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Comparative Assessment of Soil Physicochemical Properties, Heavy Metal Uptake, and Health Risk Associated with Sorghum Cultivated under Inorganic Fertilizer and Animal Manure Amendments in Kano State, Nigeria

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ABSTRACT

The use of inorganic fertilizers and animal manure can affect soil quality and may lead to high levels of heavy metals in crops. The effects of inorganic fertilizer and animal manure amendments on the physicochemical properties of the soil and heavy metal uptake in sorghum grown in Faragai town, Albasu Local Government Area of Kano State, Nigeria, were investigated in this study. Samples of the soil and sorghum grain were taken from the inorganic fertilizer, manure-amended, and control farms. The soil physicochemical parameters were measured, and the concentrations of the heavy metals: lead, zinc, copper, cadmium, and chromium, were determined by dry ashing digestion using Atomic Absorption Spectrophotometry (AAS) in the sorghum grains. Estimated Daily Intake (EDI) and Hazard Quotient (HQ) models were used to assess the possible health risks of sorghum consumption. The results showed that the soils treated with inorganic fertilizers had lower pH and higher electrical conductivity, Nitrogen content, and organic matter than manure and control soils. Sorghum grains cultivated on fertilizer-treated farms recorded higher concentrations of Pb, Zn, Cu, and Cr (Figure 2). Lead concentrations in sorghum grains from inorganic fertilizer and manure-amended farms slightly exceeded the WHO/FAO permissible limit for cereals. The Hazard Quotient values of all the examined metals were below the threshold value of 1.0, indicating no significant non-carcinogenic health risk to consumers. The study demonstrates that agricultural practices influence soil characteristics and heavy metal uptake in sorghum. Continuous environmental monitoring and sustainable strategies are therefore recommended to minimize food safety and environmental health risks.

Keywords: Sorghum; Heavy Metals; Soil Physicochemical Properties; Environmental Toxicology; Hazard Quotient

INTRODUCTION

Sorghum (*Sorghum bicolor* L. Moench) is one of the most important cereal crops that serves as a source of calories and dietary nutrients and is important for household income in sub-Saharan Africa's semi-arid regions (Taylor *et al.,* 2021; Ilozobhie *et al.,* 2025). In Northern Nigeria, sorghum is a staple food crop due to its drought tolerance and adaptability to marginal soils. However, due to continuous cultivation and high population density, the fertility of soil has declined, and the farmers have to put a lot of effort into soil improvement by using soil amendments like animal manure, inorganic fertilizers, and so on, to ensure the productivity of the crop and the agricultural output (Tahat *et al.,* 2020; Bolan & Kirkham, 2023). These practices improve nutrient availability and plant growth, but continual use can cause changes in soil physicochemical properties and affect the build-up of environmental contaminants within farm systems.

The use of inorganic fertilizers and organic amendments has been linked to pH change, electrical conductivity, nutrient dynamics, and composition of organic matter in the soil. Inorganic fertilizers (principally phosphate fertilizers) can be contaminated with low levels of heavy metals from raw phosphate materials or the manufacturing process (Gray *et al.,* 1999). Use of these fertilizers multiple times may therefore lead to the accumulation of toxic metals over time in the soil, which can be taken up by the crop. Animal manure is also known to enhance soil structure, water holding capacity, and microbial activity, but can also contain heavy metals depending on animal feed, veterinary manure, and environmental exposure conditions (Wang *et al.,* 2006). Heavy metals are not biodegradable and can accumulate in the soil–plant system, so they can be present in soils for a long time.

Food crops' bioaccumulation of heavy metals poses a serious public health and environmental toxicological issue due to the potential for bioaccumulation and chronic dietary exposure. Some metals, such as lead (Pb), cadmium (Cd), chromium (Cr), zinc (Zn), and copper (Cu), can be taken up by the plant roots and transported into its edible parts, and therefore can be consumed by human beings (Alloway, 2013). While Zn and Cu are micronutrients with a requirement at low concentrations, high concentrations of these elements can cause physiological effects, and Pb and Cd do not seem to have a physiological function and are toxic at low concentrations (Jaishankar *et al.,* 2014). Neurological disorders, renal dysfunction, developmental abnormalities, carcinogenicity, and more are all linked to chronic exposures to these metals (Satarug *et al.*, 2011). The level of heavy metal uptake by crops is influenced by soil properties such as pH, organic matter content, soil water availability, CEC, and the nature of the soil amendment used (Gupta *et al.,* 2021).

Sorghum has been shown to contain different amounts of heavy metals in the environment under different farming conditions. The practice of using animal manure with inorganic fertilizers is widely practiced in many parts of Nigeria, including Kano State, and little comparative information is available on the role of these practices on the uptake of heavy metals in sorghum grown under semi-arid conditions. Most of the previous studies in Nigeria have been on the level of heavy metal pollution of vegetables and roadside crops, with relatively few studies on the level of heavy metal pollution of cereal crops under varying soil treatments (Dahiru *et al.*, 2013; Osakwe and Okolie, 2015), and a few studies have focused on the connection between heavy metal transfer into the grain and the soil physicochemical parameters in a local farming system.

Thus, this research was set up to compare the effects of inorganic fertilizers and animal manure amendments on some of the physicochemical properties of the soils and the uptake of the heavy metals by sorghum plants grown in Faragai Town, Albasu Local Government Area of Kano State, Nigeria. The study also examined the levels of the metals Pb, Zn, Cu, Cd, and Cr in sorghum grains to assess any possible food safety concerns with the application of these amendments to agriculture. It was hypothesized that the type of soil amendment would significantly influence soil physicochemical properties and the accumulation of the heavy metals in sorghum grains, with inorganic fertilizer expected to result in their higher accumulation than animal manure due to its contribution of metal impurities and its effects on soil chemical characteristics.

MATERIALS AND METHODS

Study Area

The study was carried out in Faragai Town, Albasu LGA of Kano State, Nigeria, after the harvesting period of sorghum (Sorghum bicolor). The area is under the Sudan savannah agroecological zone and has a semi-arid climate with a well-defined wet and dry season. Agriculture is a key economic sector in this region, and sorghum is one of the main cereal crops grown by the region's farmers. Soils in the area are mainly sandy loam, and soil fertility and crop production are often enhanced by adding inorganic fertilizer and animal manure to the soil.

Sample Collection

Samples of soil and sorghum grains from existing farm lands under various soil amendment practices were taken. Three cultivation conditions: farms treated with inorganic fertilizers, animal manure, and a control farm. The farms using the inorganic fertilizers used NPK (15:15:15) and urea, and the organic amendment used composted and air-dried animal manure, which included cow dung, poultry manure, and goat manure. A total of 30 samples were collected from soils under different treatments with inorganic fertilizers (10), animal manure (10), and control (10), and a clean soil auger was used to collect soil samples from the topsoil at a depth of 0–20 cm. The samples were transferred into clean polyethylene bags and carried to the laboratory for analysis. One hundred and twenty sorghum grain samples were taken at harvest maturity from 40 inorganic fertilizer, 40 manure, and 40 control farms, which were also packaged in clean polyethylene bags and transported to the laboratory for subsequent preparation and analysis.

Sample Preparation and Physicochemical Analysis of Soil

The soil samples were air-dried and crushed to remove debris and stones before analysis. Physicochemical parameters such as pH, electrical conductivity, bulk density, moisture content, nitrogen content, pore space, and organic matter content were determined by using the standard procedures adopted by the Association of Official Analytical Chemists (AOAC) and related soil analytical methods (Ben-Gigirey et al., 2012; Obasi et al., 2012). The soil pH and electrical conductivity were determined with calibrated digital pH and conductivity meters, respectively. The bulk density, moisture content, organic matter, and nitrogen content were measured following standard laboratory procedures routinely used in soil physicochemical analysis.

Heavy Metal Analysis of Sorghum Grains

The grain samples of sorghum were air-dried and ground into fine powder using a clean laboratory grinder, and the dry ashing digestion method was used for heavy metal analysis (Akinyele & Shokunbi, 2015; AOAC, 2023). The ashing of the powdered samples was done in porcelain crucibles at high temperature in a muffle furnace until complete ash formation was achieved. The ash obtained was dissolved with nitric acid solution and filtered in volumetric flasks before analysis. The levels of lead (Pb), zinc (Zn), copper (Cu), cadmium (Cd), and chromium (Cr) were measured by Atomic Absorption Spectrophotometry (AAS) according to standard methods of AOAC and methods reported in related literature (Ben-Gigirey et al., 2012; Wang et al., 2016).

Health Risk Assessment

The possibility of health risk from consumption of sorghum grains contaminated with heavy metals was assessed by the Estimated Daily Intake (EDI) model and Hazard Quotient (HQ) model as per the procedure given by the United States Environmental Protection Agency (USEPA) (Eisenbrand, 2015; Ulirsch and Li, 2022) for environmental risk assessment. An average daily sorghum consumption rate of 0.2 kg/person/day and an average body weight of 70 kg were used for the assessment. The oral reference doses (RfD) used for the assessment were lead (Pb), 0.0035 mg/kg/day; cadmium (Cd), 0.001 mg/kg/day; Chromium (Cr), 0.003 mg/kg/day; Copper (Cu), 0.04 mg/kg/day; Zinc (Zn), 0.30 mg/kg/day; based on the internationally accepted environmental health risk assessment guidelines (Guo et al., 2010; Tian and Niu, 2015). Hazard Quotient values less than 1.0 were interpreted as the absence of a significant non-carcinogenic risk to consumers.

Quality Assurance and Quality Control

To reduce contamination, all glassware used during the analysis was washed and rinsed with distilled water before use. All the analytical measurements were carried out in triplicate to guarantee the accuracy and reliability of the results. A set of standard solutions was prepared and used for the calibration of the Atomic Absorption Spectrophotometer.

Statistical Analysis

The results from the analysis were given as mean and standard deviation. IBM SPSS Statistics version 25 was used for the statistical analysis. Significant differences among the treatment groups were determined by one-way analysis of variance (ANOVA), and a multiple comparison test using Tukey's test was performed. A p-value < 0.05 was regarded as statistically significant.

RESULTS AND DISCUSSION

Physicochemical Properties of Soil Samples: Table 1 shows the physicochemical properties of the soils grown under various amendment conditions. There were large differences between the treatments for a number of soil parameters measured.

Table 1: Physicochemical Properties of Soil Samples Cultivated under Different Amendments

Parameter	Inorganic Fertilizer	Animal Manure	Control
pH	5.68 ± 0.14^{c}	6.11 ± 0.08^{a}	6.04 ± 0.12^{b}
Electrical conductivity (dS/m)	0.96 ± 0.06^{a}	0.83 ± 0.13^{b}	0.54 ± 0.04^{c}
Bulk density (g/cm^{3})	1.38 ± 0.03^{a}	1.17 ± 0.02^{b}	0.82 ± 0.02^{c}
Moisture content (%)	2.14 ± 0.21^{a}	1.88 ± 0.13^{b}	1.56 ± 0.07^{c}
Nitrogen content (%)	0.25 ± 0.02^{a}	0.16 ± 0.02^{b}	0.12 ± 0.02^{c}
Pore space (cm)	0.11 ± 0.03^{a}	0.08 ± 0.03^{b}	0.04 ± 0.01^{c}
Organic matter (%)	2.56 ± 0.24^{a}	2.23 ± 0.15^{b}	1.84 ± 0.10^{c}

Values are presented as mean ± standard deviation (SD). Means with different superscript letters within rows differ significantly at $p < 0.05$ according to Tukey's post hoc test.

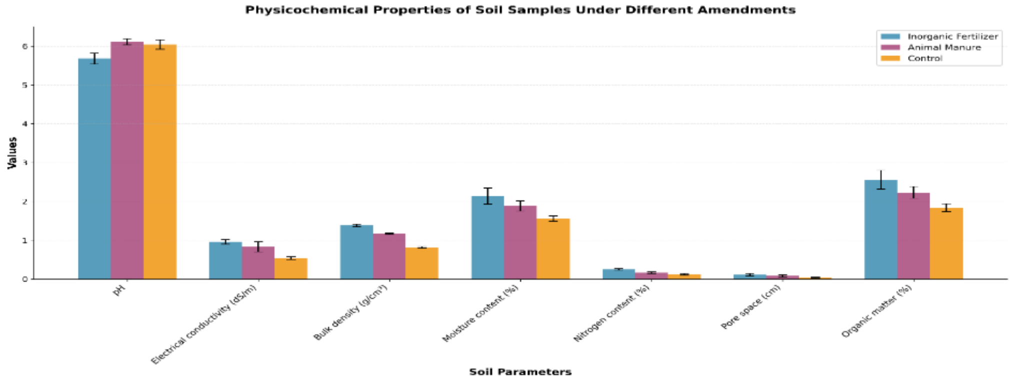

Figure 1: Physiochemical properties of soil samples under different amendments

Inorganic fertilizer treated soil had the lowest pH value (5.68 ± 0.14) which was more acidic than manure treated soil (6.11 ± 0.08) and control soil (6.04 ± 0.12). The soils amended with inorganic fertilizer (0.96 ± 0.06 dS/m) had the highest electrical conductivity and the lowest electrical conductivity was observed in the control soil (0.54 ± 0.04 dS/m). Soils receiving the inorganic fertilizer treatments all had relatively high amounts of bulk density, moisture content, nitrogen content, pore space, and organic matter compared to the other treatments. But manure amended soils recorded intermediate values for the rest of the parameters and these soils' physicochemical characteristic values were relatively closer to that of the control soil. Variance analysis showed significant differences ($p < 0.05$) between the different treatments for pH, electrical conductivity, bulk density, moisture content, nitrogen content, pore space, and organic matter content.

Heavy Metal Concentrations in Sorghum Grain: Table 2 shows the levels of Pb, Zn, Cu, Cd and Cr found in the grains of sorghum grown under various amendments.

Table 2: Heavy Metal Concentrations in Sorghum Grains Cultivated under Different Amendment

Heavy Metal (ppm)	Inorganic Fertilizer	Animal Manure	Control	WHO/FAO Permissible Limit (ppm)
Pb	0.360 ± 0.070^{a}	0.350 ± 0.080^{a}	0.070 ± 0.020^{b}	0.3
Zn	3.020 ± 0.420^{a}	2.900 ± 0.300^{a}	1.900 ± 0.300^{b}	60
Cu	3.020 ± 0.420^{a}	2.000 ± 0.100^{b}	1.900 ± 0.300^{b}	10
Cd	0.033 ± 0.004^{a}	0.032 ± 0.007^{a}	0.031 ± 0.002^{a}	0.1
Cr	0.550 ± 0.070^{a}	0.530 ± 0.040^{a}	0.500 ± 0.010^{b}	2.3

Values are presented as mean ± standard deviation (SD). Means with different superscript letters within rows differ significantly at $p < 0.05$ according to Tukey's post hoc test. WHO/FAO permissible limits adapted from Codex Alimentarius Commission and related international food safety guidelines.

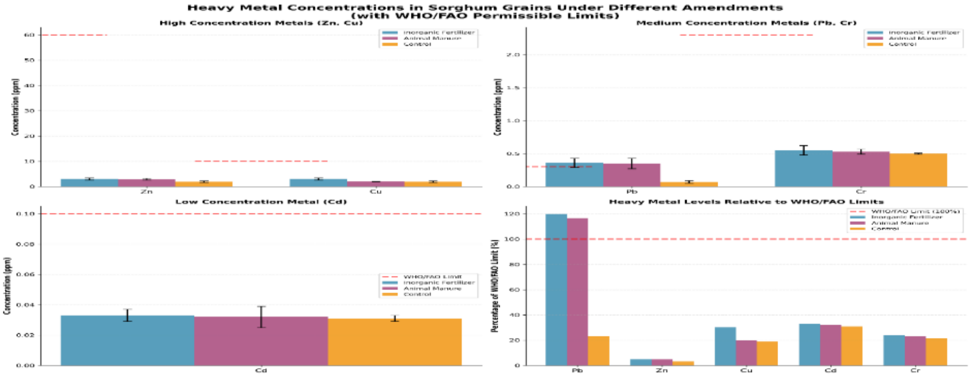

Figure 2: Metal concentration in sorghum grains under different amendments

The grains of sorghum grown on farms treated with inorganic fertilizer had the highest concentration of lead (0.36 ± 0.07 ppm), followed closely by those from the manure-amended farms (0.35 ± 0.08 ppm), and much lower concentrations were found in the control samples (0.07 ± 0.02 ppm). Grains from inorganic fertilizer farms also had the highest zinc and copper concentrations. The cadmium content was low in all treatments and differences among amendment treatments were minimal. The mean concentrations of chromium were relatively similar for the three treatments, with the highest mean concentration observed for the inorganic fertilizer treated farms. The statistical analysis showed significant differences ($p<0.05$) for Pb, Zn, Cu and Cr concentration between treatments while Cd did not differ significantly between treatment groups.

Estimated Daily Intake and Hazard Quotient Assessment: Table 3 shows the Estimated Daily Intake (EDI) and Hazard Quotient (HQ) values of heavy metals in sorghum grains. Standard procedures were used to calculate the EDI values, with the daily intake of sorghum grain (g/day) on the assumption of an average intake of 200 g of grain per day for an adult human, as described in other food safety risk assessment studies (Eisenbrand, 2015; Ulirsch and Li, 2022). The hazard quotient values were calculated by dividing the EDI values by their corresponding oral reference dose (RfD).

Table 3: Estimated Daily Intake (EDI) and Hazard Quotient (HQ) for Heavy Metals in Sorghum Grains

Heavy Metal	EDI (mg/kg/day) Inorganic Fertilizer	HQ Inorganic Fertilizer	EDI (mg/kg/day) Animal Manure	HQ Animal Manure	EDI (mg/kg/day) Control	HQ Control
Pb	0.0012	0.34	0.0011	0.31	0.0002	0.06
Zn	0.0101	0.03	0.0097	0.03	0.0063	0.02
Cu	0.0101	0.25	0.0067	0.17	0.0063	0.16
Cd	0.0001	0.1	0.0001	0.1	0.0001	0.09
Cr	0.0018	0.6	0.0017	0.57	0.0016	0.53

EDI = Estimated Daily Intake; HQ = Hazard Quotient. HQ values below 1.0 indicate no significant non-carcinogenic health risk associated with sorghum consumption.

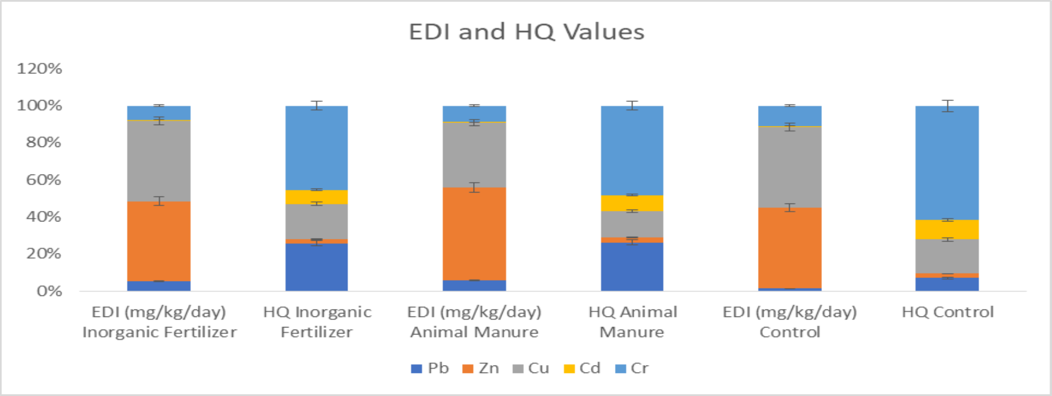

Figure 3: EDI and HQ Values

The estimated daily intake (EDI) for all metals in the three treatment groups was low. The EDI for inorganic fertilizer was higher than that for manure amended and control samples for four metals, namely: Pb, Zn, Cu and Cr. Consumption of the sorghum grains may not present a health risk of non-carcinogenic effect to consumers due to the concentrations of the heavy metals found in the samples, as all the metal Hazard Quotient values remained below 1.0. Comparatively high HQ values for the elements Cr and Pb in the soils amended by fertilizers, however, indicate the necessity of a monitoring of agricultural amendments and heavy metal accumulation in food crops.

Table 4: Oral Reference Doses (RfD) and Permissible Limits of Heavy Metals Used for Health Risk Assessment

Heavy Metal	Oral Reference Dose (RfD) (mg/kg/day)	WHO/FAO Permissible Limit in Cereals (mg/kg)
Pb	0.0035	0.3
Cd	0.001	0.1
Cr	0.003	2.3
Cu	0.04	10
Zn	0.3	60

Reference doses were adopted from USEPA Integrated Risk Information System (IRIS) and international environmental health risk assessment guidelines. Permissible limits were adapted from the WHO/FAO Codex Alimentarius standards for food safety assessment.

Discussion

Results of the present study showed that the use of inorganic fertilizers and animal manure significantly affected the physicochemical properties of the soils and the uptake of heavy metals by sorghum grown in Faragai Town, Kano State. The differences among the treatments showed that the nutrient dynamics, soil quality, and mobility of trace metals are key factors that soil amendments affect in agricultural systems. Inorganic fertilizer-treated soils had a relatively low soil pH, which could indicate that soils are becoming more acidic with longer use of inorganic fertilizer. A similar phenomenon was reported in previous studies that the use of nitrogen fertilizers for crop production caused soil acidification due to nitrification processes in the soil (Guo *et al*., 2010; Tian and Niu, 2015). Heavy metals could be more soluble and mobile in soils due to acidification and thus available for higher crop uptake.

Soils fertilized with inorganic fertilizers had the highest electrical conductivity values, which were related to the higher level of soluble ions and salt accumulation in the soil matrix. This is consistent with previous research, which showed that multiple fertilizer applications can cause considerable chemical imbalance and salinity build-up in the soils (Rengel, 2011). The manure-amended soils also showed better physicochemical properties than the control soil, but the results were not as significantly high as the inorganic fertiliser-amended soils. Organic amendments have been known to aggregate soil, buffer nutrients, retain soil moisture, and may help to reduce the mobility of heavy metals in the soil by adsorption and complexation reactions (Adeleye *et al*., 2014).

The study also found that the concentration of the heavy metals Pb, Zn, Cu, and Cr was higher in sorghum grains grown in soil amended with fertilizer than in non-fertilizer soil. Increased concentrations may be due to trace metal impurities found in inorganic fertilizers and higher bioavailability of metals under acidic soil conditions (Atafar *et al*., 2010; Nziguheba and Smolders, 2008), which may explain the higher concentrations seen on inorganic fertilizer-treated farms. Higher levels of Zn and Cu found in fertilizer-treated soils could also be due to the presence of these metals as micronutrients in some fertilizer formulations.

The highest levels of lead recorded from the sorghum grains grown in the inorganic fertilizer (0.360 ppm) and manure-amended soils (0.350 ppm) were slightly higher than the permissible limit of 0.300 ppm for cereal set by WHO/FAO. Continuous agricultural amendment practices and long dietary exposure can lead to potential food safety concerns, as indicated by this observation. Lead is a highly toxic metal, which, upon chronic exposure, may cause neurological, renal, hematological, and developmental disorders, and is not considered essential (Tchounwou *et al.*, 2012). The same research has been documented in others with higher levels of lead found in food crops grown in contaminated agricultural environments and soils that have been fertilized for an extended period of time (Genchi *et al.*, 2020). The levels found in the current study were fairly low, but if exposure occurs over the diet, it can lead to cumulative toxicity effects over time.

Cadmium levels were generally low in all treatment groups, with no levels being above recommended safety levels. However, cadmium is still considered one of the most dangerous environmental pollutants because of its long half-life in the environment and its tendency to bioaccumulate and have a long biological half-life in humans (Shahid *et al*., 2017). Environmental monitoring is thus of importance because chronic low-level exposure can result in the accumulation of toxic chemicals over time in biological tissues. Concentrations of chromium were relatively small between the treatments, but slightly higher concentrations were found in sorghum grown in inorganic fertilizer-treated soils, and the mobility and plant uptake were influenced by soil pH, interactions with organic matter, and redox conditions (Bortey-Sam *et al*., 2015). This limited mobility of chromium could, therefore, be related to the relatively small range found in the present study. The slightly higher concentrations in the fertilized soils, however, indicate that the use of fertilizer for a number of years may change the dynamics of chromium in the soil–plant system.

Generally, low exposure levels were found from the Estimated Daily Intake (EDI) and Hazard Quotient (HQ) calculations for all metals studied. The consumption of the sorghum grains does not currently appear to be posing significant non-carcinogenic human health risks because the Hazard Quotient values were below the threshold value of 1.0. In other food safety studies, where contamination of the environment was demonstrated, but the presence of heavy metals was not detected in cereals, comparable data have been reported, indicating that they are not detected under heavy metal concentration limits that are considered safe for human consumption (Rehman *et al*., 2016; US EPA, 2009). The relatively higher HQ values noted for lead and chromium in the fertilizer-amended samples, however, suggest an ongoing need for monitoring of agricultural soils and food crops, to help reduce potential progressive environmental accumulation and future dietary exposure risk.

The results of this study clearly indicate the need to adopt sustainable soil amendment practices to reduce heavy metal contamination in food crops and ensure soil fertility. Inorganic fertilizers helped to achieve higher nutrient status, which resulted in better soil physicochemical properties, but overuse and overuse of inorganic fertilizers can lead to a higher accumulation of trace metals in agricultural systems. However, manure amendments seemed to have relatively low levels of heavy metals and were effective in enhancing soil quality. Such integrated nutrient management systems that involve careful control of fertilizer application, optimum use of organic amendments, and periodic management of the environment could then offer more sustainable solutions to enhance agricultural productivity without compromising food safety and public health.

CONCLUSION

The study assessed the impact of inorganic fertilizers and animal manure on the soil properties and heavy metal uptake by sorghum in Faragai Town, Kano state, Nigeria. It found that the pH and EC values of soils treated with inorganic fertilizers were lower, whereas the nitrogen and organic matter values were higher. This means that there have been substantial changes in the quality of the chemical characteristics of soils caused by the continued use of fertilizer. The levels of lead (Pb), zinc (Zn), copper (Cu), and chromium (Cr) in the sorghum of the amended fertilizer farms were significantly higher than in the control farms, suggesting a higher likelihood of heavy metal buildup in the soil-plant system. The concentrations of the metals observed were found to be within safe limits, but the study cautions that there is a possibility of accumulation in the environment over the years. Up to this date, the consumption of these grains of sorghum does not appear to pose significant non-carcinogenic health risks, as there are no hazard quotient values greater than 1.0. However, the higher exposure estimates for Pb and Cr suggest the importance of continued monitoring of the environment and the use of sustainable soil management techniques. The study highlights the importance of balanced nutrient management, proper nutrient application, and regular monitoring to ensure soil productivity, minimize heavy metal pollution, and protect human health.

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