tools. Conversely, SnH, SnF, and SnG showed lower Fe concentrations, suggesting minimal environmental Fe availability at these locations.

The 95% CI provides an estimate of the precision of the mean values; wider intervals at some sites indicate less certainty and greater sample heterogeneity, consistent with the elevated CV values. The CV values themselves reflect the relative dispersion of Fe levels: higher CVs suggest that Fe distribution in snails is highly variable within certain sites, possibly due to inconsistent exposure sources, feeding behavior, or site-specific contamination events.

Comparing these findings with earlier studies, Fe concentrations observed here are generally consistent with reports across Nigeria. For example, Kalu et al. (2024) found Fe ranging from 211.4 to 342.85 mg/kg in Abia State, whereas lower values were recorded in Edo State (14.95–70.49 mg/kg; Awharitoma et al., 2016) and multiple southern states (3.06–48.90 mg/kg; Iwegbue et al., 2008). Hassan (2022) reported exceptionally high Fe levels (732.32–734.24 mg/kg) in Lagos, while Ikimi and Addy (2024) reported 28.2–286.13 mg/kg in *A. fulica* from Okolobiri and Odi. These variations likely reflect differences in soil mineralogy, anthropogenic inputs, industrial activity, and environmental Fe bioavailability.

Mechanistically, Fe bioaccumulation in snails may occur through several pathways: dissolution of Fe oxides in moist tropical soils, enhanced bioavailability in acidic environments, adsorption of Fe-rich particles onto epithelial surfaces, and ingestion of detritus or soil. Additional exposure may occur during harvesting and food preparation, especially if metal tools or corrosive containers introduce Fe contamination.

Although Fe is essential for hemoglobin synthesis and electron transport, the observed dry weight values and some wet weight values exceed the 100 mg/kg permissible limit for food organisms (Biswas et al., 2021), implying a potential health risk. Excessive Fe intake may lead to oxidative stress through hydroxyl radical formation and iron overload disorders.

Manganese (Mn) concentrations in snails exhibited considerable spatial variation. On a dry weight basis, Mn ranged from 65.516 mg/kg (SnI) to 146.889 mg/kg (SnH), while the corresponding wet weight concentrations ranged from 18.573 to 41.631 mg/kg WW. The 95% CI (14.243–44.913 mg/kg WW) and coefficient of variation (CV, 3.540–38.890%) further highlight the variability in Mn accumulation across sampling sites.

The higher Mn levels in SnH and SnE suggest increased environmental exposure, likely due to Mn-rich soils and anthropogenic activities including vehicular emissions, agricultural runoff, metal waste disposal, and crude oil-related operations. Conversely, the lower Mn concentration in SnI reflects a site with reduced exposure to these sources. The wide 95% CI values indicate a degree of uncertainty in the population mean, reflecting both natural variability and site-specific factors influencing Mn accumulation. Sites with higher CVs (up to 38.890%) demonstrate significant heterogeneity in Mn concentrations among individual snails, suggesting localized hotspots of contamination or differences in snail feeding and movement patterns.

When compared to previous studies, the present Mn concentrations are substantially elevated. For example, Onuoha et al. (2016) reported 5.97–12.10 mg/kg in Rivers State, Awharitoma et al. (2016) found 2.85–8.90 mg/kg in Edo State, and Iwegbue et al. (2008) documented 0.61–1.27 mg/kg across several southern states. The marked enrichment of Mn in Yenagoa Metropolis underscores the influence of both geochemical and anthropogenic factors on bioaccumulation.

Mechanistically, Mn accumulation in snails reflects a combination of environmental geochemistry and snail physiology. Mn is mobilized under reducing soil conditions, increasing its bioavailability for uptake through ingestion of Mn-laden soil particles and decaying organic matter. High traffic corridors and market zones contribute to particulate deposition on vegetation, further enhancing dietary exposure. The snail's slow metabolism and efficient metal sequestration amplify Mn bioaccumulation, consistent with the elevated mean values observed.

From a health perspective, all recorded Mn values far exceed the 1 mg/kg permissible limit (Biswas et al., 2021), indicating substantial contamination. While Mn is essential for antioxidant enzyme activity and metabolic regulation, chronic exposure to elevated levels can lead to neurotoxicity, Parkinson-like symptoms, and cognitive impairment (Izah et al., 2016). The high CV and broad 95% CI values further imply that some snail populations may experience particularly intense exposure, increasing the risk of human and ecological health effects when these snails are consumed.

Nickel (Ni) concentrations (dry weight) in *A. achatina* ranged from 0.537 mg/kg (SnJ) to 7.410 mg/kg (SnD), showing statistically significant spatial variations ($p < 0.05$). The corresponding wet weight values ranged from 0.152 to 1.838 mg/kg, with 95% CI spanning 0.132–2.182 mg/kg and CV values of 5.701–21.1%. The highest Ni levels were observed at SnD and SnC, while the lowest was recorded at SnJ. This pattern indicates pronounced anthropogenic influence at SnD and SnC, likely from activities such as waste combustion, vehicular emissions, and metal-related industrial processes. Conversely, the low concentration at SnJ suggests minimal local contamination.

The 95% CI values indicate the reliability of the mean wet weight concentrations. Narrower CI at certain sites reflects lower variability and higher precision in measured values, whereas broader CIs suggest heterogeneous contamination or fluctuating environmental inputs. Similarly, the CV values provide insight into data dispersion relative to the mean: low CV (<10%) at some sites implies consistent Ni levels across sampled snails, while higher CV (up to 21.1%) highlights pronounced variability, likely due to spatially inconsistent anthropogenic deposition. Collectively, the CI and CV values highlight both the precision of measurements and the influence of site-specific factors on Ni accumulation.

Notably, nearly all observed values exceeded the FAO/WHO permissible limit of 0.6 mg/kg for Ni in food (Joseph et al., 2021; Hassan, 2022), signaling potential health risks. Chronic Ni exposure is linked to dermatitis, respiratory ailments, and carcinogenic effects, emphasizing the public health implications of these findings.

Comparatively, the Ni concentrations recorded in this study fall within or exceed ranges reported in other Nigerian studies. Joseph et al. (2021) observed 0.01–3.601 mg/kg in *A. marginata* from Akwa Ibom, Gabriel et al. (2025) documented 0.05–1.45 mg/kg in *A. fulica* from Delta State, whereas Samuel et al. (2018) reported higher values of 8.98–12.821 mg/kg in *A. achatina* from Abia, Enugu, and Ebonyi States. Similarly, Awharitoma et al. (2016) recorded 3.26–16.58 mg/kg in *A. marginata* from Edo State, Hassan (2022) documented 21.14–21.28 mg/kg in Lagos, and Onuoha et al. (2016) reported 0.78–3.54 mg/kg in Rivers State. The present values are lower than the extremely high Ni concentrations (1.17–22.36 mg/kg) reported from Okolobiri and Odi, Bayelsa State (Ikimi and Addy, 2024).

Mechanistically, Ni bioaccumulation in *A. achatina* is influenced by soil contamination through industrial effluents, disposal of Ni-containing alloys, and fossil fuel combustion, which increase Ni availability in soils and vegetation. The snails assimilate Ni via grazing on contaminated plant material, ingestion of soil particles, and dermal absorption during locomotion. Factors such as soil pH and organic matter content modulate Ni mobility, while the feeding ecology, movement patterns, and substrate interactions of *A. achatina* contribute to observed site-specific variations.

Lead (Pb) concentrations in *A. achatina* exhibited clear spatial variability. On a dry weight basis, Pb ranged from 2.456 mg/kg (SnH) to 8.881 mg/kg (SnC), showing statistically significant differences across sites ($p < 0.05$). Corresponding wet weight concentrations ranged from 0.696 to 2.518 mg/kg WW, with 95% CI of 0.610–3.021 mg/kg WW and CV between 9.770 and 25.790%, indicating moderate to high variability among sampled populations.

The elevated Pb levels observed in SnC and SnE likely reflect environmental contamination sources such as atmospheric deposition, vehicular emissions, and potential contact with lead-containing

materials during snail handling and processing. Conversely, SnH had the lowest concentration, suggesting minimal environmental Pb exposure at that location. The fact that all dry weight values and some wet weight values exceeded the FAO/WHO permissible limit of 1.5 mg/kg (Hassan, 2022; Joseph et al., 2021) highlights potential health risks associated with chronic Pb exposure, including neurotoxicity, renal impairment, and hematological effects (Izah et al., 2016).

Comparative literature reveals that the present Pb range (2.456–8.881 mg/kg) is generally higher than many reported levels. Joseph et al. (2021) documented 0.01–3.601 mg/kg in Akwa Ibom, Gabriel et al. (2025) found 0.025–3.210 mg/kg in Delta State, and Awharitoma et al. (2016) reported 0.14–0.71 mg/kg in Edo State. Similar or slightly higher concentrations were noted by Iwegbue et al. (2008) (0.77–7.51 mg/kg) and Onuoha et al. (2016) (2.60–5.00 mg/kg). Exceptionally high values have been recorded by Samuel et al. (2018) (61.914–114.559 mg/kg), Ikimi and Addy (2024) (0.13–31.53 mg/kg), Kalu et al. (2024) (0.00–66.60 mg/kg), and Hassan (2022) (1.20–1.22 mg/kg), reflecting site-specific contamination.

Mechanistically, Pb accumulation in snails is driven by environmental exposure pathways, including atmospheric deposition of vehicular exhaust residues, hydrocarbon pollution, improper battery disposal, lead-based paints, and contaminated soils. Snail's bioaccumulate Pb through ingestion of contaminated vegetation, soil particles, and dermal absorption. Variations in soil properties such as texture, organic matter, and cation exchange capacity affect Pb bioavailability, while differences in habitat use, feeding behavior, and exposure duration among snail populations contribute to observed spatial differences.

The statistical values provide additional insights: the 95% CI indicate the precision of mean estimates, with narrower CIs reflecting more reliable site-specific measurements, whereas wider CIs suggest greater variability and heterogeneous contamination. The CV values reveal the degree of dispersion relative to the mean, with higher CVs (up to 25.790%) indicating inconsistent Pb accumulation among individual snails, likely due to microhabitat variability or differential exposure. These metrics emphasize the need for site-specific monitoring and caution in snail consumption from high-Pb areas.

Zinc (Zn) concentrations in the snail samples demonstrated notable spatial variability, reflecting both environmental inputs and biological accumulation patterns. On a dry weight basis, Zn ranged from 68.759 mg/kg (SnK) to 102.069 mg/kg (SnC), indicating statistically significant differences among sampling sites ($p < 0.05$). When converted to wet weight, concentrations ranged from 19.491 to 28.934 mg/kg WW, with 95% CI spanning 16.706–31.623 mg/kg WW. The CV ranged widely from 2.560 to 24.200%, reflecting the relative consistency of measurements at some sites (low CV) and greater heterogeneity at others (high CV).

The highest Zn levels observed in SnC and SnE suggest intense environmental loading, likely from metal scraps, fertilizer residues, and domestic waste, whereas lower concentrations in SnK and SnA may indicate reduced contamination sources or limited Zn mobility in these areas. The 95% CI values further confirm that, while some spatial variability exists, the mean Zn concentrations at heavily contaminated sites consistently exceed the lower bounds of safe exposure, reinforcing the concern of environmental enrichment. The CV values provide insight into the dispersion of data; sites with high CV indicate localized variability or heterogeneous contamination,

while low CV suggests uniform accumulation within the population sampled.

Comparatively, the Zn concentrations in this study are substantially higher than many previous Nigerian reports when considering dry weight. Joseph et al. (2021) documented 0.136–13.280 mg/kg in Akwa Ibom, Iwegbue et al. (2008) reported 0.08–0.22 mg/kg across southern states, and Onuoha et al. (2016) observed 11.6–27.6 mg/kg in Rivers State. Similarly, Kalu et al. (2024) recorded 24.21–40.81 mg/kg in Abia State, and Hassan (2022) reported 62.38–62.51 mg/kg in Lagos. The only comparable range was reported by Ikimi and Addy (2024), who found 6.63–173.29 mg/kg in Okolobiri and Odi, overlapping with the upper concentrations observed in the present study. On a wet weight basis, some alignment with previous reports is noted, indicating that moisture content plays a critical role in moderating exposure assessments.

Mechanistically, Zn accumulation in snails reflects a combination of biological essentiality and environmental exposure. Urbanization and industrial emissions increase Zn deposition in soils, while the use of Zn-based fertilizers further contributes to elevated concentrations. Snails absorb Zn efficiently due to its role in enzymatic function, making them sensitive bioindicators of environmental contamination. Soil parameters (including pH, redox potential, and organic matter) modulate Zn bioavailability, while snail-specific factors such as feeding behavior, shell formation, and habitat moisture regulate uptake, explaining the observed spatial differences.

Implications of the 95% CI and CV values are significant. Narrow CIs suggest that the mean concentrations are robust and reliable, providing confidence in the exposure assessment. Conversely, wide CIs or high CV values highlight heterogeneity in contamination or biological variability, emphasizing that certain sites may pose localized health risks if Zn levels exceed the permissible limit of 100 mg/kg (Biswas et al., 2021).

On the overall, the comparative abundance of metals followed the general descending order Fe > Mn > Zn > Cu > Cd > Pb > Ni > Co > Cr, indicating that iron was consistently the most abundant metal while chromium was the least. The dominance of Fe reflects its natural geochemical abundance in soils of the Niger Delta, largely controlled by parent material and redox conditions (Izah et al., 2017), whereas elevated Mn and Zn similarly suggest strong lithogenic inputs with possible enrichment from anthropogenic activities such as waste disposal and traffic-related emissions. Cu occurred at moderate levels, likely influenced by mixed sources

including domestic effluents and urban runoff. In contrast, Cd and Pb, though present at lower absolute concentrations, are of greater toxicological concern, as their occurrence is typically linked to anthropogenic inputs (such as refuse dumps, batteries, paints, and fuel residues), implying potential public health risks despite their lower abundance. The consistently low levels of Ni, Co, and especially Cr suggest limited industrial discharge or weaker geochemical mobility of these metals in the study area.

Pearson correlation of trace metals in *Achatina achatina* sold in Yenagoa Metropolis

The Pearson correlation analysis (Table 5) revealed several statistically significant relationships among the trace metals in *A. achatina* tissues, indicating both shared and distinct contamination sources within the Yenagoa environment. Strong positive correlations were observed between Co and Cr ($r = 0.794, p < 0.01$), Co and Pb ($r = 0.650, p < 0.01$), Cr and Pb ($r = 0.662, p < 0.01$), and Co and Ni ($r = 0.512, p < 0.01$). Fe also correlated positively with Cr ($r = 0.493, p < 0.01$) and Pb ($r = 0.495, p < 0.01$). Similarly, Cu showed positive associations with Cd ($r = 0.363, p < 0.01$) and Mn ($r = 0.310, p < 0.05$). In contrast, significant negative correlations were observed between Cd and Ni ($r = -0.692, p < 0.01$), Cd and Co ($r = -0.443, p < 0.01$), Cd and Pb ($r = -0.360, p < 0.01$), as well as between Cu and Co ($r = -0.352, p < 0.01$) and Cu and Fe ($r = -0.347, p < 0.01$). These patterns highlight important co-contamination pathways, competitive interactions, and underlying biogeochemical processes influencing metal accumulation in *A. achatina*.

The strong positive correlations among Co, Cr, Fe, Ni, and Pb suggest metals that not only share common anthropogenic inputs but also display similar environmental mobility and uptake mechanisms. Their co-occurrence may be driven by adsorption onto similar soil particle fractions (e.g., Fe–Mn oxides), co-transport in runoff, and parallel binding affinities to snail mucosal proteins. The present findings particularly imply simultaneous exposure to mixed urban pollutants such as crude oil exploration, combustion residues, and traffic emissions. The shared correlations (Co–Pb–Cr–Fe–Ni) likely reflect combined deposition from vehicular particulates, waste oils, and metal debris, which can create environmental microzones where these metals remain bioavailable to snails.

TABLE 5 Pearson correlation of trace metals in *Achatina achatina* sold in Yenagoa metropolis, Nigeria.

Parameters	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn
Cd	1								
Co	-0.443**	1							
Cr	-0.267*	0.794**	1						
Cu	0.363**	-0.352**	-0.223	1					
Fe	0.232	0.339**	0.493**	-0.347**	1				
Mn	0.130	-0.041	-0.085	0.310*	-0.157	1			
Ni	-0.692**	0.512**	0.394**	-0.138	-0.190	-0.136	1		
Pb	-0.360**	0.650**	0.662**	-0.279*	0.495**	-0.037	0.412**	1	
Zn	0.065	-0.030	0.102	0.223	0.092	0.004	0.156	0.160	1

**Correlation is significant at the 0.01 level (2-tailed); *Correlation is significant at the 0.05 level (2-tailed); $n = 5; N = 60$.

The positive associations between Cu and Cd, and Cu and Mn, further suggest metals that may behave synergistically during environmental transport. Cu and Cd, for example, tend to co-occur in agricultural soils, waste leachates, and decomposing refuse, and both can readily form soluble complexes under slightly acidic conditions. Their co-accumulation in *A. achatina* may also reflect similar affinities for metallothioneins. Conversely, the negative correlations between Cu and Co, and Cu and Fe, imply that Cu may compete with these metals for uptake or intracellular binding sites. Such antagonism can result when one metal reduces the bioavailability or transport efficiency of another, or when their ionic forms interact differently with ligands in soil pore water.

The strong negative correlations of Cd with Ni, Co, and Pb point to Cd originating from more localized or chemically distinct sources, including discarded batteries, pigments, plastics, or crude oil residues. Mechanistically, Cd often behaves more independently due to its high mobility under reducing and low-pH conditions. Its negative association with Ni, Co, and Pb may therefore indicate contrasting geochemical niches—with Cd becoming bioavailable in microenvironments where the mobility of Ni, Co, and Pb is suppressed. Cd's distinct behavior may also reflect differences in competition at biological uptake points, where the presence of Ni or Pb can inhibit Cd absorption and vice versa.

Zn, in contrast, showed weak and non-significant correlations with all other metals, implying a largely independent origin or stable environmental background level. Zn bioaccumulation in edible snails is often influenced by natural dietary sources and essential metabolic requirements rather than pollution inputs. Therefore, its lack of association with toxic metals such as Pb and Cd in this study suggests limited anthropogenic influence on Zn uptake, consistent with its typical regulation within biological tissues.

Principal component analysis of trace metals in *Achatina achatina* sold in Yenagoa Metropolis

The PCA of trace metals in *A. achatina* sold across Yenagoa Metropolis identified four unrotated components with eigenvalues greater than one, cumulatively explaining 82.71% of the total variance in the dataset (Table 6). Component 1 accounted for 38.01% of the total variance and exhibited strong positive loadings for Co (0.878), Cr (0.831), Pb (0.820), and Ni (0.644). This component likely represents a dominant anthropogenic source, reflecting emissions from industrial activities, vehicular exhaust, waste combustion, and petroleum-related operations common in the Bayelsa State. The co-association of these metals suggests their co-mobilization and deposition through atmospheric particulates and contaminated soils. This indicates that *A. achatina* inhabiting such environments bioaccumulate metals from multiple pollution pathways.

Component 2 explained 18.41% of the total variance and was mainly influenced by Fe (0.831) and Cd (0.680), implying mixed eugenic and anthropogenic origins. The presence of Fe indicates natural soil mineral composition, while Cd's association suggests additional input from human activities such as crude oil contamination, battery disposal, and refuse burning. Component 3, contributing 15.00% of the variance, showed high loadings for Cu (0.675) and Zn (0.674). These essential trace elements are often linked

TABLE 6 Unrotated variance explained of trace metals in *Achatina achatina* sold in Yenagoa metropolis, Nigeria.

	Component			
	1	2	3	4
Cd	-0.602	0.680	0.140	-0.011
Co	0.878	0.023	0.078	0.234
Cr	0.831	0.247	0.205	0.103
Cu	-0.510	-0.092	0.675	0.021
Fe	0.442	0.831	-0.075	-0.059
Mn	-0.219	-0.021	0.537	0.722
Ni	0.644	-0.623	0.183	-0.145
Pb	0.820	0.196	0.211	0.046
Zn	0.074	0.089	0.674	-0.635
Total	3.421	1.657	1.35	1.016
% of Variance	38.013	18.412	15.001	11.288
Cumulative %	38.013	56.425	71.426	82.714

Threshold ≥ 0.50 .

to agricultural inputs like fertilizers and pesticides, and domestic waste. Component 4 accounted for 11.29% of the variance and was dominated by Mn (0.722), suggesting a natural geochemical source, possibly from soil weathering or runoff from agricultural lands.

The principal component analysis (PCA) of trace metal concentrations in *A. achatina* revealed four rotated (Varimax) components that together explained 82.71% of the total variance in the dataset (Table 7). The individual contributions of each rotated component were as follows: Component 1 accounted for 32.37% of the variance, Component 2 for 22.53%, Component 3 for 14.47%, and Component 4 for 13.35%. These components provide insight into the major sources and inter-metal relationships influencing trace metal accumulation in *A. achatina* within the Yenagoa metropolis.

Component 1 exhibited strong positive loadings on Cr (0.879), Pb (0.837), and Co (0.819), as well as a moderate loading on Fe (0.724). This pattern suggests a dominant anthropogenic influence, likely from crude oil-related activities, combustion of municipal waste, and deposition of metallic debris in the environment. The co-occurrence of Cr, Pb, and Co indicates a common source, possibly linked to vehicular emissions, industrial effluents, and oil spillage and activities. The moderate loading of Fe further supports the role of soil dust and iron oxide particulates adhering to vegetation and surfaces, which are subsequently ingested by *A. achatina*.

Component 2 was defined by a strong negative loading of Cd (-0.871) and a high positive loading of Ni (0.863), indicating contrasting geochemical or anthropogenic sources for these metals. Cadmium is typically associated with industrial processes such as battery waste disposal, pigment production, plastic manufacturing, and crude oil contamination. The inverse relationship with Ni suggests that areas heavily impacted by Cd sources experience lower Ni accumulation, possibly due to competitive absorption processes or differences in pH-dependent solubility. Ni which is often derived from vehicular exhaust, lubricants, and fuel combustion, may dominate in less industrially polluted zones. Such antagonistic patterns have been reported in mollusks and sediments influenced by mixed industrial and urban runoff.

TABLE 7 Rotated (varimax) factor loadings of trace metals in *Achatina achatina* sold in Yenagoa metropolis, Nigeria.

	Component			
	1	2	3	4
Cd	-0.186	-0.871	0.148	0.172
Co	0.819	0.378	0.006	-0.138
Cr	0.879	0.170	-0.019	0.057
Cu	-0.346	-0.118	0.587	0.497
Fe	0.724	-0.534	-0.292	0.010
Mn	0.038	-0.082	0.918	-0.087
Ni	0.281	0.863	-0.064	0.172
Pb	0.837	0.213	-0.047	0.099
Zn	0.113	0.016	-0.039	0.925
Total	2.913	2.028	1.302	1.201
% of Variance	32.37	22.529	14.466	13.349
Cumulative %	32.37	54.899	69.365	82.714

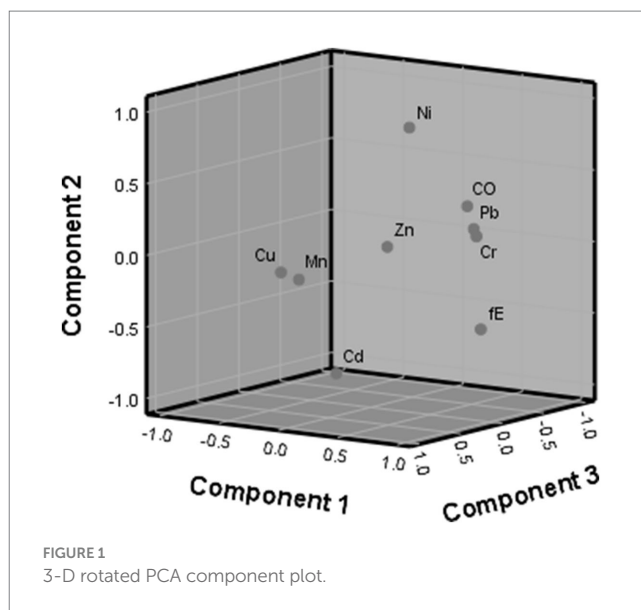
Threshold ≥ 0.50 .

Component 3 showed strong positive loading for Mn (0.918) and a moderate loading for Cu (0.587), suggesting a common natural or agricultural origin. Both Mn and Cu are essential micronutrients, and their elevated presence in *A. achatina* likely reflects bioaccumulation from soil and vegetation through feeding activities. Agricultural runoff enriched with fertilizers, pesticides, and organic residues may also contribute to these metal levels. Mn and Cu in edible *A. achatina* may be due to soil nutrient cycling and agrochemical use rather than industrial contamination.

Component 4 was dominated by Zn (0.925), with a moderate contribution from Cu (0.497). This factor likely represents dietary and eugenic sources of biologically essential metals. Zn is a crucial trace element for enzymatic and reproductive functions in mollusks, and its accumulation generally mirrors the mineral composition of soil and vegetation consumed by the *A. achatina*. The weak association of Zn with other toxic metals implies that its origin in *A. achatina* is predominantly natural rather than anthropogenic.

The 3-D rotated PCA plot shows how trace metals in *A. achatina* tissues cluster based on shared variability and environmental relationships (Figure 1). Co, Pb, Cr, and Fe (partially Ni) cluster together, reflecting common anthropogenic sources like vehicle emissions, crude-oil residues, and metal scraps. These metals share similar snail uptake pathways through soil ingestion, mucous adhesion, and absorption via the foot and digestive gland. Cu and Mn form a separate cluster, representing essential micronutrients regulated for enzymatic activity. Their variability depends more on soil type and organic matter than industrial contamination. Cd is isolated, indicating distinct contamination sources such as plastics, and crude-oil residues. It shows unique tissue accumulation probably due to high mobility and competition with Zn and Ca. Zn occupies a central position, weakly associated with pollution metals, reflecting dietary or soil-background origins controlled by snail metabolism.

The hierarchical cluster analysis (Figure 2) grouped the sampling locations of *A. achatina* sold in Yenagoa Metropolis into distinct clusters based on the similarities in trace metal concentrations. The first cluster comprised SnB, SnF, SnD, SnH, SnL, and SnG, indicating



similar contamination patterns likely influenced by shared environmental or anthropogenic factors such as market proximity, crude oil related activities, traffic emissions, and waste deposition. The second cluster included SnK, SnC, SnE, and SnJ, suggesting moderate metal similarity possibly linked to mixed urban and semi-urban influences. The third and most distinct cluster consisted of SnA and SnI, representing locations with unique metal profiles, perhaps due to localized pollution sources or differing soil and vegetation compositions.

The hierarchical cluster analysis of trace metals in *A. achatina* consumed in Yenagoa metropolis is shown in Figure 3. It revealed a clear separation of metals into distinct clusters, reflecting underlying similarities in their sources or uptake behavior. In one principal cluster, Co, Cr, Cd, Ni, Pb, Cu, Mn, and Zn are grouped together at relatively low rescaled distances, indicating a tendency for co-variation among these metals. Within this group, the closer linkage between Co, Cr, Cd, and Ni suggests they may derive from shared anthropogenic sources such as industrial emissions, vehicular discharge, and petroleum-related activities. Ama et al. (2017) have previously reported so metals in the environmental matrices could be due to vehicular emissions and crude oil related activities. Such clustering of multiple metals into a common group has been observed in soil studies, where Cd, Cr, Ni, Pb, and Cu are often placed in the same cluster, distinct from Fe (e.g., hierarchical clustering in soils: Cd, Cr, Ni, Pb, Cu, Mn, Co and Zn in one cluster; Fe alone) (Izah et al., 2017).

In contrast, Fe formed a separate cluster far apart from the rest, signifying that it behaves differently from the other trace metals in *A. achatina*. This separation suggests that Fe is likely dominated by eugenic or natural sources, such as soil mineral composition, dust deposition, or iron oxide particulates, rather than being strongly tied to anthropogenic contamination in the study area. Similar partitioning where Fe clusters separately has been reported in cluster analyses of heavy metals in soils (Izah et al., 2017) and fish from Okulu river in Rivers state (Aigberua et al., 2021) and air in Bayelsa State (Izah et al., 2021). This reaffirm that Fe often represents a background or eugenic signature distinct from pollution-driven metals.

Health risk assessment of *Achatina achatina* consumed in Yenagoa Metropolis, Nigeria

The health risk assessment of trace metals in *A. achatina* consumed in Yenagoa Metropolis, Nigeria, is summarized in Tables 8–10. The EDI of trace metals across the sampling locations (SnA–SnL) demonstrated marked spatial variations, indicating differences in environmental and anthropogenic pollution sources (Table 8). Trace metal intake in *A. achatina* varied across locations. Overall, the order of estimated daily intake for metals in *A. achatina* across all locations was Fe > Cu > Mn > Zn > Cd > Co > Pb > Ni > Cr. This indicates that Fe and Cu contributed the highest intake levels, followed by Mn and Zn, whereas Cr, Ni, and Pb contributed the lowest daily intakes. The spatial trends suggest that environmental and anthropogenic factors within specific locations strongly influenced metal accumulation in the snails.

Hazard quotient (HQ) values indicated potential health risks associated with trace metal exposure through *A. achatina* consumption (Table 9). Cadmium (Cd) posed the highest risk, with HQ values ranging from 5.30×10^{-1} to 2.85×10^0 (mean 1.44×10^0), followed by copper (Cu), which ranged from 3.01×10^{-1} to 6.72×10^{-1} (mean 4.69×10^{-1}), and manganese (Mn), with values between 1.95×10^{-1} and 4.36×10^{-1} (mean 3.18×10^{-1}). Other metals exhibited comparatively lower HQs, including cobalt (Co: 9.70×10^{-2} – 7.29×10^{-1} , mean 3.09×10^{-1}), iron (Fe: 7.20×10^{-2} – 3.02×10^{-1} , mean 1.50×10^{-1}), zinc (Zn: 9.50×10^{-2} – 1.42×10^{-1} , mean 1.18×10^{-1}), nickel (Ni: 1.10×10^{-2} – 1.54×10^{-1} , mean 8.00×10^{-2}), lead (Pb: 7.00×10^{-4} – 2.50×10^{-3} , mean 1.50×10^{-3}), and chromium (Cr: 2.00×10^{-5} – 8.60×10^{-4} , mean 3.40×10^{-4}). The overall hazard index (HI) ranged from 1.83×10^0 to 4.31×10^0 (mean 2.89×10^0), exceeding the USEPA safety threshold of 1 across all sampling locations, thereby indicating potential non-carcinogenic health concerns. Locations SnH, SnI, and SnJ had the highest HI due to combined exposure to multiple metals. The contribution of individual metals to HI followed

the order: Cd > Cu > Mn > Co > Fe > Zn > Ni > Pb > Cr. These findings are consistent with Samuel et al. (2018), who reported HQ values exceeding 1 for Ni and Pb in *A. achatina* from Abia, Ebonyi, and Enugu States, highlighting potential health concerns, particularly for children. Their study showed Cr, Zn, and Cu within safe limits, with farmed snails exhibiting the lowest HQ values.

Lifetime carcinogenic risk (LCR) values exceeded the acceptable 10^{-4} threshold across sampled sites (Table 10). Cd ranged 2.013×10^{-4} – 1.081×10^{-3} (mean 5.483×10^{-4}), Cr 2.043×10^{-2} – 4.571×10^{-2} (mean 3.189×10^{-2}), Ni 3.793×10^{-4} – 5.242×10^{-3} (mean 2.725×10^{-3}), and Pb 8.683×10^{-6} – 3.141×10^{-5} (mean 1.880×10^{-5}). Overall LCR ranged 2.193×10^{-2} – 4.839×10^{-2} (mean 3.518×10^{-2}), with Cd and Cr as the primary contributors. The trend across metals indicates that the order of contribution to carcinogenic risk is Cd > Cr > Ni > Pb, highlighting Cd and Cr as the primary drivers of LCR, while Ni and Pb contribute to a lesser extent. The spatial distribution further highlights specific locations, particularly SnH, SnL, and SnC, where metal accumulation is pronounced, implying that consumption of snails from these areas may pose higher carcinogenic risk. Spatial trends indicated higher carcinogenic risk at SnH, SnL, and SnC, likely influenced by localized environmental contamination. These results align with Onuoha et al. (2016), who reported Cd and Ni carcinogenic risks of 3.4×10^{-4} – 3.2×10^{-1} and 4.1×10^{-3} – 1.0×10^{-2} , respectively, in snails from crude-oil-contaminated environments, demonstrating industrial pollution's role in elevating metal concentrations. Similarly, Gabriel et al. (2025) observed ILCR values $>10^{-3}$ for *A. fulica* from dumpsite and market sites in Delta State, confirming the carcinogenic potential of Cd and Ni in polluted Nigerian environments. Collectively, these findings stress that edible *A. achatina* collected from contaminated locations may pose significant long-term carcinogenic risks to human health.

A major limitation of this study is the uncertainty regarding the precise origin of the snail samples, as *A. achatina* consumed in Yenagoa metropolis are sourced from a variety of ecological settings, including forested bush areas, peri-urban farmlands, riparian habitats, urban

TABLE 8 Estimated daily intake of *Achatina achatina* consumed in Yenagoa metropolis, Nigeria.

Locations	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn
SnA	1.020E-03	2.915E-03	1.290E-03	1.497E-02	1.931E-01	4.622E-02	1.708E-03	3.383E-03	3.010E-02
SnB	5.298E-04	1.419E-03	5.621E-04	1.637E-02	5.767E-02	2.884E-02	2.447E-03	1.939E-03	3.794E-02
SnC	1.129E-03	2.642E-03	1.049E-03	2.081E-02	1.322E-01	4.948E-02	2.698E-03	3.696E-03	4.246E-02
SnD	5.577E-04	1.568E-03	5.533E-04	1.556E-02	6.310E-02	3.594E-02	3.084E-03	2.130E-03	3.129E-02
SnE	1.130E-03	1.170E-03	4.873E-04	1.647E-02	1.498E-01	5.574E-02	2.279E-03	3.487E-03	4.036E-02
SnF	9.188E-04	7.896E-04	3.978E-04	1.987E-02	5.444E-02	3.549E-02	1.653E-03	2.293E-03	3.502E-02
SnG	1.192E-03	6.737E-04	3.376E-04	2.181E-02	5.087E-02	4.766E-02	1.939E-03	1.359E-03	3.537E-02
SnH	2.846E-03	6.208E-04	3.978E-04	2.577E-02	5.067E-02	6.110E-02	6.707E-04	1.022E-03	3.694E-02
SnI	2.593E-03	8.337E-04	3.713E-04	1.565E-02	2.113E-01	2.726E-02	7.794E-04	1.843E-03	3.530E-02
SnJ	2.340E-03	4.961E-04	5.504E-04	1.890E-02	1.589E-01	3.901E-02	2.231E-04	2.005E-03	3.746E-02
SnK	1.205E-03	1.300E-03	1.468E-04	1.202E-02	7.551E-02	5.174E-02	6.003E-04	1.940E-03	2.861E-02
SnL	1.854E-03	3.860E-04	2.789E-05	2.689E-02	6.088E-02	5.643E-02	1.154E-03	1.450E-03	3.432E-02
Minimum	5.298E-04	3.860E-04	2.789E-05	1.202E-02	5.067E-02	2.726E-02	2.231E-04	1.022E-03	2.861E-02
Maximum	2.846E-03	2.915E-03	1.290E-03	2.689E-02	2.113E-01	6.110E-02	3.084E-03	3.696E-03	4.246E-02
Mean	1.443E-03	1.234E-03	5.143E-04	1.876E-02	1.049E-01	4.458E-02	1.603E-03	2.212E-03	3.543E-02

Calculation done based on the wet weight of the snails; Agudama (SnA), Igbogene (SnB), Akenfa (SnC), Swali (SnD), Kpansia (SnE), Etegwe (SnF), Opolo (SnG), Okaka (SnH), Ekeki (SnI), Bossy Water (SnJ), Okutukutu (SnK), and Yenezuie-gene (SnL).

TABLE 9 Non carcinogenic risk (hazard quotient and health index) of *Achatina achatina* consumed in Yenagoa metropolis, Nigeria.

Locations	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn	HI
SnA	1.020E+00	7.287E-01	8.601E-04	3.742E-01	2.758E-01	3.301E-01	8.542E-02	2.255E-03	1.003E-01	2.918E+00
SnB	5.298E-01	3.548E-01	3.748E-04	4.091E-01	8.238E-02	2.060E-01	1.223E-01	1.293E-03	1.265E-01	1.833E+00
SnC	1.129E+00	6.605E-01	6.996E-04	5.203E-01	1.888E-01	3.534E-01	1.349E-01	2.464E-03	1.415E-01	3.131E+00
SnD	5.577E-01	3.919E-01	3.689E-04	3.889E-01	9.014E-02	2.567E-01	1.542E-01	1.420E-03	1.043E-01	1.946E+00
SnE	1.130E+00	2.924E-01	3.249E-04	4.117E-01	2.140E-01	3.982E-01	1.140E-01	2.325E-03	1.345E-01	2.698E+00
SnF	9.188E-01	1.974E-01	2.652E-04	4.968E-01	7.777E-02	2.535E-01	8.263E-02	1.528E-03	1.167E-01	2.145E+00
SnG	1.192E+00	1.684E-01	2.250E-04	5.453E-01	7.267E-02	3.404E-01	9.694E-02	9.061E-04	1.179E-01	2.535E+00
SnH	2.846E+00	1.552E-01	2.652E-04	6.443E-01	7.238E-02	4.364E-01	3.354E-02	6.810E-04	1.231E-01	4.312E+00
SnI	2.593E+00	2.084E-01	2.476E-04	3.911E-01	3.019E-01	1.947E-01	3.897E-02	1.229E-03	1.177E-01	3.848E+00
SnJ	2.340E+00	1.240E-01	3.669E-04	4.726E-01	2.270E-01	2.787E-01	1.115E-02	1.337E-03	1.249E-01	3.580E+00
SnK	1.205E+00	3.251E-01	9.785E-05	3.005E-01	1.079E-01	3.695E-01	3.001E-02	1.294E-03	9.535E-02	2.435E+00
SnL	1.854E+00	9.650E-02	1.859E-05	6.722E-01	8.697E-02	4.031E-01	5.768E-02	9.667E-04	1.144E-01	3.286E+00
Minimum	5.298E-01	9.650E-02	1.859E-05	3.005E-01	7.238E-02	1.947E-01	1.115E-02	6.810E-04	9.535E-02	1.833E+00
Maximum	2.846E+00	7.287E-01	8.601E-04	6.722E-01	3.019E-01	4.364E-01	1.542E-01	2.464E-03	1.415E-01	4.312E+00
Mean	1.443E+00	3.086E-01	3.429E-04	4.689E-01	1.498E-01	3.184E-01	8.014E-02	1.475E-03	1.181E-01	2.889E+00

Calculation done based on the wet weight of the snails; Agudama (SnA), Igbogene (SnB), Akenfa (SnC), Swali (SnD), Kpansia (SnE), Etegwe (SnF), Opolo (SnG), Okaka (SnH), Ekeki (SnI), Bossy Water (SnJ), Okutukutu (SnK), and Yenezuie-gene (SnL); An HI > 1 implies potential health concern.

TABLE 10 Carcinogenic risk of *Achatina achatina* consumed in Yenagoa metropolis, Nigeria.

Locations	Cd	Cr	Ni	Pb	LCR
SnA	3.876E-04	2.545E-02	2.904E-03	2.876E-05	2.877E-02
SnB	2.013E-04	2.782E-02	4.159E-03	1.648E-05	3.220E-02
SnC	4.289E-04	3.538E-02	4.586E-03	3.141E-05	4.043E-02
SnD	2.119E-04	2.645E-02	5.242E-03	1.810E-05	3.192E-02
SnE	4.295E-04	2.800E-02	3.875E-03	2.964E-05	3.233E-02
SnF	3.491E-04	3.378E-02	2.809E-03	1.949E-05	3.696E-02
SnG	4.529E-04	3.708E-02	3.296E-03	1.155E-05	4.084E-02
SnH	1.081E-03	4.381E-02	1.140E-03	8.683E-06	4.604E-02
SnI	9.855E-04	2.660E-02	1.325E-03	1.567E-05	2.892E-02
SnJ	8.890E-04	3.214E-02	3.793E-04	1.704E-05	3.342E-02
SnK	4.579E-04	2.043E-02	1.021E-03	1.649E-05	2.193E-02
SnL	7.044E-04	4.571E-02	1.961E-03	1.233E-05	4.839E-02
Minimum	2.013E-04	2.043E-02	3.793E-04	8.683E-06	2.193E-02
Maximum	1.081E-03	4.571E-02	5.242E-03	3.141E-05	4.839E-02
Mean	5.483E-04	3.189E-02	2.725E-03	1.880E-05	3.518E-02

Calculation done based on the wet weight of the snails; Agudama (SnA), Igbogene (SnB), Akenfa (SnC), Swali (SnD), Kpansia (SnE), Etegwe (SnF), Opolo (SnG), Okaka (SnH), Ekeki (SnI), Bossy Water (SnJ), Okutukutu (SnK), and Yenezuie-gene (SnL).

gardens, compost heaps, refuse sites, and small backyard or commercial snail farms. Many market samples are aggregated from multiple collectors and rural suppliers, which makes it difficult to attribute the observed trace metal concentrations to specific locations or environmental conditions. Consequently, while the study provides valuable insight into the overall contamination levels of snail tissues available for consumption in Yenagoa, the findings may not fully reflect localized differences in metal exposure, soil attributes, or habitat-specific accumulation patterns.

Another limitation of this study is the reliance on default or literature-derived exposure and toxicological parameters (such as ingestion rate, body weight, exposure duration, reference doses, and

cancer slope factors) for estimating the EDI, HQ, and carcinogenic risk associated with the consumption of *A. achatina* in Yenagoa Metropolis, Nigeria. While the application of these standardized inputs is consistent with established practice in preliminary dietary and environmental health risk assessments, particularly where site-specific data are limited, their use could introduce inherent uncertainty into the risk estimates. Thus, these assumptions may not fully reflect local consumption patterns, demographic characteristics, or exposure variability among residents of Yenagoa, which could result in under- or over-estimation of actual health risks. Therefore, the findings suggests the indicative of potential risk rather than definitive.

Conclusion

This study provides a comprehensive evaluation of trace metal contamination and associated health risks from the consumption of edible *A. achatina* sold in Yenagoa Metropolis, Nigeria. The results demonstrate that *A. achatina* bioaccumulates appreciable concentrations of both essential and toxic trace metals, with pronounced spatial variability across sampling locations. On a dry weight basis, several metals (particularly Cd, Pb, Cu, Fe, Mn, Ni, and Zn) exceeded internationally recommended permissible limits in multiple locations, while wet weight concentrations, though generally lower, still indicated potential exposure concerns. The overall abundance pattern (Fe > Mn > Zn > Cu > Cd > Pb > Ni > Co > Cr) reflects a combination of strong eugenic influences (notably for Fe and Mn) and significant anthropogenic inputs, including vehicular emissions, waste disposal, crude oil-related activities, and market handling practices.

Pearson correlation, PCA, and hierarchical clustering further confirmed that trace metal accumulation in *A. achatina* is governed by mixed pollution sources. Metals such as Co, Cr, Pb, Ni, and Fe were strongly associated with anthropogenic activities, whereas Mn, Cu, and Zn were more influenced by natural soil composition, dietary uptake, and agricultural inputs. Cadmium exhibited distinct behavior, suggesting localized contamination from specific sources such as battery waste, plastics, and crude oil residues. Health risk assessment revealed that the EDI of several metals varied markedly by location, reflecting uneven environmental contamination. The HI exceeded the USEPA safe threshold of 1 at all sampling sites, with Cd, Cu, and Mn being the major contributors to potential adverse health effects. Lifetime carcinogenic risk estimates for Cd, Cr, Ni, and Pb exceeded the acceptable lifetime cancer risk threshold (10^{-4}), indicating a possible significant long-term health concern for regular consumers.

Based on the findings of this study, there is an urgent need for continuous environmental and food safety monitoring to track trace metal accumulation in terrestrial food sources, particularly *A. achatina* within Yenagoa Metropolis. Regulatory and environmental protection authorities may also need to strengthen pollution control measures and enforce effective waste management strategies, especially in high-risk areas such as zones impacted by crude oil exploration and related activities. In parallel, the promotion of controlled snail farming systems using uncontaminated substrates and feeds should be encouraged as a safer alternative to wild harvesting. Furthermore, studies are recommended to clearly identify and characterize the ecological zones from which *A. achatina* sold in local markets are sourced, as this will improve traceability, risk attribution, and the development of targeted, evidence-based mitigation strategies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

Ethics statement

Ethical permission for the research was obtained from the Bayelsa Medical University Research and Ethics Committee.

Author contributions

TJ: Supervision, Writing – review & editing, Conceptualization, Writing – original draft, Funding acquisition, Data curation. SCI: Writing – review & editing, Project administration, Validation, Resources, Supervision, Writing – original draft, Formal analysis, Methodology, Visualization, Data curation, Investigation, Conceptualization.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This study was funded by TETFUND, Nigeria, through Institutional-based Research Intervention 2025.

Acknowledgments

The authors wish to thank TETFUND for funding this research through Institutional based Research intervention 2025.

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.

Author SCI specifically declare that he is an associate editor to Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2026.1724347/full#supplementary-material>

References

- Abdullahi, A., Lawal, M. A., and Salisu, A. M. (2021). Heavy metals in contaminated soil: source, accumulation, health risk and remediation process. *Bayero J. Pure Appl. Sci.* 14, 1–2. doi: 10.4314/bajopas.v14i1.1
- Aigberua, A. O., Izah, S. C., and Isaac, I. U. (2018). Level and health risk assessment of heavy metals in selected seasonings and culinary condiments used in Nigeria. *Biol. Evidence* 8, 6–15. doi: 10.18502/jehsd.v6i3.7242
- Aigberua, A. O., Izah, S. C., and Richard, G. (2021). Hazard analysis of trace metals in muscle of *Sarotherodon melanotheron* and *Chrysichthys nigrodigitatus* from Okulu River, Rivers state, Nigeria. *J. Environ. Health Sustain. Dev.* 6, 1340–1356. doi: 10.5376/be.2018.08.0002
- Ama, I. N., Nwajei, G. E., and Agbair, P. O. (2017). Distribution of trace elements in surface water and sediments from Warri River in Warri, Delta state of Nigeria. *World News Nat. Sci.* 11, 65–82.
- Awharhitoma, A. O., Ewere, E. E., Alari, P. O., Idowu, D. O., and Osowe, K. A. (2016). Assessment of heavy metals in African giant snail (*Archachatina marginata*) and its parasites collected from three communities in Edo state, Nigeria. *Int. J. Sci. Eng. Res.* 7, 793–797.
- Biswas, C., Soma, S. S., Rohani, M. F., Rahman, M. H., Bashar, A., and Hossain, M. S. (2021). Assessment of heavy metals in farmed shrimp, *Penaeus monodon*, sampled from Khulna, Bangladesh: an inimical to food safety aspects. *Heliyon* 7:e06587. doi: 10.1016/j.heliyon.2021.e06587
- Chokor, A. A., and Ogonegbu, A. C. (2023). Assessment of petroleum hydrocarbons in terrestrial snails (*Achatina achatina*) and mud fishes (*Clarias anguillaris*) from some parts of Ogbia LGA, Nigeria. *Arab. J. Chem. Environ. Res.* 10, 92–105.
- Chukwudebe, E. P. (2024). Nutrient analysis of edible land snails (*Achatina achatina*) in the Enugu state, Nigeria. *J. Nutr. Food Process.* 7. doi: 10.31579/2637-8914/266
- Enaji, I., Wuana, R., and Akpan, U. (2016). Trace metals levels in African giant land snails (*Achatina achatina*) from selected local government areas in Akwa Ibom state, Nigeria. *Open Access Libr. J.* 3, 1–9. doi: 10.4236/oalib.1102244
- Eze, C. N., and Ohanele, O. O. (2021). Heavy metals and parasites in African giant snail (*Achatina achatina*) from three communities in Ogoni, Rivers state, Nigeria. *IOSR J. Agric. Vet. Sci.* 14, 27–35. doi: 10.9790/2380-1403022735
- Falae, T. T., Ossai, C. P., Orosun, M. M., Abdulai, P. M., Udom, G. J., Nduka, J. K., et al. (2025). Probabilistic health risk assessment of heavy metals in vegetables cultivated near tin mining sites in Jos plateau state, Nigeria. *J. Hazard. Mater. Adv.* 20:100934. doi: 10.1016/j.hazadv.2025.100934
- Gabriel, O. E., Eyankware, M. O., and Chigoziem, O. (2025). Public health and environmental risk assessment of African giant snails (*Achatina fulica*) in urban areas of Asaba, Nigeria. *J. Toxicol. Environ. Health Sci.* 17, 12–20. doi: 10.5897/JTEHS2025.0526
- Hassan, I. A. (2022). Comparative and health risk assessment of heavy metals in mangrove forest and farm-bred African giant snails (*Archachatina marginata*). *FUOYE J. Eng. Technol.* 7, 420–423. doi: 10.46792/fuoyet.v7i4.892
- Ikimi, C. G., and Addy, P. S. (2024). Level of selected heavy metals in land snail (*Achatina fulica*) from Okolobiri, a community exposed to petroleum pollution in Bayelsa state. *World J. Pharm. Med. Res.* 10, 49–53.
- Iwegbue, C. M., Arimoro, F. O., Nwajei, G. E., and Eguavoen, O. (2008). Heavy metal content in the African giant snail *Archachatina marginata* (Swainson, 1821) (Gastropoda: Pulmonata: Achatinidae) in southern Nigeria. *Folia Malacol.* 16, 31–34. doi: 10.24925/turjaf.v1i1.1-7.1
- Iwegbue, C. M. A., Nwozo, S. O., Overah, C. L., Basse, F. I., and Nwajei, G. E. (2013). Concentrations of selected metals in some ready-to-eat foods consumed in southern Nigeria: estimation of dietary intakes and target hazard quotients. *Turk. J. Agric. I.* 1–7. doi: 10.24925/turjaf.v1i1.1-7.1
- Izah, S. C., and Aigberua, A. O. (2020). Microbial and heavy metal hazard analysis of edible tomatoes (*Lycopersicon esculentum*) in Port Harcourt, Nigeria. *Toxicol. Environ. Heal. Sci.* 12, 371–380. doi: 10.1007/s13530-020-00060-8
- Izah, S. C., Aigberua, A. O., and Richard, G. (2022). Concentration, source, and health risk of trace metals in some liquid herbal medicine sold in Nigeria. *Biol. Trace Elem. Res.* 200, 3009–3020.
- Izah, S. C., Basse, S. E., and Ohimain, E. I. (2017). Assessment of heavy metal in cassava mill effluent contaminated soil in a rural community in the Niger Delta region of Nigeria. *EC Pharmacol. Toxicol.* 4, 186–201. doi: 10.1007/s12011-021-02879-9
- Izah, S. C., Chakrabarty, N., and Srivastav, A. L. (2016). A review on heavy metal concentration in potable water sources in Nigeria: human health effects and mitigating measures. *Expo. Health* 8, 285–304. doi: 10.1007/s12403-016-0195-9
- Izah, S. C., Richard, G., Stanley, H. O., Sawyer, W. E., Ogwu, M. C., and Uwaeme, O. R. (2023). Integrating the one health approach and statistical analysis for sustainable aquatic ecosystem management and trace metal contamination mitigation. *ES Food Agroforest.* 14:1012. doi: 10.30919/esfaf1012
- Izah, S. C., Richard, G., Stanley, H. O., Sawyer, W. E., Ogwu, M. C., and Uwaeme, O. R. (2024a). Prospects and application of multivariate and reliability analyses to one health risk assessments of toxic elements. *Toxicol. Environ. Heal. Sci.* 16, 127–134. doi: 10.1007/s13530-023-00199-0
- Izah, S. C., Stanley, H. O., Richard, G., Sawyer, W. E., Uwaeme, O. R., and Sylva, L. (2024b). Source and health risks of trace metals in *Clarias batrachus* and *Chrysichthys nigrodigitatus* from surface waters in Bayelsa state, Nigeria: a probabilistic model. *Front. Sustain. Food Syst.* 8:1419143. doi: 10.3389/fsufs.2024.1419143
- Izah, S. C., Uzoekwe, S. A., and Aigberua, A. O. (2021). Source, geochemical spreading and risks of trace metals in particulate matter 2.5 within a gas flaring area in Bayelsa state, Nigeria. *Adv. Environ. Technol.* 7, 101–118. doi: 10.22104/aet.2021.5053.1368
- Joseph, A., Iwok, E., and Ekanem, S. (2021). Public health threats of heavy metals due to the consumption of *Achachatina marginata* (African giant land snail) from a partially remediated site in Ikot Ada Udo, Akwa Ibom state, South-South Nigeria. *Environ. Pollut.* 271:116392. doi: 10.1016/j.envpol.2020.116392
- Jota Baptista, C., Seixas, F., Gonzalo-Orden, J. M., and Oliveira, P. A. (2022). Biomonitoring of heavy metals and metalloids with wild mammals in the Iberian Peninsula: a systematic review. *Environ. Rev.* 31, 66–75. doi: 10.1139/er-2022-0071
- Kalu, E., Akporube, K. A., Akpabio, U., Obinnaya, O. D., and Ezenduka, V. E. (2024). Public health risk assessment of heavy metal contamination in ready-to-eat snails in Umuahia, Abia state, Nigeria. *J. Sustain. Vet. Allied Sci.* 6, 236–240. doi: 10.54328/covm.josvas.2024.207
- Macrotrends (2025). Nigeria life expectancy (1950–2025). Available online at: <https://www.macrotrends.net/global-metrics/countries/nga/nigeria/life-expectancy> (Accessed September 30, 2025).
- N’guessan, O., and Kouassi, D. (2024). Distribution of heavy metals and herbicides in the cephalopod, viscera and shell of the snail *Achatina achatina*. *Adv. Res. Biol. Sci.* 72, 72–85. doi: 10.9734/bpi/arbs/v5/11125F
- Nnamonu, E., Odo, G., Ajuzie, I., and Nwani, C. (2021). Proximate composition and bioaccumulation of heavy metals in edible *Achatina* spp. in some rural agro-settlements, South-East Nigeria. *J. Basic Appl. Zool.* 82:52. doi: 10.1186/s41936-021-00259-2
- Odubo, T. C., and Izah, S. C. (2025). Safety considerations of trace metals in locally produced nutritive food-drinks consumed in Yenagoa Metropolis, Nigeria. *Biol. Trace Elem. Res.* 203, 4408–4419. doi: 10.1007/s12011-024-04488-8
- Ogamba, E. N., Charles, E. E., and Izah, S. C. (2021). Distributions, pollution evaluation and health risk of selected heavy metals in surface water of Taylor Creek, Bayelsa state, Nigeria. *Toxicol. Environ. Heal. Sci.* 13, 109–121. doi: 10.1007/s13530-020-00076-0
- Oloruntoba, A., Omoniyi, A. O., Shittu, Z. A., Ajala, R. O., and Kolawole, S. A. (2024). Heavy metal contamination in soils, water, and food in Nigeria from 2000–2019: a systematic review on methods, pollution level and policy implications. *Water Air Soil Pollut.* 235:586. doi: 10.1007/s11270-024-07408-7
- Onuoha, S., Anelo, P., and Nkpa, K. (2016). Human health risk assessment of heavy metals in snail (*Archachatina marginata*) from four contaminated regions in Rivers state, Nigeria. *Am. Chem. Sci. J.* 11, 1–8. doi: 10.9734/acsj/2016/22163
- Samuel, U. C., Nmaduka, N. J., and Ekene, J. (2018). Human health probabilistic risk assessment of *Achatina achatina* (African giant snail) consumption as models of mining activities. *Int. J. Sci. Eng. Res.* 9, 1124–1133.
- Ugbaja, R. N., Enilolobo, M. A., James, A. S., Akinhanmi, T. F., Akamo, A. J., Babayemi, D. O., et al. (2020). Bioaccumulation of heavy metals, lipid profiles, and antioxidant status of snails (*Achatina achatina*) around cement factory vicinities. *Toxicol. Ind. Health* 36, 863–875. doi: 10.1177/0748233720954995
- United States Environmental Protection Agency (USEPA) (2011). Exposure factors handbook (EPA/600/R-09/052F). United States: US Environmental Protection Agency.
- United States Environmental Protection Agency (USEPA) (2012). Regional screening levels (RSLs) for chemical contaminants. United States: US Environmental Protection Agency.
- United States Environmental Protection Agency (USEPA) (2020). Regional screening levels (RSLs) - user’s guide. Available online at: <https://www.epa.gov/risk/regional-screening-levels-rsls-users-guide> (Accessed September 30, 2025).
- United States Environmental Protection Agency (USEPA) (2024). CT: DRAS 4 frequently asked question (FAQ): Should sample analytical (total) concentrations be entered as “wet weight” or “dry weight”? United States: US Environmental Protection Agency. Available online at: https://www.epa.gov/system/files/documents/2025-04/epa_may_2024_dras4_dry_weight_memo_508.pdf
- United States Environmental Protection Agency (USEPA) (2025a). Exposure assessment tools by routes – ingestion. Available online at: <https://www.epa.gov/expobox/exposure-assessment-tools-routes-ingestion> (Accessed September 30, 2025).
- United States Environmental Protection Agency (USEPA) (2025b). Conducting a human health risk assessment. Available online at: <https://www.epa.gov/risk/conducting-human-health-risk-assessment> (Accessed September 30, 2025).
- Uzoekwe, S. A., Izah, S. C., and Aigberua, A. O. (2021). Environmental and human health risk of heavy metals in atmospheric particulate matter (PM10) around gas flaring vicinity in Bayelsa state, Nigeria. *Toxicol. Environ. Heal. Sci.* 13, 323–335. doi: 10.1007/s13530-021-00085-7
- Vesković, J., and Onjia, A. (2025). Exposure and toxicity factors in health risk assessment of heavy metal(loid)s in water. *Water* 17:2901. doi: 10.3390/w17192901