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Assessment of Heavy Metal Concentrations in Selected Nigerian-Grown Rice Grains: Implications for Public Health

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ABSTRACT: Contamination of the food chain by heavy metals poses a serious threat to human health and disrupts sustainable agriculture. This study aims to evaluate heavy metal contamination in locally grown rice from selected states across Nigeria. Rice and soil samples were collected from rice paddy fields in Ogun, Kwara, Ekiti, Edo, Jigawa, and Kano. Atomic absorption spectrophotometry was employed to evaluate the elemental composition of rice and soil samples. Toxic metals such as Pb, Ni, Cd, and As were detected in some of the local rice varieties sampled. Notably, Pb (0.040±0.00) and Cd (0.277±0.02) were found in Ofada rice from Ogun state. Higher concentrations of Ni were found in Igbemo rice from Ekiti, with the lowest levels observed in Umza rice from Kano. Variations in As levels in the rice types followed the order: Ofada rice, Ogun > Sese rice, Edo > Pategi rice, Kwara > Costus rice, Kano > Igbemo rice, Ekiti > Umza rice, Kano. In soil samples, variations in Pb levels followed the order: Kwara soil > Kano soil > Ogun soil > Edo soil. Cadmium (Cd) levels were highest in Kwara soil (0.856±0.11) and lowest in Jigawa soil (0.119±0.01). However, the lifetime cancer risk (LCR) assessment for rice samples from different regions reveals that most of the samples exceed the US EPA *LCR* acceptable upper limit is 1.0×10^{-4}, suggesting a substantial danger of exposure to life cancer risk throughout a lifetime. Hence, underscoring the need for continuous monitoring and stringent control measures in vulnerable regions.

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Protecting human health and preserving environmental resources for future generations are core elements of the global sustainability agenda, especially as industrialization and civilization have become more pronounced (Farinmade *et al.*, 2019; Omoyajowo *et al.*, 2023; Omoyajowo *et al.*, 2024a, b). Increasing global awareness on environmental protection has underscored the critical importance of monitoring contaminants, especially pesticides and heavy metals, in staple foods like rice. This monitoring

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is especially critical in Nigeria, where the cultural significance of the African rice is profound. The bioaccumulation of these pollutants in rice plants poses serious risks to human health, biodiversity, and the environment; thereby emphasizing the essential role of environmental sustainability ensuring food security. Concerns about foods that exceed established maximum residue limits (MRL) have garnered significant attention worldwide (Akas *et al*., 2017; Omoyajowo *et al*., 2017; Omoyajowo *et al*., 2018; Omoyajowo *et al*., 2022; Toth *et al*., 2016). Although heavy metals, which include mercury (Hg), cadmium (Cd), arsenic (As), chromium (Cr), nickel (Ni), and lead (Pb), are essential in trace amounts for various biological functions in plants and humans, they become toxic when concentrations surpass threshold levels, posing significant health risks due to their non-biodegradable and persistent nature in environments contaminated by pollutants from sources such as mining, agricultural fertilizers, and pesticides, with heavy metal contamination being a critical global concern that exacerbates pollution and threatens public health (Afonne *et al*., 2020; Adegbite *et al*., 2024; Ghouma *et al*., 2022; Ogunyebi *et al*, 2019; Sharma *et al*., 2021).

Heavy metals, sourced from both natural and anthropogenic origins, can contaminate rice fields, posing significant risks to ecosystems and human consumers due to their toxic and persistent nature, with the bioaccumulation of these contaminants in rice plants highlighting the complex interconnections between agricultural practices, environmental health, and food security (Kader *et al*., 2023; Oshatunberu *et al*., 2023; Ghouma *et al*., 2022; Adegbite *et al*., 2024; Amiolemen *et al*, 2024). Previous research works have demonstrated the toxicity of rice contaminated with heavy metals such as Cd, As, and Pb (Song *et al*., 2021; Chen *et al*., 2021).

Assessing heavy metal contamination in locally grown rice is crucial for food safety and public health. Regular monitoring and analysis of heavy metal concentrations in rice can help identify polluted sources and implement appropriate risk mitigation strategies. Given the persistence and ubiquity of heavy metals in the environment and their potential harmful effects, addressing heavy metal contamination has become a critical issue for environmental management. Therefore, continuous monitoring of heavy metals in the environment is essential for protecting human health, preserving soil fertility, and promoting sustainable agricultural practices. Hence, the objective of this study was to investigate the public health implication of toxic metals Concentrations in locally grown rice from selected regions in Nigeria.

MATERIALS AND METHODS

Sample Collection and Preparation: The study was conducted across six states in Nigeria—Jigawa, Kano, Kwara, Ekiti, Ogun, and Edo—which occupy a strategic position for rice agriculture at both regional and national levels (Fig. 1). These states support rain-fed farming during the rainy season and irrigated farming practices during the dry season. Agricultural soil and rice grain samples were systematically collected from predominant accessible areas of rice production in Hadejia (Jigawa), Makwaro (Kano), Pategi (Kwara), Igbemo (Ekiti), Isoku (Ogun) and Akeke (Edo). The sampling followed a stratified random sampling technique to ensure representative data from different geographic and agronomic conditions within each state. Using a soil auger and following the soil sampling protocols and guidelines by Carter and Gregorich (2007), soil samples were collected at depths of 0-15 cm for surface soil and 15-30 cm for subsurface soil, with the auger being rinsed and cleaned between each collection to prevent cross-contamination. Soil samples collected at different depths were thoroughly mixed to ensure homogeneity and accurate representation of the soil properties across the sampled area. Each rice paddy field was divided into nine (9) uniform grids based on soil topography and historical land use, from which each sample of matured rice grains and soil were collected and combined into composite samples representatively; GPS coordinates were recorded for each site. A total of 108 samples (54 local rice and 54 soil samples) were carefully collected at harvest stage, and stored in clean, labelled plastic bags at room temperature to prevent cross-contamination. The collected samples were divided into smaller pieces and air-dried on paper for approximately two hours to remove excess moisture before further analysis. All sampling activities were conducted from May — December 2022.

Laboratory Analysis: All lab analysis was jointly carried out at the CTX-ION Laboratory Ikeja, Lagos and the Central laboratory of Nigeria Natural Medicine Development Agency, Victoria Island, Lagos. The following analyses were carried out on the samples.

Determination of heavy metal content: Soil and Rice Samples: For the heavy metal analysis, 1.5 g of each sample was pre-ashed by heating gently on a Bunsen burner in a fume cupboard until smoking ceased, then transferred to a muffle furnace at 550°C until all carbon was burnt away. The resulting ash was cooled in a desiccator, treated with 20 ml of 0.1M HCl to break up the ash, and filtered through acid-washed Whatman filter paper into a 100 ml volumetric flask, which was then filled to the mark with distilled water. The concentrations of Cr, Pb, Cd, Ni and As were determined using an atomic absorption spectrophotometer, with standards prepared for each metal and measurements taken using hollow cathode lamps and an air-acetylene flame, following AOAC (2005) procedures.

Health risk assessment of local rice grain samples: To assess the significance of metal and mineral status in rice and its impact on consumption, the estimated daily intake (EDI) was calculated using a formula (Eq. 1; (Azeez *et al*., 2020; Weber *et al*, 2021). The target hazard quotient (THQ) for heavy metals in rice was calculated using another formula (Eq. 2; Azeez *et al*., 2020; Weber *et al*, 2021) as reported by Aregbede *et al*. (2019) and Chijioke *et al*. (2020). The hazard index (HI), which is the sum of individual THQs, was also calculated to assess potential non-carcinogenic risks from consuming rice with heavy metals. An HI value less than 1 indicates minimal and safe exposure, while an HI greater than 1 indicates hazardous risk. Additionally, the possible lifetime cancer risk (LCR) from exposure to carcinogenic heavy metals and pesticides in rice was calculated (Eq. 3; Liao *et al*, 2018; Weber *et al*, 2021).

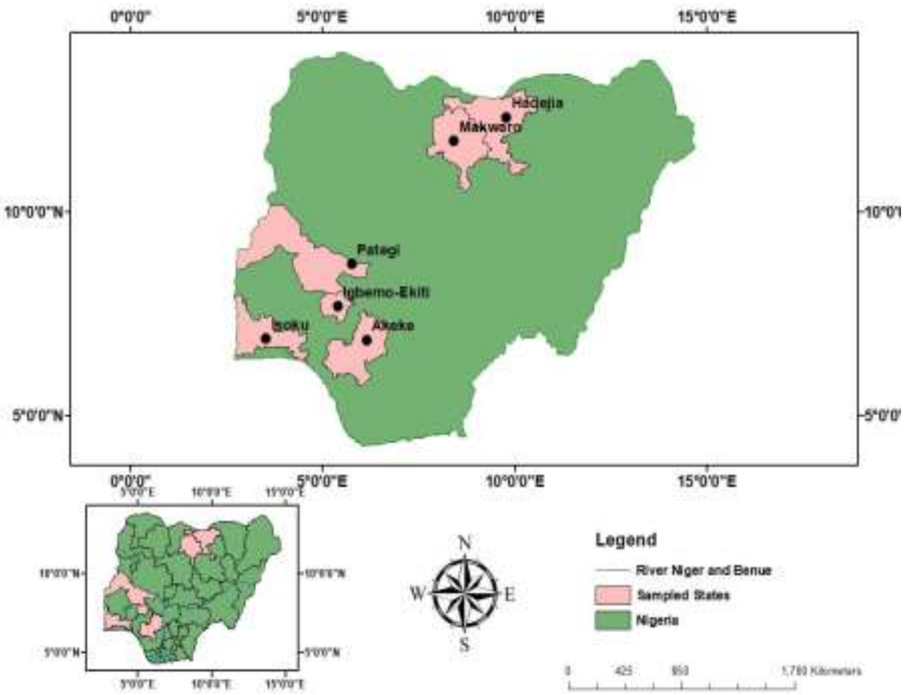

Fig. 1: Map of Study Area showing Sampling Locations

$$EDI(mgkg^{-1}BW day^{-1}) = \frac{metal\ concentration\left(\frac{mg}{kg}\right) x\ average\ daily\ consumption\ of\ rice(kg)}{Average\ body\ weight\ (kg)} \quad (1)$$

Daily average consumption of rice was assumed to be 70g (0.07 kg person^{-1} day^{-1}) from reports of Adedire *et al*. (2015). Average body weight of Nigerians was taken as 60 kg.

$$THQ = \frac{EDI}{RfD} \quad (2)$$

RfD: oral reference dose. Reference dose (RfD) for metals such as Zn, Cr, Mn, Pb, Fe, Ni, Cd, and As are 0.3, 0.003, 0.14, 0.0035, 0.3, 0.02, 0.001, and 0.0003 (mgkg^{-1} day^{-1}) respectively.

$$LCR = EDI\ x\ CSF \quad (3)$$

CSF: cancer slope factor (mg/kg/day)-1, and CSF values for Cd, Ni, Pb, Cr, and As are 0.38, 1.7, 0.01, 0.5, and 3.5 (mgkg day)-1, respectively (Azeez *et al*, 2020; US EPA, 1989). The normal range of ∑LCR acceptability is between 10-6 and 10-4. When the ∑LCR < 10^{-6}, the cancer risk is insignificant; and ∑LCR > 10^{-4} indicates a substantial danger of exposure to life cancer risk throughout a lifetime (ATSDR, 2024; USEPA, 2014; 2020).

Data analysis: Data reported in this work was analyzed using SPSS version 28. All variables were calculated as mean ± standard error. To assess differences between different rice and soil sample variables collected at various sites, a Tukey post-hoc Analysis of Variance (ANOVA) test was used. Pearson correlation was used to understand the linear relationship between the concentrations of metals in rice and soil samples. Hierarchical Cluster Analysis (HCA) was used to classify and evaluate the interrelationships among metal components in rice and soil samples. Heatmap was used to identify patterns and differential distribution for the elemental composition of rice and soil samples.

RESULTS AND DISCUSSION

Concentration level of metal in rice samples: The presence and accumulation of toxic metals in rice and other food commodities pose significant health risks to consumers. Levels of each metal or trace elements varies across all sampled locations ($P<0.05$). Cr levels ranged from 0.102±0.03 mg/kg in Ofada rice (Ogun State) to 1.114±0.00 mg/kg in Costus rice (Kano State), not detected in rice species sampled Kwara and Ekiti States. Cr levels in Sese rice (Edo) and Costus rice (Kano) with respective concentrations of 1.012±0.00 and 1.114±0.0 mg/kg were slightly higher than WHO/FAO permissible limit. Pb and Cd was only detected in Ofada rice (Ogun State), 0.04±0.00 mg/kg. and 0.277± 0.02 mg/kg respectively but lower than WHO/FAO permissible limit of 0.2 and 0.4 respectively. Arsenic (As) levels ranged from 0.002±0.00 mg/kg for Danmodi rice (Jigawa State) to 0.022±0.00 mg/kg in Ofada rice (Ogun State) but values are within WHO/FAO permissible limit. Ni levels ranged from 0.060± 0.00 in Umza rice (Kano) to 0.300±0.00 mg/kg in Igbemo rice (Ekiti) and all values were within WHO/FAO permissible limit. For trace elements, levels of Zn ranged from Sese rice (Edo) to 28.000±0.00 mg/kg in Pategi rice samples (Kwara State) but values are within WHO/FAO permissible limit. Mn levels generally ranged from 1.418±0.01 mg/kg in Danmodi rice (Jigawa) to 4.183±0.02 in Igbemo rice (Ekiti). Higher Mn values of 4.071±0.01, 4.113±0.02, and 4.183±0.02 mg/kg were reported in Sese rice (Edo), Pategi rice (Kwara), and Igbemo rice (Ekiti) respectively and observed to be above the WHO/FAO permissible limit. Fe ranged from 10.264±0.03 in Danmodi rice (Jigawa) to 34.292±0.16 mg/kg in Umza rice (Kano) and values were within WHO/FAO permissible limit (Table 1). Lead (Pb) and cadmium (Cd) concentrations were found to be generally low in rice samples from Ogun showing values within World Health Organization/Food and Agriculture Organization (WHO/FAO) maximum tolerable values (Opaluwa *et al*., 2012). Variability in metal concentrations across samples can be attributed to various factors, including geographic location, soil composition, agricultural practices, and environmental pollution (Zhao *et al*, 2018; Mandall *et al*, 2022). Essential metals like manganese (Mn), zinc (Zn), iron (Fe), and nickel (Ni) were found in the rice samples, with concentrations generally within acceptable ranges. However, inadequate iron levels in some samples suggest a potential need for dietary supplementation. Toxic metals, including chromium (Cr), arsenic (As), Pb, and Cd, were detected in some rice samples but generally within acceptable limits, and lower compared to some previous studies (TatahMentan *et al*, 2020; Wei *et al*, 2023). Even when levels of toxic metals meet safety standards, continuous monitoring and regulatory measures are essential to mitigate health risks from prolonged exposure to toxic metals in rice, which can cause hypertension, neurological disorders, and cancers (Pipoyan *et al*., 2023; Wei *et al*., 2023). Mn, Zn, Fe, and Ni are required in the human diet for their varied biological roles (Pinto *et al*., 2016; TatahMentan *et al*., 2020). In this study, the concentrations of these important metals in rice were in the following decreasing order: Zn > Fe > Mn > Ni. This is consistent with the results of Arhin *et al*. (2023). In the human diet, iron (Fe) is an essential trace element for optimal health. Insufficient iron consumption can harm the immune system and alter cognitive function (Arredondo and Núñez, 2005). In this investigation, the content of Fe in rice ranged from 10.264 to 34.292 mg/kg, as indicated in Table 1 and Fig. 2. These results are lower than those reported by Yaday *et al*. (2017), who documented Fe levels as high as 58.80 mg/kg in rice samples from Northern India. However, the Fe levels in this study are lower than the WHO maximum permitted limit of 450 mg/kg in diet (WHO, 2007). This shows that not all rice samples are high in Fe, as the values found are significantly lower than the required amounts. As a result, consumers may need to supplement their diets with more iron, as iron-rich rice can treat anaemia (Lucca *et al*., 2002).

Zinc (Zn) is an essential element found in human tissues, where it plays important roles in cell signaling, acts as an antioxidant, and provides anti-inflammatory properties (Arhin *et al*., 2023). A zinc shortage in the diet can cause seizures, hypothermia, eczema, nausea, and hair loss (Tapiero and Tew, 2003). In this study, Zn contents in rice ranged from 8.753 to 31.280 mg/kg, and with mean average Zn of 15.429 mg/kg indicating good nutritional status as indicated in Table 1 and Fig.2. These levels are within the WHO acceptable limit of 50 mg/kg (WHO, 2007). Although excessive Zn levels can have a negative impact on health by weakening immune processes and harming the renal

system (Harmanescu *et al*., 2011), the levels detected in this investigation were moderate. Inadequate dietary zinc can induce diarrhea and impaired growth (Hambidge and Krebs, 2007).
Manganese (Mn) concentrations in this study ranged between 1.418 and 4.183 mg/kg. These levels are lower than those found in previous studies: 5.68-10.96 mg/kg in rice from Ghana (Arhin *et al*., 2023), 6.2-10 mg/kg in Thai rice (Rahman *et al*., 2014), 5.90-10.3 mg/kg in Italian research, and 5.7 mg/kg in a Vietnamese study (Rahman *et al*., 2014). The dietary reference values for Mn suggest a daily consumption of 3 mg (EFSA, 2013). Manganese is a vital nutrient in the human diet, helping to sustain and regulate biochemical and cellular activities. Mn, in small concentrations, contributes to efficient nutrition metabolism and blood sugar management. However, whereas Mn is important for several physiological functions, excessive ingestion can result in substantial toxicity (O'Neal and Zheng, 2015).

In this study, nickel (Ni) concentrations varied from 0 to 0.300 mg/kg, falling below the WHO's maximum permissible level of 1.5 mg/kg in food (Yasmin *et al*., 2019). Nickel accumulation in the body can have negative consequences, including metal allergies that cause skin infections like dermatitis (Sharma, 2007), migraines, asthma, hypoglycemia, and even nasal and lung cancer (Genchi *et al*., 2020; Lu *et al*., 2005). Cadmium (Cd), arsenic (As), lead (Pb), and chromium (Cr) are non-essential minerals for human nutrition and health (Pinto *et al*., 2016; TatahMentan *et al*., 2020). The levels of these non-essential elements were identified in the following decreasing order: Cr > As > Cd > Pb. Lead is highly toxic to humans and has a significant carcinogenicity profile. Exposure to lead levels exceeding the optimum can lead to various health implications, including increased blood pressure, abortions, paralysis, headaches, decreased cognitive performance, and damage to the renal and neurological systems (de Jesus *et al*., 2021; Arhin *et al*., 2023). In this investigation, lead (Pb) was found in only one sample with a mean concentration of 0.040 mg/kg. Previous research findings found Pb levels in rice samples ranging from 0.03 mg/kg in Nepal to 0.05 mg/kg in China, and 0.007 mg/kg, 0.010 mg/kg, and 0.011 mg/kg in Vietnam, Thailand, and the United States, respectively (Norton *et al*., 2014). All these results are within the WHO's maximum acceptable limit of 0.2 mg/kg (Naseri *et al*., 2015). A comparable study by Otitoju *et al*. (2019) found greater Pb levels in rice, ranging from 0.229 to 0.812 mg/kg. Despite the low dietary content, the high consumption of lead-contaminated rice raises the risk of toxin accumulation. Rice is a staple food in Nigeria, and consumers may be exposed to lead and toxicity because of its frequent intake. Arsenic (As) occurs naturally in geological processes, but it can also be introduced into the environment by human activity. As levels in food are caused by environmental contamination, flooding, and farming methods (Arhin *et al*., 2023). Rice accumulates the most As of any grain crop due to the plant's affinity for the element (Zavala and Duxbury, 2008; Rokonuzzaman, 2022). Arsenic (As) concentrations in this investigation varied from 0.002 to 0.022 mg/kg, which is less than the 1.57 mg/kg observed in rice samples from Thailand in the Arhin *et al*. (2023) study. Furthermore, the As levels measured in this study are lower than those reported in China (0.31-0.70 mg/kg), India (0.03-0.04 mg/kg), the United States (0.11-0.66 mg/kg), and Vietnam (0.03-0.47 mg/kg) (Zavala and Duxbury, 2008; Arhin *et al*., 2023). The European Commission has proposed a maximum As concentration of 0.20 mg/kg in polished rice (Soni *et al*., 2001; Roychowdhury *et al*., 2002). Although the As readings in this study are within the suggested limit, continued buildup of this metal in soil and food samples may cause human harm. Arsenic accumulation in the human body can cause skin lesions, cancer, and diabetes (Halder *et al*., 2020). Cadmium (Cd) levels in this investigation varied from 0.00 to 0.277 mg/kg, which exceeded the 0.00-0.06 mg/kg range described by Arhin *et al*. (2023). Rahman *et al*. (2014) found considerably higher Cd levels in rice samples (8.7-17.1 mg/kg). Although all rice samples in this investigation contained Cd in amounts below the WHO's maximum acceptable level of 0.3 mg/kg in food (Yasmin *et al*., 2019), the metal can still offer health hazards by accumulating in the body and causing kidney damage (Park, 2012). Elevated Cd levels can cause anaemia, joint pain, lung and kidney difficulties, effects on sperm quality and birth weight, cardiovascular illness, hypertension, and low blood pressure (Mathew *et al*., 2018; Giuseppe *et al*., 2020; Mathew *et al*., 2020). The presence of Cd in rice samples in this study may be attributed to the widespread use of fertilizers, pesticides, and fungicides in rice farming (Park, 2012). However, the Cd levels observed in this study are significantly lower than the average level of 40.8 mg/kg reported by Baghaie and Aghili (2018) in rice from northern Iran.

Chromium is recognized as a carcinogenic and toxic element (Jaishankar *et al*., 2014; Mitra *et al*., 2022). Exposure to chromium (VI) can cause occupational asthma, kidney and liver damage, pulmonary congestion and edema, upper abdominal pain, nasal irritation and damage, respiratory cancer, and skin irritation. Studies have indicated that rice cultivated in soils contaminated with chromium and zinc may experience adverse effects on grain milling quality, morphology, plant biomass, photosynthetic rate, and seedling growth (Ma *et al*., 2016; Basit *et al*., 2021). In this study, the level of chromium ranged from 0.00 to 1.114 mg/kg. Although higher than the 0.248–0.660 mg/kg reported in rice samples from Surin Province, Thailand, by Kheangkhun *et al*. (2020), the values observed are still within acceptable limits when compared to the maximum permissible value of chromium in cereal agricultural products, which is 1.0 mg/kg (Ministry of Health of the People's Republic China, 2013). The elevated chromium content observed in Costus rice, Kano, may be attributed to the presence of heavy metal residues left on the rice grain during husking.

Concentration level of metals in soil: As indicated in Table 2, the study revealed the presence of zinc (Zn), chromium (Cr), manganese (Mn), lead (Pb), iron (Fe), cadmium (Cd), and arsenic (As) in all soil samples. No significant difference (P>0.05) in Zn levels for different soil samples in Ekiti, Kwara and Kano. However, soil sampled from Ogun, Jigawa and Edo significantly differs in their Zn levels (P<0.05); Zn levels ranged from 0.08±0.00 mg/kg in soil samples from Ogun to 0.230±0.00 mg/kg in that of Edo. Cr levels ranged from 0.686±0.08 mg/kg in soil samples from Ekiti, to 1.080±0.00 mg/kg in soil samples from Ogun. No significant differences (P>0.05) for Cr levels in soil samples from Ogun, Kwara, Jigawa, and Kano. Mn was not detected in soil samples from Ekiti and Edo but detected in that of Ogun (0.740±0.00 mg/kg), Kwara (0.897±0.00), Jigawa (0.841±0.01 mg/kg) and that of Kano (0.750±0.09 mg/kg). Pb was not detected in soil samples from Ekiti and Jigawa. However, there was a significant difference (P<0.05) for Pb levels across soil samples the rest of the sampled sites. Soil Pb level assumed the order: Ogun (0.010±0.00 mg/kg) < Edo (0.062±0.01 mg/kg) < Kwara (0.131±0.03 mg/kg). No significant difference (P>0.05) for soil Pb levels among samples from Kano and Ogun. No Fe was detected from soil samples from Ogun and Jigawa and no significant difference (P>0.05) between soil Fe levels detected in Ekiti (0.820±0.00 mg/kg), Kwara (0.900±0.00 mg/kg) and Edo (0.880 ±0.00). Surprisingly, Ni was not detected in all soil samples but was detected in some rice samples especially from Ogun, Kano, Ekiti and Jigawa. No Cd was detected in Edo soil samples. Cd levels ranged from 0.119±0.001 mg/kg in Jigawa to 0.856±0.11 mg/kg in Kwara. Arsenic (As) level ranged from 0.010±0.00 mg/kg in Jigawa to 6.085±0.00 mg/kg in Ogun. No significant difference (P>0.05) in As level among soil samples from Kwara and Edo, and also for values among Jigawa and Kano. Furthermore, the data demonstrate variations in the concentrations of heavy metals in agricultural soil samples across different regions in Nigeria. Regions such as Edo and Kwara consistently exhibit relatively higher concentrations of multiple metals, whereas others like Ogun and Kano show lower levels. These variations may be attributed to environmental factors (Albanese *et al*., 2015), including differences in geographical region, geological composition, and agricultural practices ranging from fertilizer to pesticide applications (Nguyen *et al*., 2016; Yu *et al*., 2016; Santos-Francés *et al*., 2017). According to the findings of this study, by simply comparing the current levels of heavy metals in the farmlands with the WHO permissible limits, there seem to be no apparent health risks. However, there is a possibility of continuous accumulation and an increase in heavy metal concentrations, which could be largely attributed to anthropogenic sources such as the application of fertilizers, pesticides, and herbicides on the farmlands.

In general, metal concentrations in soil samples were in decreasing order as follows: As > Cr > Fe > Mn > Cd > Zn > Pb > Ni. The heavy metal concentrations ranged between 0.00 and 6.085 mg/kg. These levels are lower than the 0.08 mg/kg to 35.31 mg/kg range recorded in soil samples from Spain in a study by Santos-Francés *et al*. (2017). The values found in our investigation are consistent with the world mean values for heavy metal concentration in soil reported by Santos-Francés *et al*. (2017).

The soil samples contained chromium (Cr) concentrations ranging from 0.686 to 1.08 mg/kg and cadmium (Cd) concentrations ranging from 0.00 to 0.856 mg/kg, which were like the control values reported for soils from the post office area, Bulunkutu, and Bama station in Maiduguri metropolis, Borno state, Nigeria (Abdullateef *et al*., 2014). These values also fall within the WHO desirable maximum levels for Cr and Cd in unpolluted soils (100 and 0.80 mg/kg, respectively) (WHO, 1996; Osmani *et al*., 2015). However, the heavy metal levels observed in the study by Osmani *et al*. (2015) were relatively higher than the permissible limit due to metallurgical activities conducted at the sample location. Excessive chromium levels beyond the permissible limit can be detrimental to plants, severely affecting their biological functions and entering the food chain upon consumption of these plant materials (Jaishankar *et al*., 2014). Chromium toxicity significantly disrupts biological processes in various plants, leading to phytotoxic effects such as reduced root growth, inhibited seed germination, decreased biomass, chlorosis, and necrosis (Ghani, 2011). Cadmium, a very hazardous nonessential heavy metal, is known for its negative effects on cellular enzymatic systems, oxidative stress, and inducing nutritional deficits in plants (Irfan *et al*., 2013).

The concentrations of manganese (Mn), zinc (Zn), and lead (Pb) in this study were lower, while iron (Fe) showed a significantly lower concentration compared to the control values in Abdullateef *et al*. (2014). The level of Pb recorded is below the WHO recommended limit of 85 mg/kg (Osmani *et al*., 2015). Zinc concentrations observed in the rice and soil samples were also below the WHO/FAO limit of 99.4 mg/kg (Mathew *et al*., 2022). Elevated zinc levels can disrupt the activities of earthworms and microorganisms, thereby hindering the biodegradation of organic matter (Wuana and Okieimen, 2011). While the soil samples in this study recorded low amounts of Pb and Fe, the concentrations of Cd and Mn were higher than those reported by Yaradua *et al*. (2020) in a similar study on heavy metal concentrations in soils from Katsina State, Nigeria.

The arsenic (As) concentrations in the soil samples from this investigation ranged from 0.01 to 6.085 mg per kilogram. Soil serves as a substantial sink for arsenic, which is highly bioavailable to rice roots under normal rice production circumstances (Kumarathilaka *et al*., 2018; Mandal *et al*., 2021). Total arsenic levels in uncontaminated soil typically vary from 0.1 to 10 mg/kg (Zhao *et al*. 2010). The European Union (EU) recommends that arsenic levels in agricultural soil not exceed 20 mg/kg (Rahaman *et al*., 2013; Hussain *et al*., 2021). The arsenic levels found in the soil samples in this investigation are under the recommended range. Although nickel (Ni) was not discovered in the soil samples, the concentration in the rice samples is within the allowed limits by WHO/FAO (FAO/WHO, 2021; Alkhatib *et al*., 2022).

Metals in soil compared to metal in local rice samples: The relationship between metals in soil and their presence in rice, as seen in Table 3, illustrates the plant's ability to absorb ionic metals through their roots to aerial parts, known as the transfer factor (TF) (Olguín and Sánchez-Galván, 2012). The low TFs for Ni and Pb may be due to their ability to form stable complexes with amino acids (Mengel, 2001). Other factors, such as soil pH and soil properties, also influence metal TFs from soil to crops (Islam *et al*., 2016; Anwarul Hasan *et al*., 2022). The negative correlations observed for several metals suggest that soil contamination does not always lead to high metal accumulation in rice, potentially mitigating health risks associated with metal exposure through rice consumption. Elevated metal levels in soil can cause phytotoxic effects on plants, inducing stress and impairing growth. In response to metal stress, plants may employ defense mechanisms to limit metal uptake and accumulation in their tissues, including rice grains (Lee *et al*., 2007; Atkinson and Urwin, 2012; Ningombam *et al*., 2024). This can result in lower metal concentrations in rice grains despite higher soil concentrations. Additionally, some metals may form insoluble complexes in the soil or exist in less bioavailable forms, making them less available for plant uptake. Previous studies found As and Cd as the most critical elements contributing to 64.57% and 22.38% of the overall human health respectively (Wei *et al*, 2023).

Relationship between metal concentrations in Rice and Soil samples: The Hierarchical Cluster Analysis (HCA) of metal concentration in rice and soil samples reveals distinct patterns of metal interrelationships. In rice samples, three main clusters were identified: the first cluster comprises toxic heavy metals (As, Cd, Cr, Ni, Pb), with Ni and Pb forming a subgroup and As, Cd, and Cr forming another. The second cluster contains only Mn, while the third cluster groups Zn and Fe into two distinct subgroups. This clustering suggests a strong association between these toxic metals in rice, which may be indicative of similar sources or pathways of accumulation in the rice grains (Weber *et al*, 2021).

In soil samples, the HCA also identified three distinct clusters: the first cluster includes Pb, Ni, Zn, Fe, and Cd, with Ni and Pb forming one subgroup, and Zn, Fe, and Cd forming another. The second cluster groups Cr and Mn into separate subgroups, while the third cluster consists solely of As. The different clustering patterns in soil compared to rice suggest variations in metal mobility, availability, or uptake mechanisms by the rice plants, reflecting the complex interactions between soil composition and plant absorption processes (Weber *et al*, 2021). These findings highlight the need for targeted soil management practices to mitigate the transfer of toxic metals into rice crops.

Toxic hazard quotient (THQ), LCR regarding consumption risks by Average Adult: The Toxic Hazard Quotient (THQ) is a valuable metric for assessing the risk associated with consuming food containing heavy metals. When THQ is less than 1, there is no significant risk to the public. Similarly, the Hazard Index (HI), which is the cumulative THQ of multiple heavy metals, must also be below 1 to deem the food safe. For all rice samples, the THQ values were found to be below 1 for all metals, indicating they are safe for consumption without obvious risks of heavy metal toxicity (Table 5). Specifically, the THQ for zinc (Zn) was highest in sample G and lowest in B; for chromium (Cr), it was highest in G and lowest in A; for manganese (Mn), it was highest in F and lowest in D; for iron (Fe), it was highest in C and lowest in D;

for nickel (Ni), it was highest in F and lowest in C; and for copper (Cu), it was highest in A and lowest in D. In this present study, the Estimated Daily Intake (EDI) of mineral nutrients and heavy metals from rice generally indicates no significant health risks for the average adult (Table 4). Studies by Chijioke *et al*. (2020), Ezeofor *et al*. (2019), Guadie *et al*. (2024), and Kelle *et al*. (2017) show that EDI values remain within recommended limits, with occasional slight exceedances for lead (Pb). EDI reported for metals were considerably lower than that reported in Qadir (2023). Chronic effects from high zinc (Zn) intake, such as altered iron function and reduced immune function, are typically observed only at higher daily intake levels. Overall, the Target Hazard Quotient (THQ), Hazard Index (HI) values for heavy metals in rice samples were below 1, suggesting low potential health risks. These findings align with previous studies by Atique *et al*. (2017), Ezeofor *et al*. (2019), and Guadie *et al*. (2019), which reported low THQ and HI values for heavy metals in rice. However, some studies in Nigeria have reported HQ and HI values exceeding 1, indicating potential metal toxicity in certain rice samples. As shown in Table 6, The Lifetime Cancer Risk (LCR) assessment for rice types grown in different regions of Nigeria reveals significant variability in the contributions of toxic metals. In Ogun rice (A), Nickel (Ni) is the primarily contributes 59.68%, followed by Cadmium (Cd) at 17.08%, Arsenic (As) at 14.75%. Chromium (Cr) at primarily contributes about 89.39% of LCR in Sese rice (B) whilst Arsenic (As) contributes about 10.61%. In Umza rice (C), Nickel (Ni) and Chromium (Cr) are the leading contributors at 49.79% and 35.56%, respectively, while Danmodi rice (D) shows a nearly even split between Chromium (Cr) and Nickel (Ni), contributing 53.80% and 46.20% to the LCR. Pategi rice (E) uniquely has Arsenic (As) as the sole contributor to its LCR. Igbemo rice (F) is predominantly affected by Nickel (Ni), which contributes 94.44% to its LCR, and Costus rice (G) is primarily influenced by Chromium (Cr) at 94.89%. These findings indicate that while Nickel and Chromium are the most common contributors to cancer risk across most rice types, Arsenic presents a significant risk in specific regions. Previous study found high LCR values for Arsenic in certain Chinese rice samples (Liao *et al*, 2018).

Table 1: Concentration of metals levels in local rice samples (mg/kg)

	Concentration of metal (mg/kg)							
Rice sample	**Zn**	**Cr**	**Mn**	**Pb**	**Fe**	**Ni**	**Cd**	**As**
Ogun rice (Ofada)	12.329 ± 0.01^{a}	0.102 ± 0.03^{a}	2.446 ± 0.00^{a}	0.040 ± 0.00	18.819 ± 0.06^{a}	0.210 ± 0.00^{a}	0.277 ± 0.02	0.022 ± 0.00^{a}
Sese rice, Edo	8.753 ± 0.02^{b}	1.012 ± 0.00^{d}	4.071 ± 0.01^{b}	ND	17.039 ± 0.03^{b}	ND	ND	0.017 ± 0.00^{b}
Umza rice, Kano	24.511 ± 0.10^{d}	0.149 ± 0.01^{b}	3.207 ± 0.01^{d}	ND	34.292 ± 0.16^{d}	0.060 ± 0.00^{b}	ND	0.004 ± 0.00^{d}
Danmodi, Jigawa	13.360 ± 0.04^{e}	0.848 ± 0.01^{c}	1.418 ± 0.01^{e}	ND	10.264 ± 0.03^{e}	0.210 ± 0.01^{a}	ND	0.002 ± 0.00^{e}
Pategi rice, Kwara	28.000 ± 0.00^{f}	ND	4.113 ± 0.02^{b}	ND	16.156 ± 0.09^{f}	ND	ND	0.012 ± 0.00^{f}
Igbemo rice, Ekiti	18.200 ± 0.027^{c}	ND	4.183 ± 0.02^{f}	ND	13.114 ± 0.08^{g}	0.300 ± 0.00^{c}	ND	0.005 ± 0.00^{d}
Costus rice, Kano	31.280 ± 0.04^{g}	1.114 ± 0.0^{e}	2.901 ± 0.01^{g}	ND	26.053 ± 0.04^{k}	ND	ND	0.007 ± 0.00^{g}
PL *(mg/kg)*	50	1.0	3	0.2	450	1.5	0.3	0.2

*Data are represented as mean ± standard error (n=9). Values with different superscripts across the group (rice sample) (a,b,c, d,e,f,g,h,I,j,k) are significantly different at $p < 0.05$; ND: Not detected. * Trace elements; PL=Permissible limit WHO (2007); EFSA (2013) All values are reported in mg/kg.*

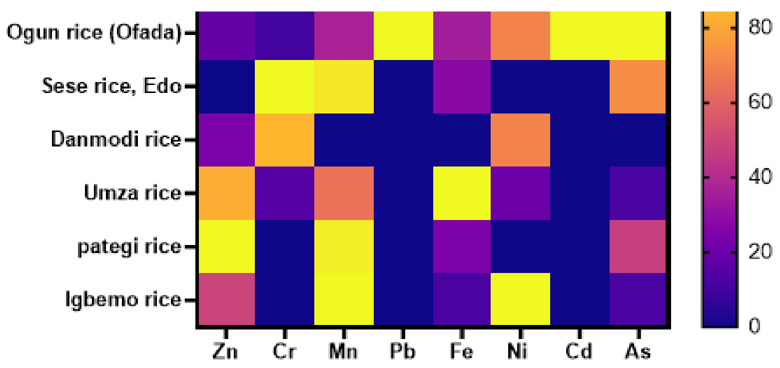

Fig. 2. Heatmap showing the differential distribution of metals in local rice types

Evidently, the lifetime cancer risk (LCR) assessment for rice samples from different regions reveals that most of the samples exceed the acceptable threshold of 0.0001, indicating potential health risks. Specifically, Ogun rice (A) exhibits an LCR of 0.0007121, Sese rice (B) 0.0006600, Umza rice (C) 0.0002390, Danmodi rice (D) 0.0009200, Igbemo rice (F) 0.0006300, and Costus rice (G) 0.0006850.

Table 2: Mean, standard error and ANOVA of Metal levels in soil (mg/kg)

Soil type	Zn	Cr	Mn	Pb	Fe	Ni	Cd	As
Ekiti soil	0.109±0.01^{b}	0.686±0.08^{a}	ND	ND	0.820±0.00^{b}	ND	0.752±0.12^{cd}	5.145±0.01^{b}
Ogun soil	0.080±0.00^{a}	1.080±0.00^{c}	0.740±0.00^{b}	0.010±0.00^{a}	ND	ND	0.484±0.17^{bc}	6.085±0.00^{c}
Kwara soil	0.110±0.00^{b}	1.000±0.00b^{c}	0.897±0.00^{c}	0.131±0.03^{c}	0.900±0.00^{b}	ND	0.856±0.11^{d}	4.597±0.02^{b}
Edo soil	0.230±0.00^{d}	0.889±0.02^{b}	ND	0.062±0.01^{b}	0.880±0.00^{b}	ND	ND	5.175±0.00^{b}
Jigawa soil	0.182±0.01^{c}	1.074±0.02^{c}	0.841±0.01^{b}	ND	ND	ND	0.119±0.01^{a}	0.010±0.00^{a}
Kano soil	0.124±0.00^{b}	1.040±0.05^{c}	0.750±0.09^{b}	0.011±0.01^{a}	0.100±0.00^{a}	ND	0.217±0.11^{ab}	0.570±0.59^{a}
Ekiti soil	0.109±0.01^{b}	0.686±0.08^{a}	ND	ND	0.820±0.00^{b}	ND	0.752±0.12^{cd}	5.145±0.01^{b}

Data are represented as mean ± standard error (n=9). Values with different superscripts down the groups (soil type) (^{a,b,c,d}) are significantly different at $p < 0.05$. ND: Not detected.

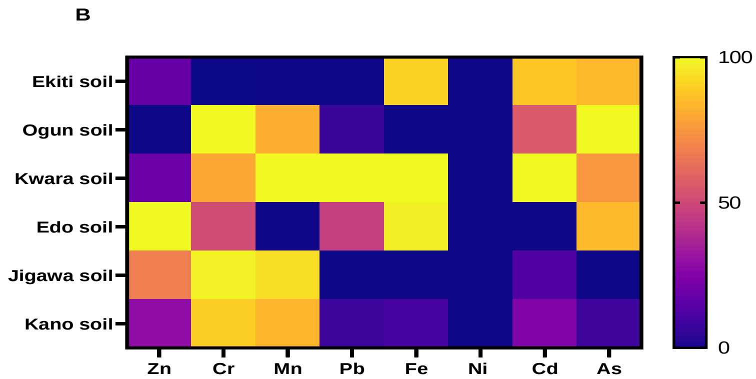

Fig. 3. Heatmap showing the differential distribution of metals in soil (B) from across the sampled states

Table 3. Correlation coefficient of the association between metal in soil and metal in local rice samples

Metals in soil	Zn	Cr	Mn	Pb	Fe	Ni	Cd	As
Zn	**-0.27**	0.15	0.65**	-0.03	0.25	ND	0.67**	-0.52**
Cr	0.67**	**0.09**	-0.25	0.04	-0.19	ND	-0.72**	-0.06
Mn	-0.09	-0.70**	**-0.27***	0.26	0.73**	ND	0.32*	0.27
Pb	-0.65**	0.28*	-0.10	**0.11**	-0.43**	ND	-0.07	0.65**
Fe	-0.24	0.22	-0.04	0.22	**-0.13**	ND	-0.23	0.33*
Ni	-0.46**	0.00	-0.35*	-0.72**	-0.57**	**0**	0.26	0.11
Cd	-0.65**	0.28*	-0.10	0.11	-0.43**	ND	**-0.07**	0.65**
As	-0.36**	-0.18	-0.25	0.61**	0.19	ND	-0.21	**0.83****

***Correlation is significant at the 0.01 level; *Correlation is significant at the 0.05 level. ND: not detected*

Table 4. Estimated daily intake (EDI) of metals in local rice through consumption of rice by average adult.

Metal	A	B	C	D	E	F	G	DI intake limit
Zn	0.01438	0.01021	0.02860	0.01559	0.03267	0.02123	0.03649	0.010
Cr	0.00012	0.00118	0.00017	0.00099	0.00000	0.00000	0.00130	0.143
Mn	0.00285	0.00475	0.00374	0.00165	0.00480	0.00488	0.00338	
Pb	0.00005	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.010
Fe	0.02196	0.01988	0.04001	0.01198	0.01885	0.01530	0.03040	0.800
Ni	0.00025	0.00000	0.00007	0.00025	0.00000	0.00035	0.00000	0.017
Cd	0.00032	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.005
As	0.00003	0.00002	0.00001	0.00000	0.00001	0.00001	0.00001	0.3000

A: Ogun rice, B: Sese rice, C: Umza rice, D: Danmodi rice, E: Pategi rice, F: Igbemo rice, G: Costus rice. EDI: mgkg^{-1}BW day^{-1}. DI: dietary intake mgkg^{-1}day^{-1}

Table 5. THQ of exposure to trace and heavy metals in local rice through consumption of rice by average adult

	Target Hazard Quotient						
Metal	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Zn	0.0479	0.0340	0.0953	0.0520	0.1089	0.0708	0.1216
Cr	0.0396	0.3936	0.0579	0.3297	0.0000	0.0000	0.4334
Mn	0.0204	0.0339	0.0267	0.0118	0.0343	0.0349	0.0242
Pb	0.0133	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fe	0.0732	0.0663	0.1334	0.0399	0.0628	0.0510	0.1013
Ni	0.0123	0.0000	0.0035	0.0123	0.0000	0.0175	0.0000
Cd	0.3234	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
As	0.0855	0.0645	0.0172	0.0084	0.0447	0.0176	0.0288
HI	0.0400	0.0360	0.0726	0.0305	0.0563	0.0418	0.0716

A: Ogun rice, B: Sese rice, C: Umza rice, D: Danmodi rice, E: Pategi rice, F: Igbemo rice, G: Costus rice. THQ: Target Hazard Quotient, HI: Hazard Index

Table 6. Lifetime cancer risk of exposure to heavy metals in local rice through consumption of rice by average adult

	Lifetime cancer risk (LCR)						
Metal	A	B	C	D	E	F	G
Cr	0.00006	0.00059	0.000085	0.000495	0.000000	0.000000	0.00065
Pb	0.0000005	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ni	0.000425	0.000000	0.000119	0.000425	0.000000	0.000595	0.000000
Cd	0.0001216	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
As	0.000105	0.00007	0.000035	0.000000	0.000035	0.000035	0.000035
∑LCR	0.0007121	0.00066	0.000239	0.00092	0.000035	0.00063	0.000685

A: Ogun rice, B: Sese rice, C: Umza rice, D: Danmodi rice, E: Pategi rice, F: Igbemo rice, G: Costus rice. LCR: Lifetime Cancer Risk.

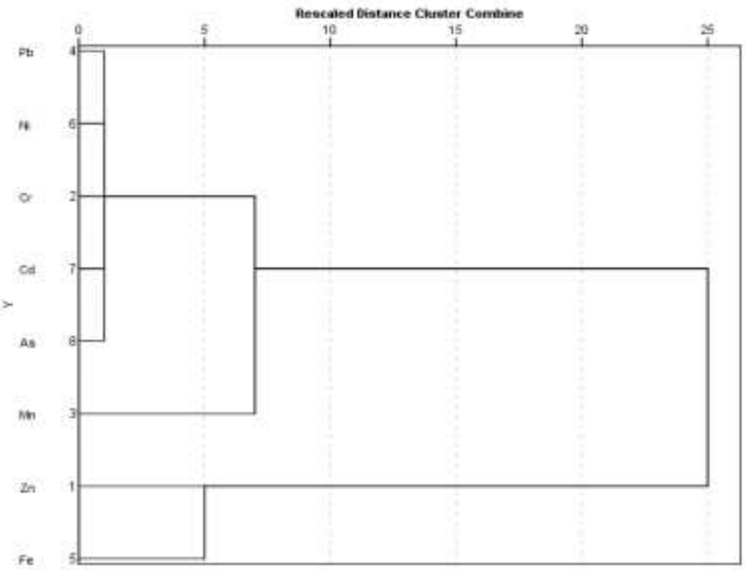

Fig 4. Dendrogram of hierarchical cluster analysis relationship among elemental components in rice samples

These values suggest that the consumption of these rice types could pose significant health risks due to elevated levels of carcinogenic metals. In contrast, Pategi rice (E) has an LCR of 0.0000350, which is below the threshold, indicating a lower potential health risk. The findings show that there is a high likelihood that an individual or community is predisposed to cancer risks from these metals through rice consumptions (Azeez *et al*, 2020; Chijioke *et al*., 2020; Qadar, 2023). This observation clearly underscored the critical need for continuous monitoring and management of carcinogenic metal concentrations in rice, particularly in regions where rice types show LCR values exceeding the safety threshold. The findings of this present study suggest continuous monitoring and management of heavy metal contamination in rice are essential to safeguard public health and environmental quality because there could still be health risks for certain individual groups, toddlers (2-5 years), and children (5-12 years). In other words, sustainable agricultural practices and food safety measures need to be taken more serious according to local conditions and with more risk acceptance.

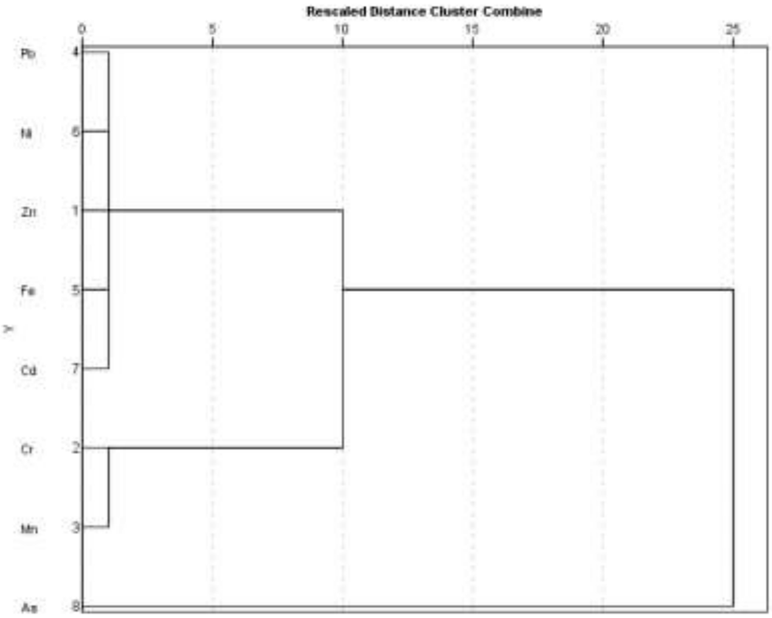

Fig 5: Dendrogram of hierarchical cluster analysis relationship among elemental components in soil samples

Conclusion: For the first time, this study provided a comprehensive analysis of toxic metal and organochlorine concentrations in rice and soil samples across different rice growing regions in Nigeria, providing reliable scientific basis to prepare national food safety and environmental resilience plan especially towards mitigating heavy metal and pesticide rice field contamination. Findings generally revealed that essential metals like iron (Fe) showed variability, indicating potential dietary supplementation needs. Soil samples from Edo and Kwara exhibited higher concentrations of multiple metals, highlighting the need for targeted monitoring in these regions. The lifetime cancer risk (LCR) assessment for rice samples from the sampling regions reveals that most of the samples exceed the US EPA LCR acceptable upper limit is 1.0×10^{-4}, suggesting a substantial danger of exposure to life cancer risk throughout a lifetime.

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Declaration of Conflict of Interest: The authors declare that there is no conflict of interest.

Data Availability Statement: The authors declare that data for this research are available upon reasonable request from the corresponding author

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