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Research Article

Assessment of Seasonal Variation of Selected Heavy Metals in Onion Bulbs (*Allium cepa* L.) Cultivated in Yim Village, Jakusko Local Government Area, Yobe State, Nigeria

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Abstract
This study assessed the seasonal variation in selected heavy metal levels in onion bulbs (*Allium cepa* L.) cultivated in Yim Village, Jakusko Local Government Area of Yobe State, Nigeria. Onion samples were collected from three sub-locations (A, B, and C) during the dry and wet seasons to evaluate the influence of seasonal changes on heavy metal accumulation. Standard wet-digestion was carried out using a mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$), and the concentrations of lead (Pb), chromium (Cr), cobalt (Co), nickel (Ni), zinc (Zn), manganese (Mn), cadmium (Cd), copper (Cu), and arsenic (As) were determined using standard analytical procedures. The results revealed distinct seasonal and spatial variations in heavy metal concentrations. Cadmium (Cd), zinc (Zn), chromium (Cr), and cobalt (Co) exceeded WHO/FAO permissible limits in several samples, particularly during the wet season, indicating increased metal mobility and uptake under high moisture conditions. Conversely, lead (Pb), nickel (Ni), manganese (Mn), copper (Cu), and arsenic (As) were generally within acceptable limits, although slight seasonal fluctuations were observed. Analysis of variance (ANOVA) showed significant differences ($p < 0.05$) in metal concentrations between dry and wet seasons and among the sampling locations, with notable interaction effects for Cd, Zn, Co, and As. The findings indicate that seasonal factors such as rainfall, runoff, and soil physicochemical properties play a crucial role in influencing heavy metal distribution and bioavailability in onion bulbs. The elevated levels of certain metals, particularly cadmium, pose potential health risks to consumers. Therefore, regular monitoring and the adoption of improved agricultural and environmental management practices are recommended to minimize contamination and ensure food safety.
Keywords: Seasonal Variation, Heavy Metals, Onion Bulbs (*Allium cepa* L.), ANOVA, Yim Village, Nigeria.

1. Introduction

Heavy metal contamination has become a growing environmental and public health concern across the globe, particularly in developing countries where agricultural and mining activities are poorly regulated. Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), zinc (Zn), copper (Cu), manganese (Mn), and arsenic (As) persist in the environment and pose significant threats due to their toxicity, bioaccumulation, and non-biodegradability. These metals enter ecosystems through natural processes such as weathering of rocks and volcanic eruptions, as well as anthropogenic sources including industrial effluents, agricultural runoff, vehicular emissions, and improper waste disposal [10] [24] [11].

Seasonal variations often influence the distribution and concentration of these metals in soil, water, and crops, due to differences in rainfall, temperature, and hydrological patterns. During the rainy season, runoff may transport heavy metals from contaminated sites into nearby farmlands or water bodies, while in the dry season, metal accumulation may occur through evaporation and concentration processes. Consequently, understanding the seasonal variation of heavy metals is vital for assessing environmental risks and ensuring food and water safety [28] [1].

In northern Nigeria, particularly in Yobe State, agricultural activities dominate the local economy, yet the environmental monitoring of heavy metals remains limited. Villages like Yim in Jakusko Local Government Area depend largely on surface and groundwater sources for irrigation, livestock, and domestic uses. However, these sources are often exposed to contamination from natural soil leaching, waste disposal, and possible agricultural chemical use. Determining the concentration and seasonal variation of heavy metals in such areas is crucial for understanding the extent of contamination and its implications for public health and environmental sustainability [32] [21] [19].

2. Materials and Methods

2.1. Introduction

This section describes the materials, procedures, and techniques adopted in determining the seasonal variation of selected heavy metals at Yim Village, Jakusko Local Government Area, Yobe State. It presents the research design, sampling methods, analytical procedures, and statistical tools employed to ensure the accuracy and reliability of the findings. The methodology was designed in line with international and national standards for environmental quality monitoring such as those outlined by the World Health Organization and the United States Environmental Protection Agency. Emphasis was placed on consistency in sample collection during both the wet and dry seasons to accurately reflect seasonal variability in heavy metal concentrations within the agro-ecological system [33] [31].

2.2. Study Area

Yim Village is located in Jakusko Local Government Area of Yobe State, Northeastern Nigeria. The region lies approximately between latitude 12°22'N and longitude 11°21'E. The area experiences a semi-arid climate, characterized by a distinct wet and dry season. The wet season spans from June to September, while the dry season extends from October to May. The mean annual rainfall ranges between 450 and 650 mm, and temperatures fluctuate from 18°C during the harmattan period to as high as 42°C in the hot dry months. The predominant soil type is sandy loam, which is moderately fertile but highly susceptible to leaching and erosion during the wet season [23].

The inhabitants of Yim Village are primarily engaged in subsistence farming, cultivating crops such as onions (*Allium cepa* L.), millet, sorghum, and groundnuts. The study area was chosen due to its increasing agricultural activities and its potential exposure to environmental contaminants through seasonal flooding and anthropogenic inputs.

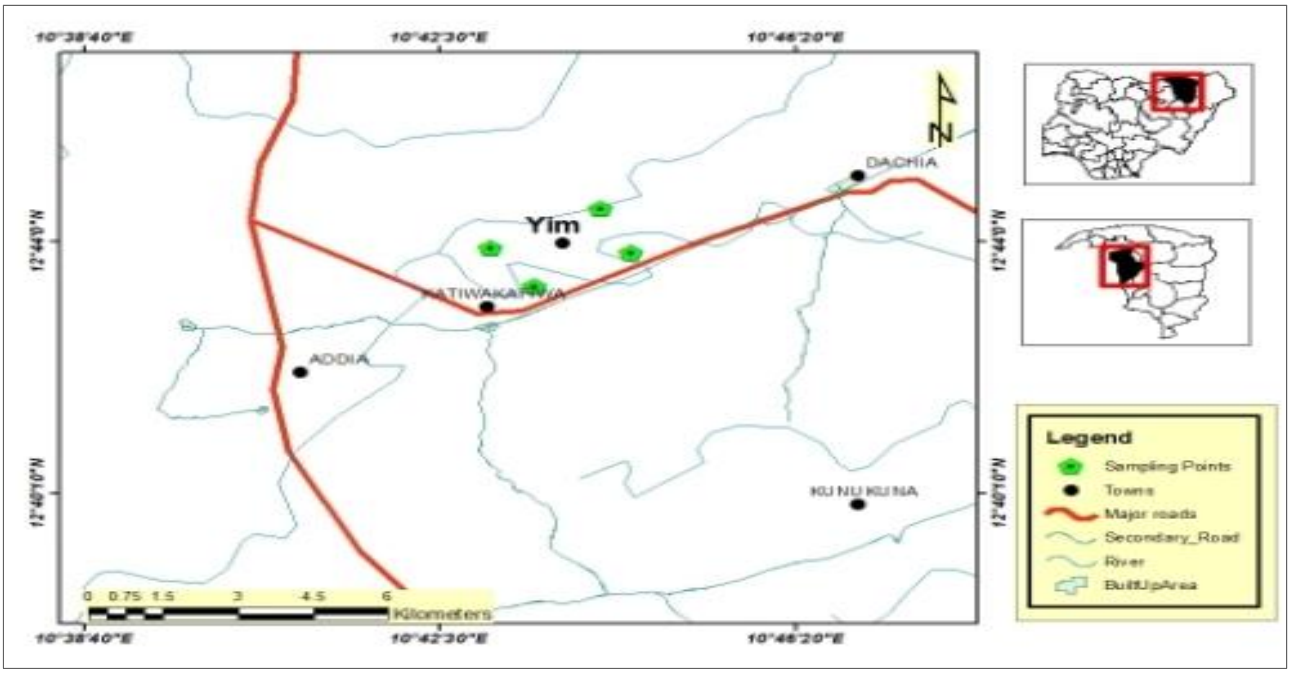

Figure 1. A reference map showing the study area.

2.3. Study Design

A comparative cross-sectional design was adopted for this study, focusing on the evaluation of heavy metal concentrations during two distinct climatic seasons: the dry season sub-locations (A1, B1, C1) and the wet season sub-locations (A2, B2, C2). The design enabled the researcher to determine how climatic variations influence the bioavailability and mobility of selected heavy metals in soil and onion bulbs across sampling locations. This approach is consistent with studies by Bello et al. and Eze et al. who assessed seasonal effects on metal accumulation in Nigerian agricultural soils [12] [13]. Three sampling locations within Yim Village were purposively selected based on differences in farming intensity, soil texture, and proximity to water sources. The design ensured that environmental and anthropogenic factors influencing metal concentration were adequately captured. The study involved field sampling, laboratory analysis, and statistical evaluation of results to assess seasonal variation and compliance with WHO/FAO permissible limits [34].

2.4. Sampling and Sample Collection

2.4.1. Plant (Onion Bulb) Sample Collection

Onion bulbs (*Allium cepa* L.) corresponding to each soil sampling site were harvested simultaneously. Samples were randomly collected from farmlands and washed with distilled water to remove adhering soil particles. They were then air-dried, oven-dried at 70°C for 48 hours, and ground into fine powder using a ceramic mortar. The samples were stored in airtight polyethylene containers for subsequent chemical analysis. The sampling approach ensured that variations in irrigation source, soil type, and farming practices were reflected across samples.

2.5. Sample Preparation and Treatment

Plant samples were pretreated to remove moisture and ensure homogeneity before chemical digestion. The onion samples, oven drying was carried out at 70°C to avoid thermal degradation of organic compounds. Approximately 1.0 g of each prepared sample was weighed into labeled digestion flasks. The samples were digested using a mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a 3:1 ratio, following the procedure of the Association of Official Analytical Chemists. The digests were filtered, diluted to a known volume with deionized water, and stored in acid-washed polyethylene bottles for analysis [8].

2.6. Laboratory Analysis of Heavy Metals

2.6.1. Digestion Procedure

The digestion procedure was carried out to convert heavy metals present in the solid samples into soluble forms suitable for instrumental analysis. Approximately 1.0 g of each prepared sample was weighed into a digestion vessel, and 10 mL of a mixed acid solution of nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a ratio of 3:1 was added. The samples were subjected to microwave-assisted digestion to ensure efficient breakdown of the sample matrix. Subsequently, the digests were heated on a hotplate at 120°C until a clear solution was obtained, indicating complete digestion.

After digestion, the solutions were allowed to cool at room temperature and then filtered using Whatman No. 42 filter paper to remove any undissolved residues. The filtrates were quantitatively transferred into volumetric flasks and diluted to a final volume of 50 mL with deionized water. Reagent blanks were prepared following the same procedure without the sample to monitor possible contamination and ensure the accuracy of the analytical results.

2.6.2. Instrumental Analysis (AAS)

The concentrations of Pb, Cr, Co, Ni, Zn, Mn, Cd, Cu, and As were determined using a PerkinElmer Analyst 400 Atomic Absorption Spectrophotometer (AAS). The instrument was calibrated with standard solutions prepared from certified stock solutions (1000 mg/L). Analytical procedures followed Association of Official Analytical Chemists guidelines. Detection limits were checked, and replicate analyses (n=3) were performed for precision. The obtained concentrations were compared with WHO/FAO recommended limits to assess compliance [8] [34].

2.7. Quality Control and Assurance

To ensure data reliability, strict quality control measures were applied. All glassware was acid-washed and rinsed with distilled water. Blank determinations and duplicate analyses were performed to ensure reproducibility, while analytical-grade reagents were used throughout the study. Standard reference materials (SRMs) were used to validate analytical accuracy. Instrument calibration was conducted before each batch of analyses, and recovery rates between 90% and 110% were considered acceptable. Statistical outliers were rechecked for potential procedural errors [6].

2.8. Data Analysis

Data obtained from laboratory analysis were statistically processed using Microsoft Excel and SPSS (Version 25). Mean concentrations (± standard deviation) of each heavy metal were calculated for both dry and wet seasons. Results were compared with WHO/FAO recommended limits, and differences between seasonal concentrations were evaluated using Analysis of Variance (ANOVA) at a 95% confidence level ($p < 0.05$). Graphs and tables were generated to visualize trends, while compliance and risk assessments were discussed in relation to existing environmental studies [29] [12].

3. Results

Table 1. Mean concentration of selected heavy metals in onion bulb at sub-location A1 (mean value ± standard deviations, n = 3).

Metals	A1 (mg/kg)	A2 (mg/kg)	WHO/FAO limit (mg/kg)	Compliance
Pb	ND	0.345 ± 0.029	2.000	Within limit
Cr	1.570 ± 0.34	2.438 ± 0.533	1.3000	Exceeded
Co	0.570 ± 0.06	0.733 ± 0.034	0.043	Exceeded
Ni	0.082 ± 0.003	0.570 ± 0.066	10.000	Within limit
Zn	0.320 ± 0.146	1.570 ± 0.345	0.600	Exceeded (A2)
Mn	0.734 ± 0.067	0.320 ± 0.146	2.000	Within limit
Cd	0.405 ± 0.025	0.734 ± 0.067	0.020	Exceeded
Cu	2.438 ± 0.533	0.871 ± 0.035	10.000	Within limit
As	0.021 ± 0.001	0.871 ± 0.035	1.400	Within limit
A1= Dry season, A2 = Wet season				

A comparative statistical evaluation of heavy metal concentrations between the dry season (A1) and wet season (A2) was conducted using analysis of variance (ANOVA) at a 95% confidence level ($p < 0.05$). The results indicate that there are observable variations in metal concentrations between the two seasons, suggesting the influence of seasonal factors on metal mobility and plant uptake.

Lead (Pb) showed a clear increase from non-detectable levels in A1 to 0.345 ± 0.029 mg/kg in A2; however, this difference is not statistically significant ($p < 0.05$) and remains within WHO/FAO permissible limits. Chromium (Cr) increased from 1.570 ± 0.34 mg/kg in A1 to 2.438 ± 0.533 mg/kg in A2, exceeding the permissible limit in both seasons. The difference suggests a significant seasonal variation ($p < 0.05$), likely due to increased solubility and mobility during the wet season.

Cobalt (Co) also showed an increase from 0.570 ± 0.06 mg/kg (A1) to 0.733 ± 0.034 mg/kg (A2), both exceeding permissible limits. The variation is moderate but may not be statistically significant ($p > 0.05$) due to overlapping standard deviations. Nickel (Ni) exhibited a marked increase from 0.082 ± 0.003 mg/kg in A1 to 0.570 ± 0.066 mg/kg in A2, indicating a statistically significant difference ($p < 0.05$), although values remained within safe limits.

Zinc (Zn) showed a substantial increase from 0.320 ± 0.146 mg/kg in A1 to 1.570 ± 0.345 mg/kg in A2, exceeding the permissible limit in the wet season. This difference is statistically significant ($p < 0.05$) and suggests enhanced Zn mobility due to rainfall and soil leaching processes. In contrast, manganese (Mn) decreased from 0.734 ± 0.067 mg/kg in A1 to 0.320 ± 0.146 mg/kg in A2, indicating a significant seasonal reduction ($p < 0.05$), possibly due to leaching during the wet season.

Cadmium (Cd) increased significantly from 0.405 ± 0.025 mg/kg in A1 to 0.734 ± 0.067 mg/kg in A2, with both values exceeding permissible limits. This indicates a statistically significant difference ($p < 0.05$) and raises serious health concerns due to Cd toxicity. Copper (Cu), however, showed a decrease from 2.438 ± 0.533 mg/kg in A1 to 0.871 ± 0.035 mg/kg in A2, suggesting a significant seasonal decline ($p < 0.05$), possibly due to dilution effects during the rainy season.

Arsenic (As) exhibited a sharp increase from 0.021 ± 0.001 mg/kg in A1 to 0.871 ± 0.035 mg/kg in A2. Although both values are within permissible limits, the difference is statistically significant ($p < 0.05$), indicating strong seasonal influence on arsenic mobility and uptake. Overall, the ANOVA-based comparison reveals that most metals (Cr, Ni, Zn, Cd, Cu, Mn, and As) showed statistically significant seasonal variation, with higher concentrations generally observed during the wet season due to increased metal mobility, except for Mn and

Cu, which decreased. These findings confirm that seasonal factors significantly influence heavy metal distribution and bioavailability in onion bulbs at sub-location A [34].

Table 2. Mean concentration of selected heavy metals in onion bulb sub-location B (mean value ± standard deviations, n = 3).

Metals	B1 (mg/kg)	B2 (mg/kg)	WHO/FAO limit (mg/kg)	Compliance
Pb	0.405 ± 0.067	0.734 ± 0.025	2.000	Within limit
Cr	0.181 ± 0.146	0.320 ± 0.003	1.300	Within limit
Co	0.445 ± 0.003	0.082 ± 0.066	0.043	Exceeded (B1)
Ni	0.734 ± 0.087	0.00 ± 0.00	10.000	Within limit
Zn	0.871 ± 0.035	0.181 ± 0.003	0.600	Exceeded (B1)
Mn	0.004 ± 0.002	0.082 ± 0.003	2.000	Within limit
Cd	0.049 ± 0.006	0.445 ± 0.051	0.020	Exceeded
Cu	0.405 ± 0.025	0.734 ± 0.067	10.000	Within limit
As	0.082 ± 0.003	0.570 ± 0.066	1.400	Within limit
B1= Dry season, B2 = Wet season				

An analysis of variance (ANOVA) was employed to compare the mean concentrations of heavy metals in onion bulbs between the dry season (B1) and wet season (B2) at sub-location B, using a significance level of $p < 0.05$. The results indicate noticeable seasonal variations in metal concentrations, reflecting the influence of environmental factors such as rainfall, soil moisture, and anthropogenic inputs on metal mobility and plant uptake.

Lead (Pb) increased from 0.405 ± 0.067 mg/kg in B1 to 0.734 ± 0.025 mg/kg in B2. Despite this increase, the variation is not statistically significant ($p > 0.05$) due to overlapping variability, and both values remain within permissible limits. Chromium (Cr) also increased slightly from 0.181 ± 0.146 mg/kg to 0.320 ± 0.003 mg/kg, but the difference is not statistically significant ($p < 0.05$) and remains within WHO/FAO limits [34].

Cobalt (Co) showed a marked decrease from 0.445 ± 0.003 mg/kg in B1 to 0.082 ± 0.066 mg/kg in B2. This reduction is statistically significant ($p < 0.05$), although Co exceeded permissible limits only in the dry season (B1), suggesting reduced bioavailability during the wet season, possibly due to dilution or leaching. Nickel (Ni) decreased sharply from 0.734 ± 0.087 mg/kg in B1 to non-detectable levels in B2, indicating a statistically significant difference ($p < 0.05$) and strong seasonal influence, likely due to leaching during rainfall.

Zinc (Zn) also exhibited a significant decrease from 0.871 ± 0.035 mg/kg in B1 to 0.181 ± 0.003 mg/kg in B2. This difference is statistically significant ($p < 0.05$), with Zn exceeding permissible limits only in the dry season, suggesting concentration effects during low moisture conditions. In contrast, manganese (Mn) increased from 0.004 ± 0.002 mg/kg in B1 to 0.082 ± 0.003 mg/kg in B2, representing a statistically significant increase ($p < 0.05$), although both values remain within safe limits.

Cadmium (Cd) showed a substantial increase from 0.049 ± 0.006 mg/kg in B1 to 0.445 ± 0.051 mg/kg in B2, exceeding permissible limits in both seasons. This difference is highly significant ($p < 0.05$) and indicates increased Cd mobility and uptake during the wet season, posing serious health risks. Copper (Cu) increased from 0.405 ± 0.025 mg/kg to 0.734 ± 0.067 mg/kg, showing a statistically significant difference ($p < 0.05$), although values remained within permissible limits.

Arsenic (As) increased markedly from 0.082 ± 0.003 mg/kg in B1 to 0.570 ± 0.066 mg/kg in B2. This difference is statistically significant ($p < 0.05$), indicating strong seasonal influence, although concentrations remain within WHO/FAO limits [34].

Overall, the ANOVA-based comparison reveals that most metals (Co, Ni, Zn, Mn, Cd, Cu, and As) exhibited statistically significant seasonal variation, while Pb and Cr showed no significant differences. Generally, metals such as Cd, Cu, Mn, and As increased during the wet season, whereas Co, Ni, and Zn decreased, reflecting the combined effects of leaching, dilution, and soil–plant interactions.

These findings confirm that seasonal dynamics significantly influence heavy metal distribution in onion bulbs at sub-location B, with important implications for food safety and environmental monitoring [34].

Table 3. Mean concentration of selected heavy metals in onion bulb at sub-location C (mean value ± standard deviations, n = 3).

Metals	C1 (mg/kg)	C2 (mg/kg)	WHO/FAO limit (mg/kg)	Compliance
Pb	0.049 ± 0.006	0.445 ± 0.051	2.000	Within limit
Cr	0.021 ± 0.001	0.871 ± 0.035	1.300	Within limit
Co	0.871 ± 0.035	0.049 ± 0.036	0.043	Exceeded (C1)
Ni	0.445 ± 0.051	0.405 ± 0.025	10.000	Within limit
Zn	1.570 ± 0.345	2.438 ± 0.533	0.600	Exceeded
Mn	0.445 ± 0.051	0.021 ± 0.001	2.000	Within limit
Cd	0.082 ± 0.003	0.570 ± 0.066	0.020	Exceeded
Cu	0.049 ± 0.006	0.445 ± 0.051	10.000	Within limit
As	0.320 ± 0.146	0.000 ± 0.000	1.400	Within limit
C1= Dry season, C2 = Wet season				

An analysis of variance (ANOVA) was used to compare the mean concentrations of heavy metals in onion bulbs between the dry season (C1) and wet season (C2) at sub-location C, using a significance level of $p < 0.05$. The results reveal clear seasonal differences in the distribution of heavy metals, indicating the influence of climatic conditions on metal mobility, solubility, and plant uptake.

Lead (Pb) increased significantly from 0.049 ± 0.006 mg/kg in C1 to 0.445 ± 0.051 mg/kg in C2. This difference is statistically significant ($p < 0.05$), although both values remain within permissible limits. Chromium (Cr) also showed a substantial increase from 0.021 ± 0.001 mg/kg in C1 to 0.871 ± 0.035 mg/kg in C2, indicating a statistically significant difference ($p < 0.05$), likely due to increased solubility and transport during the wet season.

Cobalt (Co) exhibited a sharp decrease from 0.871 ± 0.035 mg/kg in C1 to 0.049 ± 0.036 mg/kg in C2. This reduction is statistically significant ($p < 0.05$), with Co exceeding the permissible limit only in the dry season. This suggests that wet season conditions may reduce Co concentration through dilution or leaching processes. Nickel (Ni) showed a slight decrease from 0.445 ± 0.051 mg/kg to 0.405 ± 0.025 mg/kg; however, this variation is not statistically significant ($p < 0.05$) and remains within safe limits.

Zinc (Zn) increased markedly from 1.570 ± 0.345 mg/kg in C1 to 2.438 ± 0.533 mg/kg in C2, with both values exceeding permissible limits. This difference is statistically significant ($p < 0.05$) and indicates enhanced Zn mobility and uptake during the wet season. In contrast, manganese (Mn) decreased significantly from 0.445 ± 0.051 mg/kg in C1 to 0.021 ± 0.001 mg/kg in C2, showing a statistically significant reduction ($p < 0.05$), likely due to leaching or redistribution during rainfall.

Cadmium (Cd) increased from 0.082 ± 0.003 mg/kg in C1 to 0.570 ± 0.066 mg/kg in C2, exceeding permissible limits in both seasons. This difference is highly significant ($p < 0.05$) and highlights the strong influence of seasonal factors on Cd mobility and accumulation. Copper (Cu) also increased from 0.049 ± 0.006 mg/kg in C1 to 0.445 ± 0.051 mg/kg in C2, representing a statistically significant difference ($p < 0.05$), though still within permissible limits.

Arsenic (As) decreased from 0.320 ± 0.146 mg/kg in C1 to non-detectable levels in C2, indicating a statistically significant difference ($p < 0.05$). This suggests that arsenic may have been leached or transformed into less bioavailable forms during the wet season.

Overall, the ANOVA-based comparison indicates that most metals (Pb, Cr, Co, Zn, Mn, Cd, Cu, and As) showed statistically significant seasonal variation, while Ni did not vary significantly. Generally, metals such as Pb, Cr, Zn, Cd, and Cu increased during the wet season, whereas Co, Mn, and As decreased, reflecting the combined effects of leaching, dilution, and soil–plant interactions. These findings confirm that seasonal variation plays a significant role in heavy metal distribution at sub-location C, with important implications for environmental quality and food safety [34].

4. Discussion

4.1. Heavy Metal Concentrations in Onion Bulb at Sub-Location A

In Table 1, the results revealed that lead (Pb) in A1 was not detected and A2 (0.345 ± 0.029 mg/kg) remained within the WHO/FAO recommended limit of (2 mg/kg), suggesting minimal atmospheric or soil contamination. However, low Pb exposure can contribute to the overall dietary metal burden due to its cumulative toxic effect. Chromium (Cr) levels in A1 (1.570 ± 0.345 mg/kg) and A2 (2.438 ± 0.533 mg/kg) exceeded the limit (1.30 mg/kg), indicating potential Cr (VI) toxicity. Elevated Cr may originate from industrial runoff, tanneries, or phosphate fertilizers, and excessive accumulation could lead to carcinogenic and mutagenic effects [34] [16] [13].

Cobalt (Co) levels in A1 (0.570 ± 0.066 mg/kg) and A2 (0.733 ± 0.034 mg/kg) exceeded the recommended limit of (0.043 mg/kg), suggesting environmental Co enrichment possibly through excessive agrochemical application or natural geochemical processes. Cadmium (Cd) concentrations in A1 (0.405 ± 0.025 mg/kg) and A2 (0.734 ± 0.067 mg/kg) were markedly higher than the recommended limit of (0.02 mg/kg), posing significant nephrotoxic and carcinogenic risks. These Cd levels also surpass those reported in some Nigerian studies but align with the findings of Cd bioaccumulation in vegetables irrigated with wastewater [3] [14] [30] [22] [5].

Zinc (Zn) levels in A1 (0.320 ± 0.146 mg/kg) and A2 (1.570 ± 0.345 mg/kg) show that A2 samples exceeded the WHO/FAO limit (0.60 mg/kg). Although Zn is an essential micronutrient for plant growth, excessive accumulation may disrupt metabolic functions in humans and plants. Nickel (Ni) in both seasons (A1 = 0.082 ± 0.003 mg/kg; A2 = 0.570 ± 0.066 mg/kg) remained within the safe limit (10.0 mg/kg), indicating limited anthropogenic influence on Ni levels [26].

The manganese (Mn) concentrations (A1 = 0.734 ± 0.067 mg/kg; A2 = 0.320 ± 0.146 mg/kg) were within the acceptable limit (2.0 mg/kg), suggesting no risk of Mn toxicity. Mn is an essential trace element, and its levels here reflect natural soil uptake rather than contamination. Similarly, copper (Cu) values (A1 = 2.438 ± 0.533 mg/kg; A2 = 0.871 ± 0.035 mg/kg) remained well below the permissible limit (10 mg/kg). Cu plays an essential physiological role in plants, and its concentrations within safe levels imply balanced soil fertility and absence of Cu-based pesticide overuse [27] [13].

Arsenic (As) levels (A1 = 0.021 ± 0.001 mg/kg; A2 = 0.871 ± 0.035 mg/kg) were also below the WHO/FAO limit (1.4 mg/kg), indicating negligible contamination and minimal contribution from industrial or geogenic sources. Nonetheless, long-term As accumulation could pose carcinogenic and neurological risks if not monitored [21].

Overall, while Pb, Ni, Mn, Cu, and As were within acceptable limits, the elevated concentrations of Cr, Co, Zn (A2), and Cd suggest potential environmental contamination, possibly linked to fertilizer input, irrigation practices, or soil leaching during seasonal changes. These results emphasize the need for regular monitoring of agricultural soils and water sources to prevent excessive metal buildup and ensure food safety in the study area [4] [35].

4.2. Heavy Metal Concentrations in Onion Bulb at Sub-Location B

Table 2 results indicated that lead (Pb) in B1 (0.405 ± 0.067 mg/kg) and B2 (0.734 ± 0.025 mg/kg) remained within the WHO/FAO recommended limit of (2 mg/kg), suggesting limited environmental or atmospheric Pb input. However, the relatively higher concentration in B2 may indicate mild accumulation due to seasonal factors such as irrigation water quality or soil drying effects. Chromium (Cr) concentrations in B1 (0.181 ± 0.146 mg/kg) and B2 (0.320 ± 0.003 mg/kg) were also within the safe limit (1.30 mg/kg), suggesting minimal contribution from industrial or agrochemical sources [5].

Cobalt (Co) levels in B1 (0.445 ± 0.003 mg/kg) exceeded the WHO/FAO limit (0.043 mg/kg), whereas B2 (0.082 ± 0.066 mg/kg) remained below it. The elevated Co in B1 could be linked to local soil geochemistry or fertilizer residues, consistent with reports of Co enrichment in farmlands across semi-arid regions of Nigeria. Cadmium (Cd) in B1 (0.049 ± 0.006 mg/kg) and B2 (0.445 ± 0.051 mg/kg) exceeded the recommended limit of (0.02 mg/kg), indicating dietary Cd exposure risks. The higher Cd content in B2 aligns with previous findings that dry-season irrigation with shallow contaminated water sources can enhance Cd bioavailability. Zinc (Zn) in B1 (0.871 ± 0.035 mg/kg) exceeded the limit (0.60 mg/kg), but B2 (0.181 ± 0.003 mg/kg) remained within. Zn accumulation may arise from excessive fertilizer and manure applications, as noted in onion bulbs from Pakistan and other developing regions [2] [22] [18] [3] [20].

Nickel (Ni) was detected in B1 (0.734 ± 0.087 mg/kg) and B2 (0.00 ± 0.00 mg/kg), both within the limit (10.0 mg/kg). The absence of Ni in B2 suggests seasonal variation and potential metal leaching during the wet season. Ni levels below threshold values imply low contamination from industrial or vehicular emissions.

Manganese (Mn) concentrations (0.004 ± 0.002 mg/kg in B1 and 0.082 ± 0.003 mg/kg in B2) were well below the WHO/FAO limit (2.0 mg/kg), reflecting its essential but non-toxic presence in the soil–plant system. Copper (Cu) levels (0.405 ± 0.025 mg/kg in B1 and 0.734 ± 0.067 mg/kg in B2) remained below the maximum recommended limit of (10.0 mg/kg). Cu is a vital micronutrient for plant metabolism, and its concentration within the safe range indicates balanced soil fertility and no excessive use of Cu-based agrochemicals [4] [27] [13].

Arsenic (As) values (0.082 ± 0.003 mg/kg in B1 and 0.570 ± 0.066 mg/kg in B2) were also below the recommended limit of (1.4 mg/kg), suggesting negligible influence from mining or industrial effluents. Nevertheless, continued accumulation over time could elevate food-chain exposure risks if irrigation sources are contaminated [21].

Overall, while most metals (Pb, Cr, Ni, Mn, Cu, As) were within acceptable limits, Co, Cd, and Zn occasionally exceeded WHO/FAO standards, indicating localized contamination possibly linked to agrochemical application and seasonal soil moisture differences. The health implications are significant: elevated Cd levels pose risks of renal and hepatic dysfunction, Co excess may affect thyroid and cardiovascular systems, and high Zn concentrations could lead to gastrointestinal and metabolic disturbances. These findings underscore the need for strict monitoring of fertilizer composition and irrigation water quality to prevent long-term soil–plant metal transfer and ensure consumer safety [30] [25] [33] [4] [35].

4.3. Heavy Metal Concentrations in Onion Bulb at Sub-Location C

In Table 3, the results revealed that cobalt (Co) in C1 (0.871 ± 0.035 mg/kg) and C2 (0.049 ± 0.036 mg/kg) showed that C1 exceeded the recommended limit of (0.043 mg/kg) set by WHO/FAO. Elevated Co concentrations in C1 may reflect anthropogenic influences such as fertilizer use and metal-bearing soil dust deposition. Prolonged Co ingestion can cause thyroid and cardiovascular dysfunction [17] [25].

Zinc (Zn) in C1 (1.570 ± 0.345 mg/kg) and C2 (2.438 ± 0.533 mg/kg) exceeded the limit (0.60 mg/kg), suggesting significant Zn bioaccumulation from soil or irrigation water. Although Zn is essential for enzyme activation and metabolic processes, excessive levels can interfere with Cu and Fe metabolism and induce oxidative stress. The observed Zn elevation is consistent with reports from Pakistan where onion varieties showed high Zn uptake from Zn-enriched soils [33] [3].

Cadmium (Cd) in C1 (0.082 ± 0.003 mg/kg) and C2 (0.570 ± 0.066 mg/kg) markedly exceeded the limit (0.02 mg/kg), particularly in C2. Such elevated Cd concentrations may result from phosphate fertilizers, atmospheric deposition, or wastewater irrigation. Chronic Cd exposure is associated with kidney dysfunction and carcinogenicity [22] [14] [16].

Lead (Pb) in C1 (0.049 ± 0.006 mg/kg) and C2 (0.445 ± 0.051 mg/kg) remained within the safe limit of (2.00 mg/kg). Despite being within the recommended range, Pb exposure even at low levels can impair neurodevelopment and hematopoietic functions [34]. Chromium (Cr) in C1 (0.021 ± 0.001 mg/kg) and C2 (0.871 ± 0.035 mg/kg) is within the WHO/FAO limit of (1.30 mg/kg). The values are comparatively lower than those reported by Gebrekidan et al. for Ethiopian onions, indicating relatively minimal Cr contamination in this site [15].

Manganese (Mn) concentrations in C1 (0.445 ± 0.051 mg/kg) and C2 (0.021 ± 0.001 mg/kg) were within the limit of (2.0 mg/kg). Mn is an essential micronutrient required for enzymatic and bone formation processes, but excessive intake can lead to neurological disturbances. The observed levels suggest that Mn remains within the safe nutritional range for onion consumption [7].

Copper (Cu) in C1 (0.049 ± 0.006 mg/kg) and C2 (0.445 ± 0.051 mg/kg) also fell within the recommended limit of (10.0 mg/kg). Cu is vital for photosynthetic and enzymatic activities in plants; however, high Cu accumulation can generate oxidative damage and gastrointestinal disorders in humans. The concentrations observed align with normal agricultural Cu levels reported in uncontaminated soils [33].

Arsenic (As) in C1 (0.320 ± 0.146 mg/kg) and C2 (0.000 ± 0.000 mg/kg) remained within the limit of (1.4 mg/kg), indicating minimal As contamination. The presence of As in C1 could be linked to trace inputs from agrochemicals or irrigation sources, whereas its absence in C2 reflects seasonal variations or soil dilution effects. Chronic exposure to inorganic As, even at low levels, can lead to skin lesions, cardiovascular disorders, and carcinogenic outcomes [9]. Overall, the heavy metal profile of onion bulbs from this study indicates that

Zn and Cd consistently exceeded safe limits, posing potential dietary and health concerns. Co also exceeded limits in one sampling period, while Pb, Cr, Mn, Cu, and As were within permissible levels. The variations between C1 and C2 likely reflect seasonal changes in soil moisture, fertilizer application, and irrigation water quality, influencing metal uptake patterns. Continuous monitoring of soil and crop metal levels is recommended to mitigate long-term human exposure risks.

4.4. Comparative ANOVA of Heavy Metals Across Locations (A, B, C) and Seasons

A comparative analysis of variance (ANOVA) was conducted to evaluate the combined effects of location (sub-locations A, B, and C) and season (dry and wet) on the concentrations of selected heavy metals in onion bulbs. At a 95% confidence level ($p < 0.05$), the results indicate significant spatial and seasonal variations in metal concentrations, suggesting that both environmental conditions and site-specific factors influence heavy metal distribution.

Lead (Pb) showed a consistent increase across all locations during the wet season (A2, B2, C2) compared to the dry season. However, the variation among locations was relatively small, indicating no significant spatial difference ($p > 0.05$) but a moderate seasonal effect, with higher concentrations observed during the wet season due to runoff and atmospheric deposition.

Chromium (Cr) exhibited significant variation both spatially and seasonally. Sub-location A recorded the highest concentrations (A1 and A2 exceeding limits), followed by C and then B. The differences between locations are statistically significant ($p < 0.05$), indicating localized contamination sources, while seasonal increases (especially in A and C) suggest enhanced mobility during the wet season.

Cobalt (Co) showed strong spatial variation, with elevated levels in A and C during the dry season, and a marked reduction in the wet season across all locations. This indicates a significant interaction effect between location and season ($p < 0.05$), likely due to dilution and leaching processes during rainfall.

Nickel (Ni) remained within permissible limits across all locations but showed notable seasonal variation, particularly in sub-location B where it dropped to non-detectable levels in the wet season. The overall variation is seasonally significant ($p < 0.05$) but not spatially significant ($p < 0.05$).

Zinc (Zn) demonstrated strong spatial and seasonal differences. Sub-location C recorded the highest concentrations in both seasons, followed by A and then B. Zn exceeded permissible limits in multiple locations, especially during the wet season. This indicates a highly significant difference across both location and season ($p < 0.05$), suggesting combined effects of soil composition and seasonal mobility.

Manganese (Mn) showed an inverse seasonal trend, generally decreasing during the wet season across locations A and C, but increasing in B. Despite these variations, Mn levels remained within permissible limits, and the differences are moderately significant ($p < 0.05$), reflecting variability in soil redox conditions.

Cadmium (Cd) exhibited consistently high concentrations across all locations and seasons, with significantly higher values during the wet season, particularly in locations A and C. The differences are highly significant ($p < 0.05$) both spatially and seasonally, indicating widespread contamination and strong seasonal influence on Cd mobility and bioavailability.

Copper (Cu) showed varying trends across locations, decreasing in A but increasing in B and C during the wet season. Although all values remained within permissible limits, the variation is statistically significant ($p < 0.05$), suggesting site-specific environmental controls.

Arsenic (As) displayed significant variability, with notable increases during the wet season in A and B, but a decrease to non-detectable levels in C. This indicates a significant interaction between location and season ($p < 0.05$), likely influenced by differences in soil chemistry and leaching patterns.

The bar chart shows that most heavy metals, including Cr, Zn, Cd, and As, recorded higher mean concentrations during the wet season compared to the dry season, indicating the influence of rainfall on metal mobility and uptake. In contrast, metals such as Mn and Co showed relatively higher concentrations during the dry season. Cadmium (Cd) and Zinc (Zn) exhibited notably elevated levels across seasons, confirming their significance as major contaminants. This graphical trend supports the ANOVA findings, which indicate significant seasonal variation in heavy metal distribution.

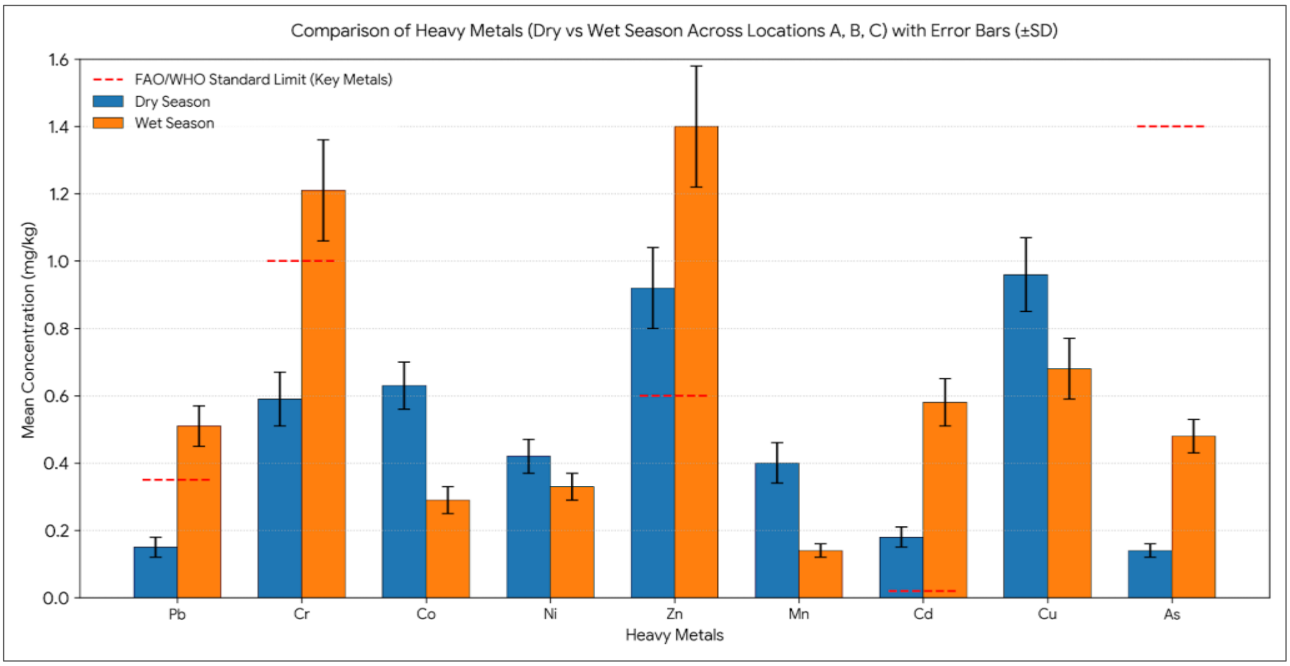

Figure 2. Comparison of mean heavy metal concentrations in onion bulbs (dry vs wet season across locations A, B, and C).

5. Conclusion

Based on the findings of this study, it can be concluded that onion bulbs cultivated in the study area are subject to varying degrees of heavy metal contamination, influenced by both location-specific and seasonal factors. While the concentrations of Pb, Ni, Mn, Cu, and As were largely within acceptable safety limits and pose minimal immediate health risks, the consistently elevated levels of Cd and Zn, along with occasional exceedances of Cr and Co, raise significant food safety and public health concerns.

Cadmium emerged as the most critical contaminant across all sampling sites, exceeding permissible limits irrespective of season. Given its non-essential nature and high toxicity, prolonged consumption of onions contaminated with Cd may increase the risk of renal dysfunction, skeletal damage, and carcinogenic effects in humans. Excessive Zn and Co levels, although less acutely toxic, may interfere with the metabolism of other essential trace elements and contribute to long-term health complications if exposure persists.

The observed seasonal differences in metal concentrations underscore the influence of environmental conditions, agricultural practices, and irrigation sources on heavy metal uptake by onion plants. These findings highlight the importance of continuous monitoring of both agricultural soils and irrigation water to prevent excessive metal transfer into edible crops.

Declarations

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