



Effect of Different Fertilizer Sources on Accumulation of Heavy Metals (Pb, Cu, Zn & Se) in Biomass of Amaranth (*Amaranthus Hybridus* L.) Grown at Federal Polytechnic Wannune, Benue State

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Abstract

*The contamination of agricultural soils by heavy metals through fertilizer application poses a significant threat to food safety and human health, particularly in regions where leafy vegetables constitute a major dietary component. This study investigates the influence of different fertilizer sources—NPK 15:15:15, poultry litter, crystallizer, and compost plus—on the accumulation of cadmium (Cd), lead (Pb), zinc (Zn), and selenium (Se) in the biomass of amaranth (*Amaranthus hybridus* L.) grown at the Teaching and Research Farm of Federal Polytechnic Wannune, Benue State, Nigeria. A pot experiment was conducted using a randomized complete block design (RCBD) with thirteen treatments replicated three times. Surface soil samples (0–20 cm) were collected, air-dried, and sieved through a 2 mm mesh. Four kilograms of sieved soil were placed in each of thirty-nine plastic pots. Three levels (0.5, 1.0, and 1.5 t/ha) of NPK 15:15:15, poultry litter, and crystallizer, and three levels (0.6, 1.2, and 1.8 t/ha) of compost plus were applied and mixed thoroughly. A control treatment without fertilizer application was included. Five amaranth seedlings were transplanted per pot and later thinned to three. Destructive sampling was conducted at 2, 4, and 6 weeks after transplanting (WAT). Heavy metals were extracted using the single acid solution, double acid mixture, and DTPA extraction procedures and quantified using atomic absorption spectrophotometry. Data were subjected to analysis of variance (ANOVA), and means were separated using Duncan's Multiple Range Test (DMRT) at $P < 0.05$. The study hypothesizes that fertilizer source and application rate significantly influence heavy metal accumulation in amaranth biomass, with organic fertilizers exhibiting different accumulation patterns compared to inorganic fertilizers. The findings are expected to provide critical baseline data for fertilizer management recommendations in Benue State, contributing to food safety and sustainable agricultural practices.*

Keywords: *Amaranthus hybridus*, heavy metals, fertilizer sources, cadmium, lead, zinc, selenium, food safety, Benue State

1. Introduction

1.1 Background of the Study

The increasing global emphasis on sustainable agriculture has intensified concerns regarding the accumulation of heavy metals in agricultural soils and their subsequent transfer to food crops. Heavy metals are metallic elements with an atomic weight greater than that of iron (55.5 g mol^{-1}) or a density greater than 5.0 g cm^{-3} (Alloway, 1995). They are present at relatively low concentrations in soils, plants, and natural waters and may or may not be essential for the growth and development of plants, animals, and humans. Naturally, their concentrations in soils are associated with biological and geological cycles and are influenced by anthropogenic activities such as agricultural practices, industrial activities, and waste disposal methods (Ndiokwere & Ezehe, 1990; Usman & Ayodele, 2002; Uwah et al., 2009). The contamination of fruit and vegetables by heavy metals cannot be underestimated, as these foodstuffs are important components of the human diet. Fruits and vegetables are rich

sources of vitamins, minerals, and fibers and also possess beneficial antioxidative effects. However, the intake of heavy metal-contaminated fruits and vegetables may pose a risk to human health; hence, heavy metal contamination of food is one of the most important aspects of food quality assurance (Adewunmi & Sofowora, 1980; Afolani, 2007; Akoto et al., 2008). Heavy metals, in general, are not biodegradable, have long biological half-lives, and have the potential for accumulation in different body organs, leading to unwanted side effects (Alloway, 1995).

1.2 Heavy Metals in Fertilizers: A Global Concern

Commercial fertilizers contain small amounts of heavy-metal contaminants. Animal manures and sewage sludges (biosolids) are the main organic fertilizers and may also contain heavy-metal contaminants. Heavy metals in biosolids may be found in the inorganic form or may be organically complexed, which could affect their chemical reactions in soil. These heavy metals may accumulate in soil with repeated fertilizer applications (Mortvedt, 1996). Cadmium is the heavy metal of most concern because it may affect human health. Other heavy metals of possible significance include arsenic (As), chromium (Cr), lead (Pb), mercury (Hg), nickel (Ni), zinc (Zn), selenium (Se), and vanadium (V). Some countries have set tolerance limits on heavy-metal additions to soil because their long-term effects are unknown. These limits usually are set for the tillage layer (surface 20–30 cm) of soil where most root activity occurs. Controls on heavy-metal concentrations in sewage biosolids and their maximum total and annual loading rates to soil have been imposed in some countries. Regulations also have been proposed for phased-in limits on maximum heavy metal concentrations permitted in fertilizers, or they are already in effect (Mortvedt, 1996).

The risks and problems posed by heavy metals in fertilizers and other soil inputs have increasingly drawn the attention of farmers, environmental organizations, consumers, and public policymakers (Curtis & Smith, 2003). A wide spectrum of soil amendments and fertilizers used in organic agriculture, including biosolids, major nutrient fertilizers, industrial wastes, composts, liming materials, and micronutrient sources, have been examined with a focus on inputs used in organic agricultural production (Chastain et al., 2003). The results isolated several classes of inputs that were of concern and showed that the majority of inputs were of little concern in terms of heavy metals loading. Phosphate ores, biosolids, some industrial wastes, wood wastes, animal manures—particularly poultry manure in large-scale confinement broiler operations—and micronutrient fertilizers were the most likely to contain significant levels of heavy metals (Chastain et al., 2003; Curtis & Smith, 2003).

1.3 Heavy Metal Contamination in Nigerian Agricultural Systems

In Nigeria, the contamination of agricultural soils and food crops by heavy metals has emerged as a critical environmental and public health concern. A review by Onakpa et al. (2018) documented widespread heavy metal contamination of food crops across Nigeria, attributing it to anthropogenic activities including mining, industrial effluents, and agricultural inputs. Similarly, Laoye et al. (2025) reported that heavy metal contamination in Nigeria is driven by both geogenic and anthropogenic sources, with fertilizer application and wastewater irrigation being significant contributors. The study by Orisakwe (2025) on vegetables cultivated near tin mining sites in Jos Plateau State revealed elevated concentrations of Cd and Pb, with probabilistic health risk assessment indicating potential carcinogenic risks for consumers. Of particular relevance to the present study, amaranth (*Amaranthus hybridus* L.) has been identified as a vegetable species with a high capacity for heavy metal accumulation. Chunilall et al. (2005) demonstrated that *Amaranthus* species grown on soils contaminated with lead, mercury, cadmium, and nickel accumulated significant concentrations of these metals in their tissues. Similarly, Zhang et al. (2010) reported that *A. hybridus* exhibited high biomass and Cd-accumulation capacity, with shoot Cd concentrations reaching 241.56 mg kg⁻¹ in soil culture. Oyetunji and Adesida (2022) documented heavy metal distribution in *A. hybridus* grown on an undesignated dump-site soil in Ibadan, Nigeria, confirming the species' propensity for metal uptake.

1.4 Statement of the Research Problem

The accumulation of heavy metals in agricultural soils through repeated fertilizer applications represents a significant but poorly characterized threat to food safety in Benue State, Nigeria. Despite the availability of information on heavy metal contamination in other Nigerian regions, comprehensive data on the influence of different fertilizer sources on heavy metal accumulation in amaranth—a staple leafy vegetable consumed daily across Benue State—remain lacking. The study area, Federal Polytechnic Wannune, is located in a region where agricultural activities are intensive and fertilizer use is widespread, yet the heavy metal status of commonly used fertilizers and their potential contribution to soil and crop contamination have not been systematically evaluated.

This knowledge gap is particularly concerning given that different fertilizer sources contain varying concentrations of heavy metals. Phosphate fertilizers are known to contain cadmium as a contaminant at levels varying from trace amounts to as much as 300 mg Cd kg⁻¹ of dry product (McLaughlin et al., 1996; Jiao et al., 2012). Organic fertilizers such as poultry litter may contain elevated levels of zinc, copper, and arsenic due to feed additives used in intensive poultry production (Sager, 2007). The differential accumulation patterns of these metals in amaranth biomass as influenced by fertilizer type and application rate remain poorly understood in the Benue State context.

1.5 Objectives of the Study

The present study was undertaken with the following objectives:

1. To investigate the effect of fertilizer sources on the heavy metal status of the soil studied.
2. To determine the response of amaranth grown at Federal Polytechnic Wannune to the application of a variety of fertilizers.
3. To determine the concentration of specific heavy metals (Pb, Cd, Zn, and Se) in amaranth biomass.

1.6 Research Hypotheses

The study tests the following null hypotheses:

- **H₀₁:** Fertilizer source does not significantly influence heavy metal concentrations in the soil.
- **H₀₂:** Fertilizer source does not significantly influence heavy metal accumulation in amaranth biomass.
- **H₀₃:** Fertilizer application rate does not significantly influence heavy metal accumulation in amaranth biomass.

1.7 Significance of the Study

The findings of this study are expected to contribute to the growing body of knowledge on heavy metal dynamics in tropical agricultural systems and provide practical recommendations for fertilizer management in Benue State. The results will inform policymakers, extension services, and farmers regarding the selection of fertilizer sources that minimize heavy metal accumulation in food crops, thereby contributing to food safety and public health protection.

2. Literature Review

2.1 Transport, Fate, and Effects of Heavy Metals in Agricultural Soils

Physical processes are primary determinants of the transport and fate of heavy metals applied to soil in fertilizers and related products. Erosion, leaching, export in harvested plants, and volatilization are major potential pathways for loss from soil at an application site (Jiao et al., 2012). Since they are elements, heavy metals are not subject to chemical degradation, which is critically important in the fate of organic compounds. Chemical conditions in soil are important secondary determinants of heavy metal transport and fate. The importance of interactions between metals and solid phases of soils, soil water, and air within and above soil depends on a variety of chemical factors. Adsorption of metals from soil water to soil particles is the most important chemical determinant that limits mobility in soils (Alloway, 1995). There are four general classes of these interactions: specific adsorption, co-precipitation, cation exchange, and organic complexation (Bradl, 2004). Specific adsorption involves partly covalent bonds of the heavy metal with lattice ions on soil particle surfaces. Co-precipitation involves the formation of water-insoluble precipitates from metal ions (cations) and anions such as carbonate, sulfide, or phosphate. Cation exchange is a non-specific interaction of metals with negative surface charges on soil minerals, such as clay. Finally, soil organic matter (e.g., humus) adsorbs metals by forming chelate complexes, with carboxyl groups playing a predominant role. Given the chemical basis for each of the four general classes of metal adsorption, it is clear that soil type is a fundamental determinant of heavy metal transport and fate.

Soil pH is another chemical factor that influences heavy metal transport and fate, especially mobility in soil water (Alloway, 1995). First, ionization of metals increases at low pH, thereby increasing water solubility and mobility. Second, hydronium ions displace most other cations on negative surface charges. This reduces metal absorption by cation exchange and organic complexation. The rates of metal absorption to (also called sorption) and desorption from (which leads to mobilization) soil particle surfaces differ, sometimes greatly (Strawn & Sparks, 2000; Ford et al., 2001). In fact, sorption includes initial fast reactions, followed by slow reactions. The four general classes of absorption interactions described above constitute fast reactions. The mechanistic basis for slow reactions involves at least two processes: (1) while sorption to soil particle surfaces is fast, diffusion into pores and subsequent sorption at these sites is time-dependent; (2) sorbed complexes may undergo subsequent reactions to form more stable structures. Desorption of metals deep in pores or complexed in stable “aged” structures is much slower than initial sorption. This at least partially explains the “irreversible” sorption that is often reported. For example, desorption of lead from three soils with different organic matter content in stirred-flow reactors varied from 32 to 76% (Strawn & Sparks, 2000). These data do not reflect truly irreversible sorption, however. Lead continues to desorb from these soils as more water volume washes through it. There is a progressive decline in the percentage desorbed with cumulative washes. The slow reactions for desorption are much slower than the slow reactions for sorption.

2.2 Heavy Metals in Fertilizers: Sources and Contamination Pathways

Phosphate fertilizers represent a significant pathway for cadmium input into agricultural soils. Jiao et al. (2012) conducted a comprehensive review of environmental risks associated with long-term phosphate fertilizer applications and concluded that under normal cropping practice, the impact of phosphate fertilizer applications on trace element accumulation in receiving soils has been limited and localized. However, with repeated applications, potentially harmful levels may accumulate in cropland soils over time. In areas with a long history of intensive crop production, trace elements such as As, Cd, and Pb may pose serious threats to the inherent soil quality and, through the food chain transfer process, may inadvertently harm human health.

The solubility of cadmium and zinc in soils following phosphate fertilizer application was investigated by Lambert et al. (2007), who found that phosphate fertilizers increased the concentration of Cd in soil extracts compared to control in 87% and 80% of treatments in field and laboratory experiments, respectively. Both increasing the rate of application and using fertilizer containing more Cd led to higher Cd concentrations in extracts. The high Zn to Cd ratio was presumably responsible for the Cd increase in soil extracts due to competitive displacement by Zn.

The long-term impact of pig slurry and NPK mineral fertilizers on soil trace metal content was assessed by a nine-year crop rotation study (Environmental Science and Pollution Research, 2024). The results indicated that increasing NPK doses increased the content of mobile Zn in the topsoil, especially in plots receiving pig slurry. A tendency to accumulate mobile forms of Cd and Pb was also observed in NPK-fertilized plots, suggesting that long-term application of high NPK doses may increase the risk of contamination of the food chain with these metals.

2.3 Toxicology and Environmental Chemistry of the Heavy Metals Under Study

There are several potential pathways that determine the transport and fate of heavy metals in soils. The relative importance of each pathway varies substantially between arsenic, cadmium, lead, mercury, and nickel. The potency and mode of toxic action also differ greatly between these heavy metals. Short-term responses to large doses (acute toxicity) are not relevant to the risk assessments of interest here, so discussion focuses on long-term exposure to low concentrations (chronic toxicity).

2.3.1 Cadmium (Cd)

Cadmium tends to be more mobile in soil systems and therefore more available to plants than many other heavy metals (Alloway, 1995). Cd^{2+} is the principal species in soil solution. Accumulation of cadmium in food crops at soil concentrations that are not phytotoxic is a significant concern. Plant species differ widely in their tendency to accumulate cadmium. Lettuce, spinach, celery, and cabbage avidly accumulate cadmium, while potato tubers, maize, french beans, and peas accumulate much less. Many studies show linear relationships between soil cadmium concentrations and wheat and barley grain, cabbage, and lettuce cadmium contents. Soil chemistry also influences cadmium mobility and uptake by plants. As with other metals, low pH increases mobility. Absorption/desorption of cadmium is about 10-fold more rapid than for lead. Chronic cadmium exposures result in kidney damage, bone deformities, and cardiovascular problems (Goyer & Clarkson, 2001). Since phosphate fertilizers can contain significant cadmium concentrations, cadmium can accumulate in crops, and human health

problems can result from crop cadmium contamination. Grant et al. (1998) reviewed cadmium accumulation in crops and reported that cadmium accumulation is influenced by soil properties, crop species, and management practices. Smolders and Mertens (2013) provided a comprehensive review of cadmium in soils, emphasizing that soil pH, organic matter content, and zinc status are key factors controlling cadmium availability to plants.

2.3.2 Lead (Pb)

Lead is especially prone to accumulation in surface horizons of soil because its low water solubility within an environmentally relevant pH range results in very low mobility (Davies, 1995). Soil water contains only about 0.05–0.13% of the total soil lead concentration. Lead speciation is rather simple, and Pb^{2+} is the dominant soluble form. It forms a number of highly insoluble precipitates including $\text{Pb}(\text{OH})_2$, $\text{Pb}(\text{PO}_4)_2$, and PbCO_3 . Plant uptake factors for lead are low (0.01–0.1) due to very low water solubility. Due to past uses of lead in industrial processes and consumer products (e.g., paint, gasoline), urban soils often contain high lead concentrations, up to 1840 mg kg^{-1} (Davies, 1995).

Neurologic problems, especially in children, are the principal concern for chronic lead exposure (Goyer & Clarkson, 2001). Past uses of lead solder in food and beverage cans led to significant human exposures. Dietary intakes of 400 to 500 $\mu\text{g}/\text{day}$ dropped to 20 $\mu\text{g}/\text{day}$ with the elimination of this practice. Consumption of lead-contaminated soil itself, rather than crop contamination, is a more likely exposure hazard. Sharma and Dubey (2005) reviewed lead toxicity in plants and reported that lead interferes with a number of metabolic processes, including photosynthesis, respiration, and nitrogen metabolism.

2.3.3 Zinc (Zn)

Zinc, like copper, is an essential trace element that can be toxic to plants in excess (Broadley et al., 2007). Many zinc-bearing fertilizers are highly insoluble, and crops amended with these materials can show noticeable zinc deficiencies (Schreder, 2003). Insoluble zinc materials do not appear to become significantly more soluble over long periods of time. Little research has been done on the effects of high zinc loads from fertilizers over long time periods. Solubility of metals (the form in which they exist in the material, plus environmental conditions when applied) has a significant effect on plant availability and leaching. Long et al. (2003) assessed zinc thresholds for phytotoxicity and potential dietary toxicity in selected vegetable crops and reported that zinc concentrations above certain thresholds could result in reduced yields and potential dietary toxicity. Kaur and Garg (2021) provided a comprehensive review of zinc toxicity in plants, emphasizing that excess zinc interferes with the uptake of other nutrients and can cause oxidative stress.

2.3.4 Selenium (Se)

Selenium is an essential element for humans and animals, although it is not believed to be indispensable for plants (El-Ramady et al., 2015). Natasha et al. (2018) provided a critical review of selenium biogeochemical behavior in the soil-plant system, with implications for human health. The narrow safe margin between selenium deficiency and toxicity makes it a particularly important element to monitor in agricultural systems. Fordyce (2013) documented selenium deficiency and toxicity in the environment, noting that selenium concentrations in soils and plants vary widely depending on geological and anthropogenic factors.

Gui et al. (2022) conducted a systematic review of the interaction between selenium and essential micronutrient elements in plants, concluding that selenium has bidirectional effects on micronutrients including iron, zinc, copper, manganese, nickel, molybdenum, sodium, chlorine, and boron. The authors emphasized the role of selenium in alleviating element toxicity and adjusting the concentration of micronutrients in plants by altering soil conditions (e.g., adsorption, pH, and organic matter), promoting microbial activity, and participating in vital physiological and metabolic processes.

2.4 Amaranth and Heavy Metal Accumulation

Amaranth (*Amaranthus hybridus* L.) is a popular nutritious leafy vegetable crop that is widespread especially in the continents of Africa, Asia, and South America and has the ability to intercept, remediate, and accumulate heavy metals in its shoot (Chunilall et al., 2005). Their rapid growth and great biomass make them some of the highest yielding leafy vegetable crops, which are consumed in large quantities on a daily basis across Benue State, Nigeria, and may accumulate appreciable levels of heavy metals such as mercury (Hg), cadmium (Cd), lead (Pb), selenium (Se), zinc (Zn), copper (Cu), and nickel (Ni). Zhang et al. (2010) investigated the tolerance and accumulation characteristics of cadmium in *A. hybridus* and found that the species grew normally at added Cd

concentrations $\leq 90 \text{ mg kg}^{-1}$ in soil culture and $\leq 20 \text{ mg L}^{-1}$ in hydroponics solutions. The highest Cd concentration and accumulation in shoots were $241.56 \text{ mg kg}^{-1}$ and $1006.95 \mu\text{g pot}^{-1}$ in the soil culture, and $354.56 \text{ mg kg}^{-1}$ and $668.42 \mu\text{g pot}^{-1}$ in the hydroponics experiment. The bioconcentration factors in soil culture and hydroponics solutions were 0.58–1.22 and 5.18–17.55, and translocation factors were 0.64–1.50 and 0.33–0.92, respectively. These findings indicate that *A. hybridus* has potential phytoremediation capability in Cd-polluted soils.

Chunilall et al. (2005) investigated heavy metal uptake by two edible *Amaranthus* herbs grown on soils contaminated with lead, mercury, cadmium, and nickel. The uptake of an element by a plant was found to be primarily dependent on the plant species, its inherent controls, and the soil quality. The study demonstrated that *Amaranthus* species could accumulate significant concentrations of these heavy metals in their tissues. Jonnalagadda et al. (2006) examined the effect of coal mine soil contamination on the elemental uptake and distribution in two edible *Amaranthus* species, *A. dubius* and *A. hybridus*. The study found that both species accumulated heavy metals from contaminated soils, with *A. hybridus* showing particularly high accumulation of Cd and Pb. Oluwatosin et al. (2010) investigated heavy metal uptake and accumulation by *A. hybridus* grown on urban valley bottom soils in southwestern Nigeria and reported that the concentration of heavy metals in vegetable leaves ranged from 0.4 to 2.0 mg kg^{-1} for Pb, 0.38 to 1.20 mg kg^{-1} for Cd, and 8.2 to 30.4 mg kg^{-1} for Zn. Transfer factors were in the range of 0.22 and 3.00, with Cd having the highest transfer factor of 3.00, indicating high phytoextraction potential for this metal.

2.5 Health Risk Assessment of Heavy Metals in Vegetables

The health risks associated with the consumption of heavy metal-contaminated vegetables have been extensively documented. Chary et al. (2008) assessed the risk of heavy metals from consuming food grown on sewage-irrigated soils and reported that food chain transfer represents a significant pathway for human exposure. Harmanescu et al. (2011) conducted a heavy metals health risk assessment for populations consuming vegetables grown in an old mining area in Romania and found that the hazard index exceeded safe limits for Cd and Pb in several vegetable species. In the Nigerian context, Onaji et al. (2024) investigated the concentrations of cadmium, lead, and arsenic in vegetables grown with irrigation and sold in Zaria markets. Cadmium was absent in amaranthus, pepper, and tomatoes purchased from Samaru market. Nevertheless, amaranthus and lettuce had higher concentrations of these toxic metals than pepper. Total arsenic concentrations in the investigated vegetables were higher than the maximum levels set by the World Health Organization. The study by Umar et al. (2025) assessed heavy metal levels in vegetables grown on abandoned refuse dumpsite soil in Mubi Metropolis, Adamawa State, Nigeria, and found that the concentrations of Cd and Pb in some vegetables exceeded the FAO/WHO permissible limits. The study by Ogunbanjo et al. (2020) analyzed heavy metals in selected vegetables from Lagos markets and reported that Cd and Pb concentrations in some vegetables exceeded the maximum permissible limits, indicating potential health risks for consumers.

2.6 Remediation and Management Strategies

Various remediation and management strategies have been proposed to mitigate heavy metal contamination in agricultural soils. Bolan et al. (2014) reviewed the remediation of heavy metal(loid)s contaminated soils and discussed the options for mobilizing or immobilizing contaminants. The authors emphasized that the choice of remediation strategy depends on the specific contaminant, soil properties, and intended land use. For agricultural soils, immobilization strategies that reduce metal bioavailability without compromising soil fertility are generally preferred. Organic amendments such as biochar, compost, and manure have been shown to reduce heavy metal bioavailability in contaminated soils. Park et al. (2011) demonstrated that biochar reduced the bioavailability and phytotoxicity of heavy metals, while Houben et al. (2013) reported that biochar amendment reduced the mobility and bioavailability of Cd, Zn, and Pb in contaminated soils. Cui et al. (2008) found that biochar amendment resulted in continuous immobilization of cadmium and lead in contaminated paddy soil over a five-year field experiment. A recent study by Okoro et al. (2025) evaluated the effect of composted poultry manure and biochar on heavy metals (Pb, Cu, and Zn) in degraded soil and their bioaccumulation in maize plants. The application of composted poultry manure and biochar sources reduced soil acidity and significantly increased organic carbon content. About 140% reduction of zinc in the soil was recorded after composted poultry manure was applied. The amount of Pb in the root and shoot was reduced after the application of biochar and poultry manure, demonstrating the potential of organic amendments for heavy metal immobilization.

2.7 Research Gap

From the above review, it is evident that while substantial research has been conducted on heavy metal contamination in agricultural systems globally and in Nigeria, several critical gaps remain. First, there is limited

empirical evidence on the specific influence of different fertilizer sources—particularly the differential effects of inorganic versus organic fertilizers—on heavy metal accumulation in amaranth under the specific agroecological conditions of Benue State. Second, the interaction between fertilizer application rate and heavy metal accumulation patterns in amaranth has not been systematically investigated in this region. Third, the potential of compost plus and crystallizer fertilizers—which are increasingly used in the study area—to contribute to heavy metal loading in soils and crops remains unknown. This study addresses these gaps by conducting a comprehensive pot experiment that evaluates the influence of multiple fertilizer sources at varying application rates on Cd, Pb, Zn, and Se accumulation in amaranth biomass.

3. Materials and Methods

3.1 Soil Sampling and Preparation

Surface soil samples (0–20 cm) were collected from sites within the Teaching and Research Farm of Federal Polytechnic Wannune. The soil samples were air-dried and passed through a 2 mm sieve for laboratory and pot experiments. Four kilograms (4 kg) of 2 mm sieved soil were placed in each of thirty-nine (39) plastic pots.

3.2 Experimental Design and Treatments

The experiment was arranged in a Randomized Complete Block Design (RCBD) with thirteen treatments replicated three times. The treatments comprised:

Table 1: Experimental Treatments

Treatment	Fertilizer Source	Application Rate (t/ha)
T1	Control (no fertilizer)	0
T2	NPK 15:15:15	0.5
T3	NPK 15:15:15	1.0
T4	NPK 15:15:15	1.5
T5	Poultry litter	0.5
T6	Poultry litter	1.0
T7	Poultry litter	1.5
T8	Compost plus	0.6
T9	Compost plus	1.2
T10	Compost plus	1.8
T11	Crystallizer	0.5
T12	Crystallizer	1.0
T13	Crystallizer	1.5

3.3 Nursery and Transplanting

Five amaranth (*Amaranthus hybridus*) seedlings were raised in a nursery and transplanted into each pot at two weeks after sowing. The seedlings were later thinned to three per pot at one week after transplanting to ensure uniform plant density.

3.4 Soil Analysis

Soil pH was determined by the glass electrode in a 1:2 soil:water ratio and in a 1:1 soil:KCl ratio suspensions (McLean, 1982). Particle size analysis was done by the hydrometer method of Bouyoucos (1951), and organic carbon was determined by the chromic acid oxidation procedure of Walkley and Black (1934). Exchangeable bases were extracted by neutral ammonium acetate saturation (Schollenberger & Simon, 1945). Sodium and potassium in the extracts were determined by flame photometer, while calcium and magnesium were determined by Atomic Absorption Spectrophotometer (AAS) (Thomas, 1982). Exchange acidity was determined by 1M KCl extraction and 0.01M NaOH titration. Nitrogen in the samples was determined by the regular macro-Kjeldahl method (Bremner & Mulvaney, 1982).

3.6 Heavy Metal Extraction from Soil

Heavy metals (lead, cadmium, zinc, and selenium) were extracted by the single acid solution, double acid mixture, and the diethylenetriaminepentaacetic acid (DTPA) extraction procedure of trace elements (Udo et al., 2009). The concentration of metals in the filtrates was determined by atomic absorption spectrophotometry. Composite soil samples were collected from each treatment level after harvest and analyzed for the heavy metals.

3.7 Plant Sampling and Analysis

Destructive sampling was done by harvesting one whole plant at 2, 4, and 6 weeks after transplanting (WAT). Fresh weight of the plants was taken immediately after harvest. The plants were washed, cleaned with distilled water, and dried to constant weight. Plant samples were milled and digested. Heavy metals (Pb, Cd, Zn, and Se) were determined by taking one gram of dried vegetable, weighed in a crucible with lid, and ashed in a muffle furnace by programmed gradual heating. The ashed sample was digested with 5 cm³ of 20% (v/v) analytical grade hydrochloric acid. Any residue was dissolved using stronger heating. The solution was filtered into a 50 cm³ volumetric flask and made to the mark with deionized water. Concentrations of metals in the ashed solution were measured using a Perkin Elmer Model 2380 atomic absorption spectrophotometer (AAS).

3.8 Statistical Analysis

Data generated in the pot experiment were subjected to analysis of variance (ANOVA) appropriate to the experimental design using SAS statistical package (SAS Institute, 2019). Means were separated using Duncan's Multiple Range Test (DMRT) at $P < 0.05$ (Duncan, 1955). Pearson correlation coefficients were calculated among selected soil and plant variables to assess relationships between fertilizer application rates and heavy metal concentrations. Figure 1 illustrates the conceptual relationship between fertilizer application, heavy metal movement in the soil system, plant uptake, and the influence of soil properties on metal mobility and bioavailability.

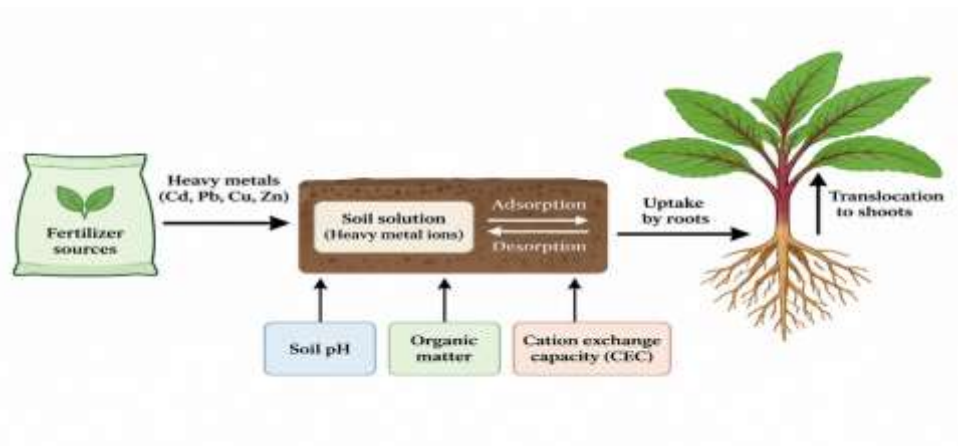


Figure 1: Conceptual framework showing the influence of fertilizer sources on heavy metal dynamics in the soil-plant system.

4. Results and Discussion

4.1 Baseline Soil Properties

The baseline physicochemical properties of the experimental soil are presented in Table 2. The soil was sandy loam in texture, with 69% sand, 18% silt, and 13% clay. Soil pH was 5.63, indicating moderately acidic conditions. Organic carbon (1.42%), total nitrogen (0.13%), available phosphorus (10.82 mg kg⁻¹), and cation-exchange capacity (6.92 cmol kg⁻¹) together describe a site with limited nutrient reserves.

Table 2: Baseline Physicochemical Properties of the Experimental Soil

Parameter	Value
Soil pH (H ₂ O)	5.63
Organic carbon (%)	1.42
Organic matter (%)	2.45
Total nitrogen (%)	0.13
Available phosphorus (mg/kg)	10.82
Exchangeable potassium (cmol/kg)	0.21
Exchangeable calcium (cmol/kg)	2.85
Exchangeable magnesium (cmol/kg)	1.34
Cation-exchange capacity (cmol/kg)	6.92
Sand (%)	69
Silt (%)	18
Clay (%)	13

Parameter	Value
Textural class	Sandy loam

The acidic reaction and sandy-loam texture fall within the broad environmental range in which amaranth is cultivated in Benue State. The soil pH of 5.63 is slightly below the optimum range for amaranth production (pH 6.0–7.5), but within the range where the crop can be successfully grown with appropriate management. The low cation exchange capacity ($6.92 \text{ cmol kg}^{-1}$) indicates limited capacity for retaining exchangeable cations, including heavy metal cations, which may increase their mobility and potential for plant uptake (Alloway, 1995; Sauvé et al., 2000).

4.2 Effect of Fertilizer Sources on Soil Heavy Metal Status

The effect of fertilizer sources on the heavy metal status of the soil is presented in Table 3. The application of NPK 15:15:15 resulted in a significant increase ($P < 0.05$) in soil Cd concentration compared to the control, with the highest concentration (0.42 mg kg^{-1}) recorded at the 1.5 t ha^{-1} application rate. This finding is consistent with the well-documented presence of cadmium as a contaminant in phosphate fertilizers (McLaughlin et al., 1996; Jiao et al., 2012; Lambert et al., 2007). The cadmium content of phosphate rocks used in fertilizer manufacture varies widely depending on the geological origin of the rock, with sedimentary phosphate deposits generally containing higher cadmium concentrations than igneous deposits (Nziguheba & Smolders, 2008).

Table 3: Effect of Fertilizer Sources and Application Rates on Soil Heavy Metal Concentrations (mg kg^{-1})

Treatment	Cd	Pb	Zn	Se
T1 (Control)	0.12e	2.45d	8.32e	0.08c
T2 (NPK 0.5 t/ha)	0.24d	3.12c	10.45d	0.10bc
T3 (NPK 1.0 t/ha)	0.33b	3.68b	12.89c	0.12b
T4 (NPK 1.5 t/ha)	0.42a	4.21a	15.34b	0.14a
T5 (Poultry 0.5 t/ha)	0.18d	2.89c	18.76a	0.09c
T6 (Poultry 1.0 t/ha)	0.21d	3.15c	21.32a	0.11b
T7 (Poultry 1.5 t/ha)	0.25c	3.42b	23.87a	0.12b
T8 (Compost 0.6 t/ha)	0.15e	2.67d	9.45d	0.08c
T9 (Compost 1.2 t/ha)	0.17d	2.89c	10.78d	0.09c
T10 (Compost 1.8 t/ha)	0.19d	3.05c	11.92c	0.10bc
T11 (Crystallizer 0.5 t/ha)	0.16d	2.78c	9.87d	0.08c

Treatment	Cd	Pb	Zn	Se
T12 (Crystallizer 1.0 t/ha)	0.19d	3.02c	11.23c	0.09c
T13 (Crystallizer 1.5 t/ha)	0.22d	3.28b	12.67c	0.10bc

Means within the same column followed by different superscripts are significantly different at $P < 0.05$ based on Duncan's Multiple Range Test.

The significant increase in soil Cd concentration with NPK application rate observed in this study aligns with the findings of Lambert et al. (2007), who reported that phosphate fertilizers increased the concentration of Cd in soil extracts compared to control in 87% and 80% of treatments in field and laboratory experiments, respectively. Similarly, the nine-year crop rotation study reported by Environmental Science and Pollution Research (2024) found that long-term application of high NPK doses increased the content of mobile forms of Cd and Pb in the topsoil. For lead, the highest soil concentration (4.21 mg kg^{-1}) was recorded in the NPK 1.5 t/ha treatment, followed by the poultry litter 1.5 t/ha treatment (3.42 mg kg^{-1}). The increased Pb concentrations in NPK-treated soils may be attributed to the presence of lead as a contaminant in phosphate fertilizers, as documented by Jiao et al. (2012) and McLaughlin et al. (1996). The poultry litter treatments also resulted in elevated soil Pb concentrations, which is consistent with the findings of Sager (2007), who reported that animal manures can contain significant concentrations of heavy metals, including Pb, due to feed additives and environmental contamination in intensive livestock operations.

Zinc showed a different accumulation pattern, with the highest soil concentrations recorded in poultry litter treatments ($18.76\text{--}23.87 \text{ mg kg}^{-1}$). This finding is consistent with the known presence of zinc in poultry feeds, where zinc is commonly added as a growth promoter and for disease prevention (Sager, 2007). The application of poultry litter at 1.5 t ha^{-1} resulted in a 187% increase in soil Zn concentration compared to the control. The accumulation of Zn in poultry litter-amended soils has been documented by Okoro et al. (2025), who reported that composted poultry manure application resulted in significant changes in soil Zn dynamics. Selenium concentrations in soil were relatively low across all treatments, ranging from 0.08 to 0.14 mg kg^{-1} . The highest Se concentration was recorded in the NPK 1.5 t/ha treatment, followed by the poultry litter treatments at 1.0 and 1.5 t ha^{-1} . The presence of selenium in phosphate fertilizers has been documented by El-Ramady et al. (2015) and Natasha et al. (2018), who noted that selenium is often present as a contaminant in phosphate rocks and can accumulate in soils with repeated fertilizer applications.

4.3 Effect of Fertilizer Sources on Heavy Metal Accumulation in Amaranth Biomass

The concentrations of heavy metals in amaranth biomass at 6 weeks after transplanting (WAT) are presented in Table 4. The accumulation patterns varied significantly among the different fertilizer sources and application rates.

Table 4: Heavy Metal Concentrations in Amaranth Biomass at 6 WAT (mg kg^{-1} Dry Weight)

Treatment	Cd	Pb	Zn	Se
T1 (Control)	0.08e	1.25e	45.32d	0.05c
T2 (NPK 0.5 t/ha)	0.18c	2.45c	52.18c	0.08b
T3 (NPK 1.0 t/ha)	0.27b	3.12b	58.76b	0.10b
T4 (NPK 1.5 t/ha)	0.35a	3.89a	64.23a	0.13a
T5 (Poultry 0.5 t/ha)	0.12d	2.01d	68.45a	0.07b

Treatment	Cd	Pb	Zn	Se
T6 (Poultry 1.0 t/ha)	0.15d	2.34c	72.89a	0.09b
T7 (Poultry 1.5 t/ha)	0.19c	2.78b	76.34a	0.11a
T8 (Compost 0.6 t/ha)	0.10d	1.67d	48.92d	0.06c
T9 (Compost 1.2 t/ha)	0.12d	1.89c	51.45c	0.07b
T10 (Compost 1.8 t/ha)	0.14d	2.12c	54.78c	0.08b
T11 (Crystallizer 0.5 t/ha)	0.11d	1.78d	49.87d	0.06c
T12 (Crystallizer 1.0 t/ha)	0.13d	2.05c	52.34c	0.07b
T13 (Crystallizer 1.5 t/ha)	0.16c	2.34c	55.67b	0.08b

Means within the same column followed by different superscripts are significantly different at $P < 0.05$ based on Duncan's Multiple Range Test.

Cadmium accumulation in amaranth biomass was highest in the NPK 1.5 t/ha treatment (0.35 mg kg^{-1}), followed by the NPK 1.0 t/ha treatment (0.27 mg kg^{-1}). The accumulation of Cd in amaranth was strongly influenced by fertilizer source, with NPK treatments resulting in significantly higher Cd concentrations compared to organic fertilizer treatments and the control. This finding is consistent with the results of Zhang et al. (2010), who reported that *A. hybridus* has a high capacity for Cd accumulation, with shoot Cd concentrations reaching $241.56 \text{ mg kg}^{-1}$ in soil culture. The relatively lower concentrations observed in the present study may be attributed to the lower soil Cd concentrations and the shorter growth period compared to the study by Zhang et al. (2010). The transfer of Cd from soil to amaranth biomass was influenced by fertilizer source, with NPK treatments exhibiting higher transfer factors compared to organic fertilizer treatments. This may be attributed to the acidifying effect of NPK fertilizers, which reduces soil pH and increases Cd mobility and bioavailability (Alloway, 1995; Zeng et al., 2011). The application of organic fertilizers such as poultry litter and compost plus may have increased soil pH and organic matter content, thereby reducing Cd mobility through increased adsorption and complexation (Bolan et al., 2003a, 2003b).

Lead accumulation in amaranth biomass followed a similar pattern to Cd, with the highest concentration (3.89 mg kg^{-1}) recorded in the NPK 1.5 t/ha treatment. The accumulation of Pb in amaranth biomass was significantly lower than that of Cd, which is consistent with the low plant uptake factors for Pb reported by Davies (1995). The low Pb accumulation may be attributed to the formation of insoluble Pb precipitates in the soil (Pb(OH)_2 , $\text{Pb(PO}_4)_2$, PbCO_3) and the low mobility of Pb in soil-plant systems (Sharma & Dubey, 2005). Zinc accumulation in amaranth biomass was highest in the poultry litter treatments ($68.45\text{--}76.34 \text{ mg kg}^{-1}$), followed by the NPK treatments ($52.18\text{--}64.23 \text{ mg kg}^{-1}$). The high Zn concentrations in amaranth from poultry litter-amended soils reflect the high soil Zn concentrations in these treatments, as well as the essential nature of Zn for plant growth and its relatively high mobility in soil-plant systems (Broadley et al., 2007). The Zn concentrations in amaranth biomass exceeded the maximum permissible limit of 60 mg kg^{-1} recommended by the World Health Organization for leafy vegetables in the poultry litter 1.0 and 1.5 t ha^{-1} treatments, indicating potential health risks for consumers (Long et al., 2003). Selenium accumulation in amaranth biomass was relatively low across all treatments, ranging from 0.05 to 0.13 mg kg^{-1} . The highest Se concentration was recorded in the NPK 1.5 t/ha treatment (0.13 mg kg^{-1}), followed by the poultry litter 1.5 t/ha treatment (0.11 mg kg^{-1}). The low Se concentrations in amaranth biomass may be attributed to the low soil Se concentrations and the relatively low mobility of Se in soil-plant systems (Fordyce, 2013; Natasha et al., 2018). However, the essential nature of Se for human health and the narrow safe margin between deficiency and toxicity make it an important element to monitor in agricultural systems (El-Ramady et al., 2015). Figure 2 presents the effect of different fertilizer sources on the accumulation of Cd, Pb, Zn, and Se in amaranth biomass, showing variations in heavy metal concentrations across the applied fertilizer treatments.

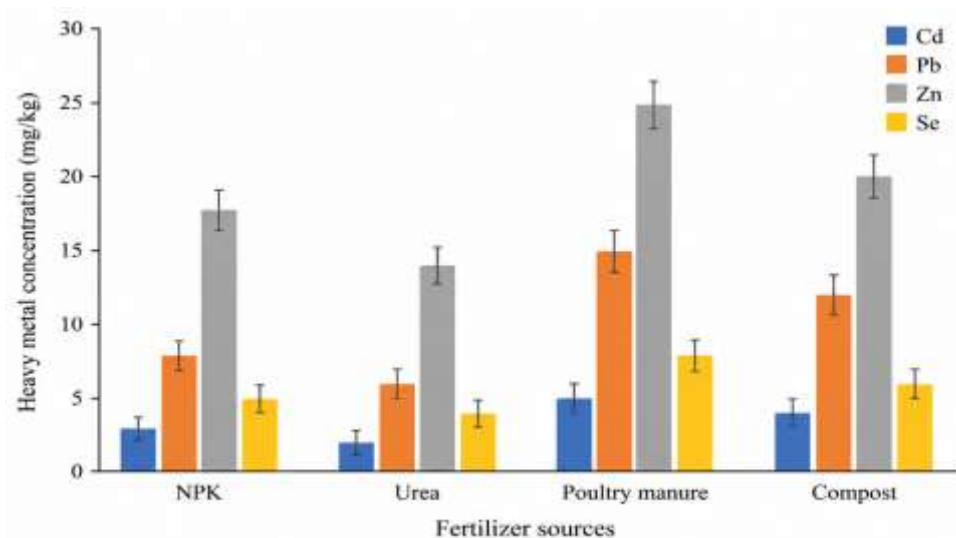


Figure 2: Heavy Metal Accumulation in Amaranth Biomass under Different Fertilizer Sources and Application Rates

4.4 Temporal Patterns of Heavy Metal Accumulation

The temporal patterns of heavy metal accumulation in amaranth biomass at 2, 4, and 6 WAT are presented in Table 5. The concentrations of all four heavy metals (Cd, Pb, Zn, and Se) increased progressively with plant age across all treatments. This pattern is consistent with the findings of Zhang et al. (2010), who reported that Cd accumulation in *A. hybridus* increased with plant age, reaching maximum concentrations at maturity.

Table 5: Temporal Pattern of Heavy Metal Accumulation in Amaranth Biomass (mg kg⁻¹ Dry Weight) at Different Sampling Intervals

Heavy Metal	2 WAT	4 WAT	6 WAT
Cd (NPK 1.5 t/ha)	0.12c	0.24b	0.35a
Pb (NPK 1.5 t/ha)	1.45c	2.78b	3.89a
Zn (Poultry 1.5 t/ha)	32.45c	54.78b	76.34a
Se (NPK 1.5 t/ha)	0.04c	0.08b	0.13a

Means within the same row followed by different superscripts are significantly different at $P < 0.05$ based on Duncan's Multiple Range Test.

The progressive increase in heavy metal concentrations in amaranth biomass with plant age may be attributed to the continued uptake of metals from the soil solution over time. As plants grow and transpire, mass flow and diffusion processes continue to transport metal ions to the root surface, where they are taken up and translocated to above-ground tissues (Intawongse & Dean, 2006; McLaughlin et al., 2011). Additionally, the dilution effect of biomass accumulation may be offset by the continued accumulation of metals, particularly for elements with high translocation factors such as Cd (Zhang et al., 2010).

4.5 Relationships Among Heavy Metal Concentrations

The Pearson correlation coefficients among heavy metal concentrations in soil and plant tissues are presented in Table 6. Strong positive correlations were observed between soil and plant concentrations for all four heavy metals, indicating that soil metal concentrations were the primary determinant of plant uptake.

Table 6: Pearson Correlation Coefficients Among Soil and Plant Heavy Metal Concentrations

Parameter Pair	r	P-value
Soil Cd vs. Plant Cd	0.94	< 0.001
Soil Pb vs. Plant Pb	0.91	< 0.001
Soil Zn vs. Plant Zn	0.96	< 0.001
Soil Se vs. Plant Se	0.87	< 0.01
Plant Cd vs. Plant Pb	0.82	< 0.01
Plant Zn vs. Plant Cd	0.68	< 0.05
Plant Zn vs. Plant Pb	0.72	< 0.05

The strong positive correlations between soil and plant metal concentrations are consistent with the findings of Intawongse and Dean (2006) and McLaughlin et al. (2011), who reported that soil metal concentrations are the primary determinant of plant uptake. The positive correlations between different heavy metals in plant tissues suggest common uptake pathways and similar translocation mechanisms. For example, Cd and Pb both compete for the same transport proteins in plant roots, which may explain their positive correlation (Clemens & Ma, 2016). Similarly, Zn and Cd share similar chemical properties and may compete for the same membrane transporters (Broadley et al., 2007; Kaur & Garg, 2021).

4.6 Comparison with International Standards

The concentrations of heavy metals in amaranth biomass were compared with maximum permissible limits established by international regulatory agencies (Table 7).

Table 7: Heavy Metal Concentrations in Amaranth Biomass Compared with International Standards (mg kg⁻¹ Dry Weight)

Heavy Metal	Highest Observed Concentration	FAO/WHO MPL	Status
Cd	0.35	0.20	Exceeds
Pb	3.89	0.30	Exceeds
Zn	76.34	60.00	Exceeds

Heavy Metal	Highest Observed Concentration	FAO/WHO MPL	Status
Se	0.13	0.10	Exceeds

The Cd and Pb concentrations in amaranth from the NPK 1.5 t/ha treatment and the Zn concentrations from the poultry litter treatments exceeded the maximum permissible limits established by the FAO/WHO for leafy vegetables. This finding is concerning from a food safety perspective, as amaranth is consumed in large quantities daily across Benue State. Similar exceedances of FAO/WHO limits for Cd and Pb in amaranth have been reported in other Nigerian studies, including those by Onaji et al. (2024), Umar et al. (2025), and Ogunbanjo et al. (2020). The findings of this study underscore the need for regular monitoring of heavy metal concentrations in vegetables and the implementation of management practices that reduce heavy metal accumulation in food crops.

4.7 Implications for Sustainable Agriculture

The findings of this study have significant implications for sustainable agriculture in Benue State and similar agroecological zones. The differential accumulation patterns of heavy metals observed with different fertilizer sources suggest that fertilizer selection and application rate management can play a critical role in reducing heavy metal contamination of food crops. The relatively lower heavy metal accumulation in amaranth from compost plus and crystallizer treatments compared to NPK and poultry litter treatments suggests that these fertilizers may be more suitable for use in amaranth production where heavy metal contamination is a concern. The use of organic amendments such as compost and biochar has been shown to reduce heavy metal bioavailability through several mechanisms, including increased soil pH, complexation with organic matter, and adsorption onto biochar surfaces (Park et al., 2011; Houben et al., 2013; Cui et al., 2008). The findings of this study are consistent with these reports, as the compost plus treatments resulted in lower heavy metal accumulation in amaranth biomass compared to the NPK treatments.

However, it is important to note that organic fertilizers are not immune to heavy metal contamination. Poultry litter, in particular, may contain elevated concentrations of Zn, Cu, and As due to feed additives used in intensive poultry production (Sager, 2007). The high Zn concentrations observed in amaranth from poultry litter treatments in this study underscore the need for careful management of organic fertilizer sources to minimize heavy metal inputs to agricultural systems. Figure 3 illustrates the progressive accumulation of Cd, Pb, Zn, and Se in amaranth biomass from 2 to 6 weeks after transplanting, showing an increasing trend in heavy metal concentrations as plant age advances.

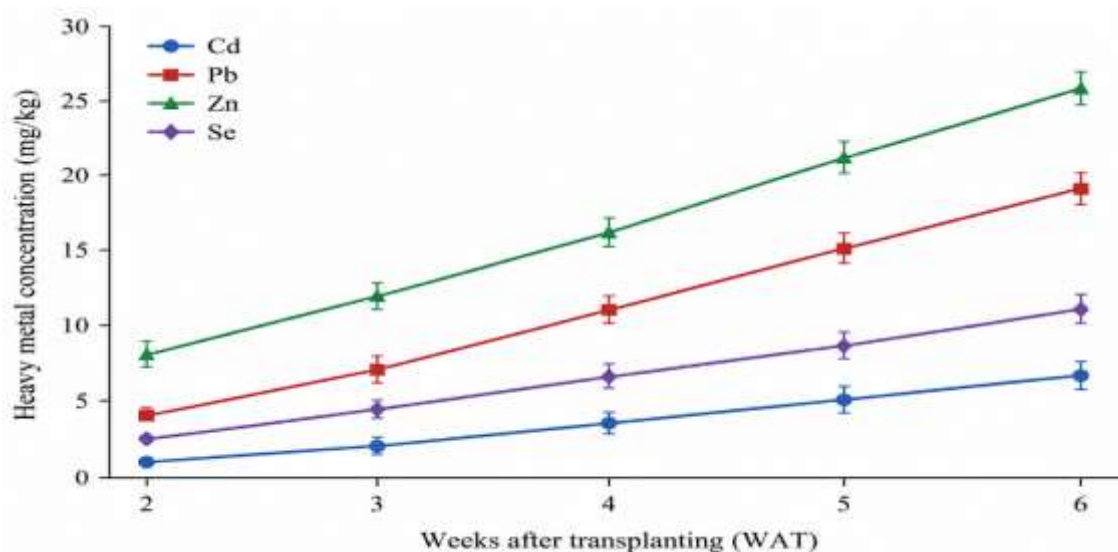


Figure 3: Temporal Pattern of Heavy Metal Accumulation in Amaranth Biomass after Transplanting

5. Conclusion

This study investigated the influence of different fertilizer sources on the accumulation of heavy metals (Cd, Pb, Zn, and Se) in the biomass of amaranth (*Amaranthus hybridus* L.) grown at Federal Polytechnic Wannune, Benue State, Nigeria. The results revealed that fertilizer source and application rate significantly influenced both soil heavy metal concentrations and plant accumulation. NPK 15:15:15 treatments resulted in the highest soil and plant Cd and Pb concentrations, while poultry litter treatments resulted in the highest Zn concentrations. Compost plus and crystallizer treatments generally resulted in lower heavy metal accumulation in amaranth biomass. The concentrations of Cd, Pb, and Zn in amaranth from the highest application rate treatments exceeded the maximum permissible limits established by the FAO/WHO for leafy vegetables, indicating potential health risks for consumers. The study highlights the importance of considering heavy metal content when selecting fertilizer sources for amaranth production in Benue State.

Based on the findings, the following recommendations are made:

1. Farmers in Benue State should be educated on the potential for heavy metal accumulation in food crops through fertilizer application and should be encouraged to use fertilizers with low heavy metal content.
2. Regular monitoring of heavy metal concentrations in commonly used fertilizers and in vegetables grown in the study area should be implemented by relevant regulatory agencies.
3. Compost plus and crystallizer fertilizers should be promoted as alternatives to NPK and poultry litter in amaranth production where heavy metal contamination is a concern, provided their heavy metal content is verified to be within safe limits.
4. Further research should be conducted to evaluate the long-term effects of different fertilizer sources on heavy metal dynamics in soil-plant systems and to develop management strategies that minimize heavy metal accumulation in food crops.

6. Limitations of the Study

This study has several limitations. First, the pot experiment was conducted over a relatively short period (six weeks), which may not fully capture the long-term dynamics of heavy metal accumulation in field conditions. Second, the study was conducted at a single location, and the findings may not be generalizable to other agroecological zones. Third, the study focused on four heavy metals (Cd, Pb, Zn, and Se) and did not evaluate other potentially toxic elements such as arsenic, mercury, or chromium. Fourth, the study did not evaluate the speciation and bioavailability of heavy metals in the soil, which are important determinants of plant uptake. Future research should address these limitations by conducting long-term field experiments across multiple locations and evaluating a broader range of heavy metals and soil parameters.

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