ADSUJSR 13 (2) (2025) 12 – 24
Adamawa State University Journal of Scientific Research
(ADSUJSR)
ISSN: 2705-1900 (Online); ISSN: 2251-0702 (Print)
http://www.adsujsr.adsu.edu.ng

SEASONAL VARIATION IN HEAVY METAL ACCUMULATION AND ASSOCIATED HEALTH-RISKS FROM THE CONSUMPTION OF WW-IRRIGATED AMARANTHUS IN THE ZAGYURI COMMUNITY TAMALE, GHANA

***MUSAH HARUNA NIMATU[a], PAUL AYEKOROK ABOWEN[b], SALIFU ABDALLAH[c]**

[a] *Department of Science, Tamale College of Education, Box 1 E/R, Tamale, Ghana.*
[b] *Evangelical Presbyterian College of Education, Bimbilla, Ghana.*
[c] *Gambaga College of Education, Gambaga, North East Region, Ghana.*
**Corresponding author email: nimatumusah1234@gmail.com;*
Tel: +223243731595

Received in July 2025
Accepted in August 2025

Abstract

The reuse of Wastewater (WW) for vegetable cultivation increases public health risks (HR) due to heavy metal (HM) contamination. The study aimed at investigating the effects of seasonal variation in HM and its HR on the consumption of WW-irrigated amaranthus in Tamale. The study employed eight different irrigation sources in a Randomized Complete Block Design with three replications. Physiochemical properties of biochar, soil, and water were studied, and HM analysed with an Absorption Spectrophotometer (Model 2380, Perkin Elmer, Inc., Norwalk, CT, USA). Variation among filtrate was determined using GenStat-Release 8.1 statistical package and means by Standard Error of the Difference (SED 5%). The Bioconcentration factors (BF) and HR assessments were conducted using estimated daily intake, hazard quotient (HQ), and hazard index models for adults and children. The HM ranges from 0.04 - 668.76 mg/kg from the soil and 0.01 - 2.05 mg /l in irrigated-water. Rice-Husk-Biochar-400^{o}C filtrate showed 99.85 % removal for (Fe); RHB600^{o}C (97.46%) for Mn and 99.58 % Cd (GHB 600^{O}C) in WW. Only % WW had a BF value of Cr (7.5000) in the dry season. Iron Fe (5.4880), Cd (5.0) and Mn (2.225) posing the greatest HR for adults and Mn (1.0953); Fe (2.7014) for children. Seasonal WW irrigation results in variable metal uptake by Amaranthus cruentus, exposing consumers, especially children, to significant HR.

Keywords: Amaranthus cruentus; Wastewater-irrigation; Heavy Metal; Health risk assessment; Hazard quotient: Biochar.

Introduction

The increasing global demand for fresh vegetables, coupled with limited freshwater, has led to the widespread use of WW for irrigation (Kalmpourtzidou *et al*., 2020) . Over 20 million hectares of agricultural land are irrigated with WW, supporting an estimated 200 million farmers and their households (Hamilton *et al*., 2007) . Although WW reuse provides a reliable water supply and contributes to nutrient input for crops, it can also pose serious environmental and public health risks due to the presence of pathogens, pharmaceutical residues, and Heavy Metal (Adegoke *et al*., 2018;

McEachran *et al*., 2017) , which can cause stomach problems and other health issues if consumed (Mputu *et al.,* 2024). Long-term exposure to these HM through polluted food and water sources is correlated with various adverse health conditions such as renal impairment, neurological conditions, anaemia, reproductive problems, and/or causing cancers, including carcinogenesis, mutagenesis, and teratogenesis, as well as cardiovascular diseases, skeletal systems, liver, and kidney. (Radwan and Salama, 2006).

Amaranth is rich in iron, folate, calcium, and antioxidants, commonly consumed in low-income urban households. Its large leaf surface area and fast nutrient uptake make it vulnerable to heavy metal bioaccumulation in polluted areas (Egwu et al., 2019; Yaradua et al., 2019; Egwu et al., 2019; Otorkpa et al., 2019). The bioconcentration factor (BCF) quantifies heavy metal absorption in edible parts (Thao et al., 2024), with BCF values exceeding 1.0 noted for cadmium in leafy greens (Karkarna et al., 2024).

This study assessed seasonal variations in HM accumulation and non-carcinogenic health risks from consuming Amaranthus irrigated with untreated wastewater, biochar-treated wastewater, and tap water in controlled pot experiments. *Amaranthus cruentus* irrigated with untreated wastewater shows higher levels of Fe, Mn, and Cd, leading to increased health risks. This study highlights biochar's effectiveness in reducing human exposure to heavy metals through contaminated vegetables, offering practical solutions for improving food safety in urban farming systems reliant on wastewater in Ghana and beyond.

Materials and Methods

Study Design and Experimental Setting

The experiments were conducted under controlled conditions at the Zagyuri irrigation site in the Tamale Metropolis, Northern Ghana, for rainy and dry seasons.

Zangyuri, located in the urban area of Tamale, is a key vegetable-growing area in Northern Ghana's regional capital. Tamale is the third-largest city in Ghana, consisting of 197 communities, of which thirty-three are urban (Agodzo *et al*., 2003). The metropolis covers approximately 930 km² and is situated between latitudes nine°16’N and 9°34’W. The site is a recognised urban vegetable production zone where untreated WW is commonly used for irrigation purposes. The common soil types are sandy, clay, and lateritic ochrosols (Agodzo *et al*., 2003).

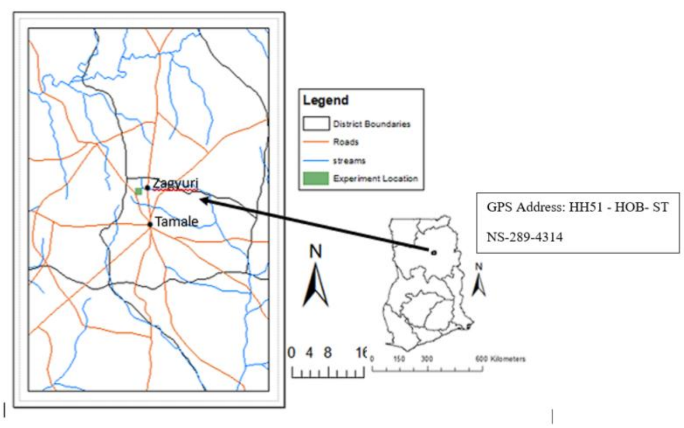

Figure 1: A map of Ghana indicating Tamale and the study site (Field study 2021; Nimatu et al., 2023).

The experiment began with biochar preparation at different pyrolysis temperatures, followed by a well-designed set-up for remediation and cultivation of crops in pots under a controlled environment for two seasons: the rainy season *(July-October 2020*) and the dry season (*January–March 2021*). The climate is characterised by unimodal rainfall (annual mean ~1100 mm), with average daily temperatures ranging between 33 and 39°C (Agodzo *et al*., 2003). Before and after remediation, the concentration of HM in WW was assessed to identify the best remediation approach for HM and pathogens. The concentrations of HM in the biochars and soil were also determined. The test crop was *Amaranthus cruentus*, which was irrigated with WW treated using various biochar-based filtration systems (BTW). It was fertilised at the recommended rate. Heavy metals such as lead (Pb), chromium (Cr), cadmium (Cd), iron (Fe), and manganese (Mn) were determined in the WW before and after biochar remediation and in/on vegetable leaves, stems, and roots after harvest.

Irrigation Water Treatments

Eight irrigation water treatments were applied: untreated WW, six biochar-filtrate WW (BFW), and Tap Water (TW) serving as the control. The BFW was produced using a three-stage, gravity-fed, anaerobic biofiltration system. The system included a sedimentation unit, a corn cob biochar pre-treatment chamber, and two main remediation chambers filled with high-performing biochars produced from rice husks and groundnut husks using laboratory-based pyrolysis at 400°C and 600°C, and open-field combustion. Corn cob biochar served as the primary filter medium, followed by selected high-performing biochars from the pre-screening phase. The treated filtrate was stored and applied daily at 1 L per pot.

Biochar Production and Characterization

Biochars were prepared from rice husks and groundnut husks using two approaches: controlled laboratory pyrolysis at 400°C and 600°C in a muffle furnace, and open-air slow combustion in covered pits. Corn cob biochar was used for the primary remediation process. The feedstock was dried, carbonised under limited oxygen conditions, cooled naturally, and stored in airtight containers before use. The biochars were sieved to 2 mm and analysed for pH, electrical conductivity (EC), ash content, organic carbon content, and metal content. The surface morphology and porosity were not examined but were inferred based on the pyrolysis temperature and feedstock type.

Description of WW Treatment Setup

The anaerobic biofiltration systems were constructed using 20 –25 L plastic containers (30 – 45 cm height) connected via ½ inch polyvinyl chloride (PVC) pipes, valves, and union joints, and sealed with silicone to prevent leakage. A constant hydraulic loading rate of 0.05 m/h was used. The pretreatment chamber removed suspended solids using the CCB. WW was then filtered through one of the six biochars: RHB400, RHB600, GHB400, GHB600, RHBOF, and GHBOF. Each remediation chamber contained 783–2349 g of biochar and 6544 g of 3 mm pebbles for support. All biochars were sieved (≤2 mm) before use. The filtrates were tested and assessed for flow rate and contaminant removal efficiency.

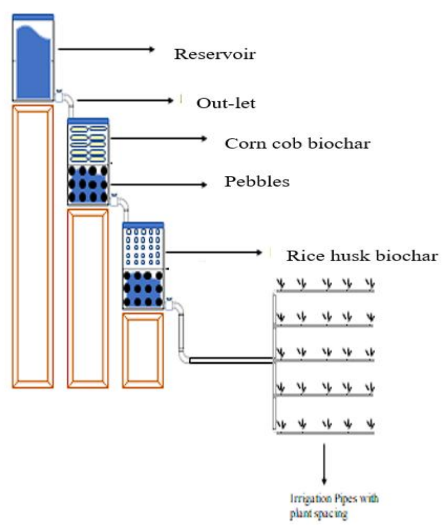

Figure 2: Anaerobic multi-chamber downwards filtration set-up. (Source: Field study, 2021; Nimatu et al., 2023) and Schematic layout of the multi-chamber downward anaerobic filtration system used to treat WW at the Zagyuri irrigation field.

Soil, Water, and Biochar Analysis (Summary Version)

Soil samples collected from the Zagyuri field (0–20 cm depth) were air-dried at room temperature and passed through a 2 mm mesh sieve to remove stones and debris. Soil pH was measured in a 1:2.5 soil-to-water suspension using a calibrated pH meter, while electrical conductivity (EC) was determined in a 1:5 soil–to–water extract using a digital conductivity meter. The soil organic carbon content was estimated using the Walkley–Black dichromate oxidation method. Total nitrogen was measured using the Kjeldahl digestion technique, and available phosphorus was determined using the Bray 1 extraction method, followed by colorimetric analysis. Exchangeable bases (Ca, Mg, K, and Na) were extracted with 1N ammonium acetate and quantified via flame photometry (for K and Na) and atomic absorption spectrophotometry (for Ca and Mg). Soil texture was determined using the hydrometer method.

Irrigation water from the UWW, BTW, and TW sources was sampled weekly. Samples were analysed for pH, EC, turbidity, and concentrations of Fe, Mn, and Cd following acid preservation and atomic absorption spectrophotometry. Measurements were performed using aqueous extracts, combustion methods, and AAS after nitric acid digestion.

Crop Management and Sample Collection

Amaranthus cruentus seedlings were transplanted into each pot one week after soil stabilisation was achieved. Each pot was irrigated daily and monitored for pests, diseases, and uniform growth. At maturity, *Amaranthus* leaves were harvested, rinsed with deionised water, oven-dried at 60°C until a constant weight was achieved, and ground into powder using a stainless-steel grinder. The powdered samples were sieved (0.5 mm mesh) and stored in airtight containers before metal analyses.

Heavy Metal Analysis

One gram of dried leaf tissue was digested using a 2:1 mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$) on a hot plate until a clear solution was achieved. The digested samples were filtered and diluted with deionised water. The concentrations of Fe, Mn, and Cd were determined using atomic absorption spectrophotometry (Perkin Elmer Model 2380). Similar methods were used for metal analysis in water and leaf samples using aqua regia and acidified digestion.

Bio-Concentration Factor (BCF)

The Bio-Concentration Factor (BCF) was used to estimate metal uptake by *Amaranthus cruentus* and was calculated as.

$$\mathrm{BCF} = \frac{\text{Metal concentration in leaf tissue } \left(\frac{\mathrm{mg}}{\mathrm{kg}}\right)}{\text{Metal concentration in soil } \left(\frac{\mathrm{mg}}{\mathrm{kg}}\right)}$$

A BCF greater than 1.0 indicates substantial metal bioaccumulation from soil to plant tissue.

Health Risk Assessment, Hazard Quotient (HQ), and Hazard Index (HI)

To estimate the non-carcinogenic HR associated with consuming *Amaranthus*, the Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI) were calculated using standard models. EDI was computed, and non-carcinogenic HR associated with consuming metal-contaminated *Amaranthus* were assessed using the (HQ) and (HI). Hazard Quotient represents the ratio of the estimated daily intake (EDI) of each heavy metal (Fe, Mn, and Cd) to its oral reference dose (RfD), whereas HI is the sum of HQs, reflecting the cumulative risk posed by multiple metals. Values above one indicates a potential for adverse health effects (USEPA, 2011; Sharma *et al*., 2016). The Estimated Daily Intake (EDI) and average daily dose (ADD) were determined using the following equations:

$$\mathrm{EDI} = \frac{\mathrm{MC\ x\ IR}}{\mathrm{BW}}$$

$$\mathrm{ADD} = \frac{MC\ x\ IR\ x\ EF\ x\ ED}{\mathrm{BW\ x\ AT}},\ \mathrm{HQ} = \frac{ADD}{\mathrm{RfD}}$$

Where MC is the concentration of metal in vegetable tissue (mg/kg), IR is the ingestion rate (0.137 kg/day), and BW is the average body weight (60.3 kg for adults and 24.5 kg for children). The reference doses (RfD) used were 0.7 mg/kg/day for Fe, 0.14 mg/kg/day for Mn, and 0.001 mg/kg/day for Cd, respectively. HQ is a unitless ratio that compares the estimated metal exposure to its toxicological threshold. The RfD values were derived from USEPA standards, and the average daily dosage (ADD) was expressed in milligrams per kilogram of body weight per day (mg/kg-day). The metal concentration (C, mg/kg) in the edible part of the vegetable, exposure frequency (EF) of 350 days annually, body weight (BW) of 60.3 kg for adults and 24.5 kg for children, and average lifetime (AT), which was determined by multiplying the exposure duration (ED) by 365 days per year, were among the exposure variables. Risk assessment was performed separately for adults and children, considering their respective body weights and exposure durations (30 years for adults and 6 years, respectively).

Statistical Analysis

All data were analysed using GenStat (Release 8.1). Descriptive statistics were computed for the metal concentrations, BCFs, and health risk indices. Seasonal differences were examined to evaluate the effects of irrigation water and climatic variations on heavy metal uptake and consumer risk. The results were interpreted against the WHO/FAO safety thresholds.

Results and Discussion

Results

Physicochemical Characteristics of WW and Irrigation Seasons

The physicochemical properties of WW used for irrigation varied significantly among seasons (Table 1). During the rainy season, the WW exhibited moderate electrical conductivity (517 µS/cm), slightly alkaline pH (7.43), and elevated turbidity levels (41–45.9 NTU), which exceeded the WHO limits. In contrast, dry season WW was more saline (EC = 1250 µS/cm), warmer (37–42°C), but less turbid. Nitrate and phosphate concentrations were also markedly higher in the rainy season, indicating a greater potential for nutrient enrichment and metal mobility. These seasonal shifts in water quality parameters likely influenced the translocation and uptake of HM by *Amaranthus cruentus* (Figure 3).

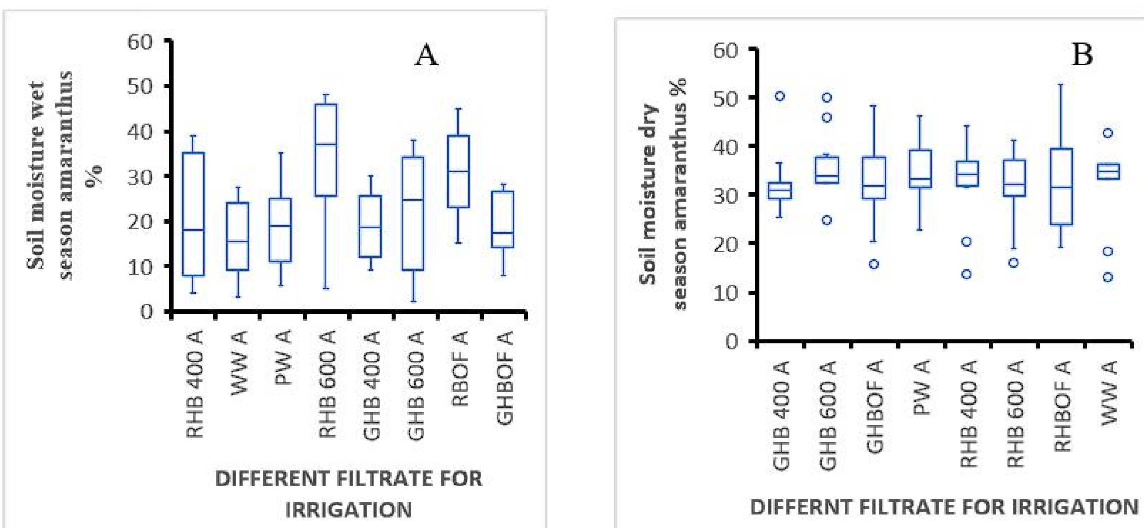

Figure 3*:* Soil moisture content under Amaranthus cultivation across treatments in (A) the rainy season and (B) the dry season. (Source: Field data, 2021; Nimatu et al., 2023)

Pre- and Post-Harvest Soil Heavy Metal Concentrations

To assess the impact of different irrigation treatments on residual soil contamination, post-harvest concentrations of iron (Fe), manganese (Mn), and cadmium (Cd) were measured and compared to baseline values recorded before planting. The initial soil concentrations were relatively low: 16.2 mg/kg for Fe, 12.6 mg/kg for Mn, and 0.21 mg/kg for Cd. These values served as references for evaluating the accumulation or depletion following crop growth. Post-harvest results revealed a substantial increase in residual Fe and Mn concentrations under untreated WW irrigation, with Fe reaching 668.76 mg/kg and Mn reaching 74.09 mg/kg. Similarly, Cd concentrations slightly increased to 0.043 mg/kg under the same treatment, exceeding the WHO soil quality guideline (0.02 mg/kg). However, biochar treatments moderated this effect. Groundnut husk biochar pyrolysed at 600 °C (GHB600) reduced Fe to 610.20 mg/kg and Cd to 0.030 mg/kg, while rice husk biochar at 600 °C (RHB600) yielded similar outcomes with Fe at 598.55 mg/kg and Cd at 0.028 mg/kg. Tap water (PW) irrigation maintained the lowest post-harvest concentrations of all metals, with values closest to the baseline.

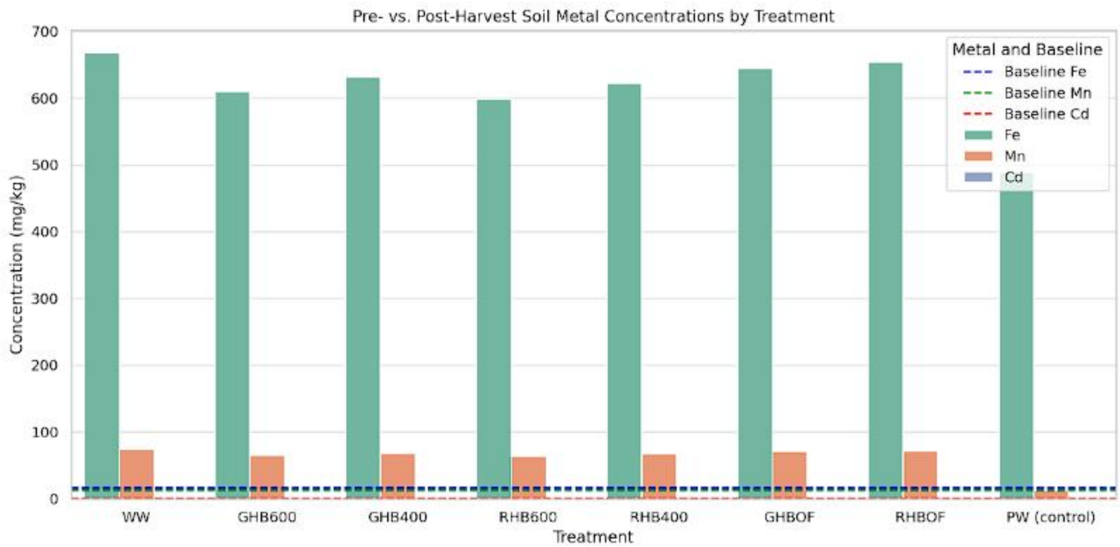

Figure 4: Pre- and post-harvest soil concentrations of Fe, Mn, and Cd across the irrigation treatments.

The graphical comparison in Figure 4 illustrates the contrast between the pre- and post-harvest metal levels. All WW-based treatments resulted in elevated residual concentrations compared to those of the control. However, biochar treatments, particularly GHB600 and RHB600, demonstrated a clear mitigation effect, reducing soil metal accumulation relative to untreated WW.

Table 1: Concentration of HM in Amaranthus cruentus Leaves

Season	Treatment	Fe	Mn	Cd
Rainy	WW	1.576	0.639	0.0764
	TW	0.111	0.009	0.002
	GHB600	0.968	0.144	0.059
	GHB400	1.185	0.116	0.021
	GHBOF	0.118	0.032	0.039
	RHB600	0.589	0.145	0.027
	RHB400	1.188	0.173	0.0177
	RHBOF	0.980	0.197	0.022
Dry	WW	0.044	0.0101	0.020

Season	Treatment	Fe	Mn	Cd
	TW	0.014	0.0011	0.022
	GHB600	0.066	0.011	0.013
	GHB400	0.024	0.068	0.020
	GHBOF	0.019	0.021	0.014
	RHB600	0.029	0.009	0.032
	RHB400	0.066	0.014	0.028
	RHBOF	0.020	0.002	0.019

Note: *GHB = Groundnut Husk Biochar; RHB = Rice Husk Biochar; OF = Open Field; 400/600 = Pyrolysis Temperature (°C); TW = Tap Water.*

The concentrations of iron (Fe), manganese (Mn), and cadmium (Cd) in the leaf tissue of *Amaranthus cruentus* differed significantly across irrigation treatments and between seasons. The highest concentrations of all three metals were consistently observed in plants irrigated with untreated WW, whereas the lowest concentrations were found in those treated with tap water (PW). During the rainy season, Fe concentrations in WW-treated *Amaranthus* reached 1.576 mg/kg, followed by RHB400 (1.188 mg/kg) and GHB400 (1.185 mg/kg) in the dry season. Mn levels also peaked under WW treatment (0.639 mg/kg), whereas RHBOF showed the highest biochar-treated Mn concentration (0.197 mg/kg). Cd concentrations ranged from 0.0764 mg/kg in WW to as low as 0.0177 mg/kg in RHB400. In the dry season, the overall metal concentrations were lower, with Fe declining to 0.044 mg/kg under WW. Interestingly, Cd levels remained relatively stable across the treatments in the dry season, although RHBOF recorded slightly elevated values. When averaged across all biochar types, BTW reduced Fe, Mn, and Cd concentrations in *Amaranthus* leaves by 43.7%, 77.6%, and 62.4%, respectively, compared with those grown using untreated WW. These findings support the effectiveness of biochar filtration in mitigating heavy metal accumulation in leafy vegetables.

Bio-Concentration Factor (BCF) of HM in Amaranthus

The highest BCF values for *cadmium (Cd) and chromium (Cr)* were recorded in the dry season under pipe water (PW) irrigation (Cd = 0.5116; Cr = 7.5), indicating substantial uptake from soil to edible tissue. In contrast, manganese (Mn) and iron (Fe) exhibited comparatively lower BCFs across the treatments and seasons. Wastewater irrigation resulted in the highest BCF for Mn in the rainy season (0.0086), while groundnut husk biochar (GHB600) and rice husk biochar open field (RHBOF) also contributed to moderate BCF values for Fe and Cd (Table 3).

Table 3: *Bio-concentration values for Fe, Mn, Cd in Amaranthus across treatments and seasons*

Treatment	Fe (Rainy)	Fe (Dry)	Mn (Rainy)	Mn (Dry)	Cd (Rainy)	Cd (Dry)
WW	5.488	0.153	0.639	0.0101	0.0764	0.02
PW	0.3865	0.0488	0.009	0.0011	0.002	0.022
GHB600	3.371	0.230	0.144	0.011	0.059	0.013
GHB400	4.126	0.0836	0.116	0.068	0.021	0.020
GHBOF	0.411	0.0662	0.032	0.021	0.039	0.014
RHB600	2.051	0.100	0.145	0.009	0.027	0.032
RHB400	4.137	0.230	0.173	0.014	0.0177	0.028
RHBOF	3.413	0.0697	0.197	0.002	0.022	0.019

Estimated Daily Intake (EDI) of Metals

The results indicated that *Amaranthus* grown with untreated WW (WW) consistently exhibited the highest EDI values, particularly during the rainy season, when metal concentrations in plant tissues were elevated. Biochar-treated WW (BTW) significantly reduced the estimated intake levels of all metals, demonstrating its effectiveness in mitigating dietary exposure to contaminants. The lowest EDI values were associated with plants irrigated with tap water (PW), which served as the control. Across all scenarios, children showed a higher EDI per kilogram of body weight than adults because of their smaller body mass. This disparity underscores the heightened vulnerability of children to dietary metal exposures. Among the metals analysed, Cd posed the greatest concern owing to its high toxicity and low permissible intake threshold. These findings highlight the importance of treatment strategies, such as biochar filtration, in reducing potential health risks from WW-irrigated vegetables and suggest that regulatory monitoring should prioritise exposure in children and during wet agricultural seasons.

Table 4: Estimated Daily Intake (EDI) of Metals

Treatment	Season	Iron (Fe)		Manganese (Mn)		Cadmium (Cd)	
		Adult	Child	Adult	Child	Adult	Child
WW	Rainy	0.055716	0.19027	0.452691	1.09532	0.055716	0.13096
	Dry	0.062680	0.02399	0.038305	0.01731	0.041787	0.03428
PW	Rainy	0.041787	0.02399	0.01543	0.01543	0.00343	0.03771
	Dry	0.041787	0.02399	0.00189	0.00189	0.03771	0.03771
GHB600	Rainy	0.066511	1.65926	0.24683	0.24683	0.10113	0.10113
	Dry	0.066511	0.11313	0.01886	0.01886	0.02228	0.02228
GHB400	Rainy	0.107949	2.03123	0.19884	0.19884	0.03599	0.03599
	Dry	0.107949	0.04114	0.11656	0.11656	0.03428	0.03428
GHBOF	Rainy	0.069645	0.20227	0.05485	0.05485	0.06685	0.06685

	Dry	0.069645	0.03257	0.03599	0.03599	0.02399	0.02399
RHB600	Rainy	0.090538	1.00961	0.24855	0.24855	0.04628	0.04628
	Dry	0.090538	0.04971	0.01543	0.01543	0.05485	0.05485
RHBOF	Rainy	0.083574	0.083574	0.132325	0.132325	0.083574	0.083574
	Dry	0.083574	0.038653	0.013233	0.013233	0.038305	0.038305

Note: EDI values are estimated based on metal concentrations in Amaranthus leaf tissue, an ingestion rate of 0.137 kg/day, and body weights of 60 kg (adult) and 24.7 kg (child).

Health Risk Assessment (HQ and HI)

The HQ results indicated that vegetables irrigated with WW consistently exhibited HQ values above the Cd threshold in both the rainy and dry seasons. In the rainy season, the HQ for Cd reached 1.30 in adults and 5.21 in children, whereas in the dry season, the values were 1.22 and 4.66, respectively. These values indicate a significant health risk, particularly in children.

Biochar-treated WW significantly reduced the HQ values for all three metals. In both seasons, groundnut husk biochar pyrolysed at 600 °C (GHB600) produced the lowest HQ values. During the rainy season, Cd HQs under GHB600 irrigation were 0.14 for adults and 0.41 for children, and Fe and Mn HQs remained low at 0.12 and 0.08 for adults and 0.34 and 0.14 for children, respectively. The HQ values for vegetables irrigated with pipe-borne water were below 0.1 in both groups.

The HI followed a similar trend. For WW irrigation, HI values were 2.13 and 5.21 for adults and children, respectively, during the rainy season, and 1.87 and 4.66 for adults and children, respectively, in the dry season. These values confirm the high cumulative risk of non-carcinogenic effects from multiple metal exposure through vegetable consumption. In contrast, HI values under GHB600 treatment were consistently below one: 0.34 and 0.89 for adults and children, respectively, in the rainy season, and 0.34 and 0.91, respectively, in the dry season. The HI values for pipe water–irrigated vegetables remained the lowest across all treatments.

These findings confirmed that WW irrigation of *Amaranthus cruentus* in the Zagyuri community poses a significant health risk, primarily due to heavy metal accumulation. The use of biochar, particularly GHB600, substantially mitigated this risk and reduced the HQ and HI values to levels within acceptable health safety thresholds.

The high concentrations of Fe, Mn, and Cd in *Amaranthus* during the rainy season are consistent with previous studies that highlight the influence of seasonal water quality dynamics on metal flexibility and plant uptake (Murtaza *et al.*, 2010; Houngla *et al.*, 2020; Otorkpa *et al.*, 2019). This reflects the enhanced solubility and mobility of metals under wetter conditions. Fe, Mn, and Cd in the rainy season under WW exceeded the concentrations observed in biochar-treated and tap-water-irrigated samples. This agrees with earlier research indicating that increased moisture and lower pH during rainy seasons can enhance the bioavailability of metals such as Cd in soil and water systems (Osobamiro & Adewuyi, 2015).

The HM levels observed in this study are consistent with the findings of Mputu *et al*. (2024) and Khan (2008), who reported high pollutant loads in urban vegetables irrigated with raw WW, leading to increased health risks from both microbial and chemical contaminants. The bio-concentration factors (BCFs) further endorsed the propensity of *Amaranthus cruentus* to hoard HM, particularly Cd, with BCF values under several treatments above the threshold for concern (Li *et al.*, 2016, and Sulaiman *et al*., 2020).

The application of GHB600°C and RHB600˚C significantly reduced metal accumulation in both plant tissue and soil. Compared to WW irrigation. This aligns with the established literature on the adsorbent capacity of biochar and its ability to immobilise HM through mechanisms such as electrostatic attraction, surface complexation, and ion exchange (Al-Wabel *et al*., 2013; Li *et al*., 2022; Otorkpa *et al*., 2019).

Health risk assessments using the EDI, HQ, and HI models revealed that children faced significantly higher risks than adults, confirming previous reports (Mputu *et al*., 2024; Najmi *et al*., 2023; Abubakari *et al*., 2017; Ametepey, 2018; Otorkpa *et al*., 2019). Under WW irrigation in the rainy season, the Cd HQ values exceed the safe thresholds by over fivefold. The HI values for Cd, Fe, and Mn combined were also highest for children in the WW group in the dry season, indicating considerable carcinogenic health risk. These outcomes support previous studies suggesting that leafy vegetables irrigated with untreated WW can pose acute and chronic health threats when consumed regularly, particularly by vulnerable populations (Sulaiman *et al*., 2020; Li *et al*., 2016). Biochar-treated WW (particularly GHB600) reduced HI values for children and adults in the rainy season, confirming the potential of biochar as a viable intervention in low-resource urban farming systems. These results highlight the effectiveness of biochar in reducing dietary exposure to HM and support its integration into safe WW reuse frameworks. Although similar studies have shown the promise of biochar in controlled settings (Sohi *et al*., 2010; Xu *et al*., 2012).

Conclusions

This study demonstrates that seasonal variations significantly influence heavy metal accumulation in *Amaranthus cruentus*, irrigated with untreated WW in the Zagyuri community of Tamale, Ghana. The results confirmed that Cd accumulated to levels that posed significant non-carcinogenic health risks, especially for children, with the highest concentrations occurring during the rainy season. In contrast, the use of biochar-treated WW, especially with groundnut husk biochar pyrolysed at 600 °C, substantially reduced the uptake of Fe, Mn, and Cd by the plants and lowered the associated health risks below critical thresholds.

Acknowledgements

The authors would like to thank the Faculty of Agriculture at the University for Development Studies (UDS), Tamale Campus, and Microbiology Laboratory CSRI -Water Research, Accra, for access to Laboratory facilities and field equipment. We also appreciate the Zagyuri farmers who permitted field access and supported sampling activities.

Funding

The authors did not receive any external funding for this study. All activities related to data collection, analysis, and manuscript preparation were self-financed.

References

Adegoke, A. A., Amoah, I. D., Stenström, T. A., Verbyla, M. E., and Mihelcic, J. R. (2018). Epidemiological evidence and health risks associated with agricultural reuse of partially treated and untreated WW: A review. In Frontiers in Public Health (Vol. 6). Frontiers Media S.A. https://doi.org/10.3389/fpubh.2018.00337.

Agodzo, S. K. Huibers, F, Chenini, F. van Lier, J. B. Duran, A. (2003). Use of WW in irrigated agriculture. Country studies from Bolivia, Ghana and Tunisia, 2 (Ghana). WUR, Wageningen, The Netherlands.

Aina, O. E., Mugivhisa, L. L., Olowoyo, J. O.,and Obi, C. L. (2024). HM and potential health risk assessment of Lactuca sativa and Daucus carrota from soil treated with organic manures and chemical fertilizer. Environmental Monitoring and Assessment, 196. https://doi.org/10.1007/s10661-024-12687-y.

Al-Wabel, M. I., Al-Omran, A., El-Naggar, A. H., Nadeem, M. and Usman, A. R. A. (2013). Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. Bioresource Technology, 131, 374–379. https://doi.org/10.1016/j.biortech.2012.12.165.

Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A. and Joseph, S. (2008). Using poultry litter biochars as soil amendments. Australian Journal of Soil Research, 46, 437–444. https://doi.org/10.1071/SR08036.

Drechsel, P., Scott, C. A., Raschid-Sally, L., Redwood, M. and Bahri, A. (2009). WW irrigation and health: Assessing and mitigating risk in low-income countries. In WW Irrigation and Health: Assessing and Mitigating Risk in Low-income Countries. https://doi.org/10.4324/9781849774666.

Egwu, O. C., Casmir, U. C., Victor, U. C., Samuel, U. C., Dickson, M. A. and Oluwanisola, O. W. (2019). Evaluation and Ecological Risk Assessment of Selected Heavy Metal Pollution of Soils and Amaranthus cruentus and Telfairia occidentalis Grown Around Dump Site in Chanchaga Minna, Niger State, Nigeria. Asian Journal of Environmentand Ecology, 1–16. https://doi.org/10.9734/ajee/2019/v10i230114.

Hamilton, A. J., Stagnitti, F., Xiong, X., Kreidl, S. L., Benke, K. K. and Maher, P. (2007). WW Irrigation: The State of Play. Vadose Zone Journal, 6, 823–840. https://doi.org/10.2136/vzj2007.0026.

Houngla, E. J. H., Gbankoto, A., Mizehoun-Adissoda, C., Anani, C. B. L., Edorh, P. A., Mouta\"\irou, K., & Sohounhloué, D. C. K. (2020). Nutrient Composition and HM Content of Three Leafy Vegetables (Amaranthus Cruentus L., Lactuca Sativa L., Solanum Macrocarpon L.) in Porto-Novo, Republic of Benin. Journal of Food and Nutrition Research, 8(2), 80–86. https://doi.org/10.12691/jfnr-8-2-2

Kalmpourtzidou, A., Eilander, A. and Talsma, E. F. (2020). Global Vegetable Intake and Supply Compared to Recommendations: A Systematic Review. Nutrients 2020, Vol. 12, Page 1558, 12(6), 1558. https://doi.org/10.3390/NU12061558.

Karkarna, M. Z., Garba, Y. I. and Salisu, A. S. (2024). Bio-Concentration Factors of HM in the Leaf and Root System of Some Selected Vegetables along the Dilimi River in Jos North, Plateau State, Nigeria. UMYU Scientifica, 3, 192–199. https://doi.org/10.56919/usci.2431.021.

Khan, S., Cao, Q., Zheng, Y. M., Huang, Y. Z. and Zhu, Y. G. (2008). Health risks of HM in contaminated soils and food crops irrigated with WW in Beijing, China. Environmental Pollution, 152, 686–692. https://doi.org/10.1016/j.envpol.2007.06.056.

Li, A., Zhang, Y., Ge, W., Zhang, Y., Liu, L. and Qiu, G. (2022). Removal of HM from WWs with biochar pyrolyzed from MgAl-layered double hydroxide-coated rice husk: Mechanism and application. Bioresource Technology, 347. https://doi.org/10.1016/j.biortech.2021.126425.

Li, B., Wang, Y., Jiang, Y., Li, G., Cui, J., Wang, Y., Zhang, H., Wang, S., Xu, S. and Wang, R. (2016). The accumulation and health risk of HM in vegetables around a zinc smelter in northeastern China. Environmental Science and Pollution Research, 23(24), 25114–25126. https://doi.org/10.1007/S11356-016-7342-5/METRICS.

Liu, H. and Jian, H. (2023). ANN-based prediction of ammonia nitrogen for WW discharge indicators under carbon neutral trend. Frontiers in Ecology and Evolution, 11, 1199870. https://doi.org/10.3389/FEVO.2023.1199870/BIBTEX.

McEachran, A. D., Shea, D. and Nichols, E. G. (2017). Pharmaceuticals in a temperate forest-water reuse system. Science of the Total Environment, 581–582, 705–714. https://doi.org/10.1016/j.scitotenv.2016.12.185.

Mishra, T., Singh, N. B. and Singh, N. (2017). Restoration of red mud deposits by naturally growing vegetation. International Journal of Phytoremediation, 19(5), 439–445. https://doi.org/10.1080/15226514.2016.1244162.

Mputu, L. M., Ndelo, P. M., Tuakuila, J., Ndelo-di-Phanzu, J. and Nuapia, Y. B. (2024). Health implications of heavy metal contamination in urban vegetables: Assessing the risks in

Kinshasa and Lubumbashi. https://doi.org/10.21203/rs.3.rs-4955506/v1.

Murtaza, G., Ghafoor, A., Qadir, M., Owens, G., Aziz, M. A., Zia, M. H., Saifullah, H. (2010). Disposal and use of sewage on agricultural lands in Pakistan: a review. Pedo- Sphere, 20, 23–34

Najmi, A., Albratty, M., Al-Rajab, A. J., Alhazmi, H. A., Javed, S. A., Ahsan, W., Rehman, Z. U., Hassani, R. and Alqahtani, S. S. (2023). Heavy Metal Contamination in Leafy Vegetables Grown in Jazan Region of Saudi Arabia: Assessment of Possible Human Health Hazards. International Journal of Environmental Research and Public Health, 20 (4)2984. https://doi.org/10.3390/ijerph20042984.

Nie, G., Tu, T., Hu, L., Wu, L. and Zhou, Y. (2023). Accumulation characteristics and evaluation of HM in soils and vegetables of plastic-covered sheds in typical red soil areas of China. Quality Assurance and Safety of Crops and Foods, 15(3), 22–35. https://doi.org/10.15586/QAS.V15I3.1222.

Osobamiro, M. T., & Adewuyi, G. O. (2015). Levels of HM in the Soil: Effects of Season, Agronomic Practice and Soil Geology. Journal of Agricultural Chemistry and Environment, 04(04), 109–117. https://doi.org/10.4236/jacen.2015.44012.

Otorkpa, O. J., Paul, A. O. and Emmanuel, S. (2019). Public Health Implications of Heavy Metal Contamination of Leaves and Stems of Amarantus Hybridus (African spinach) Consumed in Nigeria. Texila International Journal of Public Health, 7(3). https://doi.org/10.21522/TIJPH.2013.07.03.ART021.

Radwan, M. A., & Salama, A. K. (2006). Market basket survey for some HM in Egyptian fruits and vegetables. 44, 1273–1278. https://doi.org/10.1016/j.fct.2006.02.004

Sharma, R. K., Agrawal, M. and Marshall, F. M. (2009). HM in vegetables collected from production and market sites of a tropical urban area of India. Food and Chemical Toxicology, 47, 583–591. https://doi.org/10.1016/j.fct.2008.12.016.

Shehu, I., Malsiu, A. and Bajraktari, N. (2023). Assessment of Potentially Toxic Element Concentrations in Soil and Vegetables and Impact on Human Health Through TF, EDI, and HRI Indicators: Case Study Anadrinia Region (Kosovo). Biological Trace Element Research, 201, 479–492. https://doi.org/10.1007/s12011-022-03160-3.

Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). A review of biochar and its use and function in soil. Advances in Agronomy, 105(1), 47–82. https://doi.org/10.1016/S0065-2113(10)05002-9

Sulaiman, F. R., Ibrahim, N. H. and Syed Ismail, S. N. (2020). Heavy metal (As, Cd, and Pb) concentration in selected leafy vegetables from Jengka, Malaysia, and potential health risks. SN Applied Sciences, 2. https://doi.org/10.1007/s42452-020-03231-x.

Thao, T., Gonzales, M., Ryals, R., Dahlquist-Willard, R., Diaz, G. C. and Ghezzehei, T. A. (2024). Biochar impacts on soil moisture retention and respiration in a coarse-textured soil under dry conditions. Soil Science Society of America Journal, 88(6), 1919–1931. https://doi.org/10.1002/SAJ2.20746.

Xu, R. kou, Zhao, A. zhen, Yuan, J. hua, & Jiang, J. (2012). pH buffering capacity of acid soils from tropical and subtropical regions of China as influenced by incorporation of crop straw biochars. Journal of Soils and Sediments, 12(4), 494–502. https://doi.org/10.1007/s11368-012-0483-3

Yaradua, A. I., Alhassan, A. J., Nasir, A., Matazu, K. I., Usman, A., Idi, A., Muhammad, I. U., Yaro, S. A. and Muhammad, Y. Y. (2019). Concentrations and Risk Evaluation of

Selected HM in Amaranthus (L.) Leaf Cultivated in Katsina State, North West Nigeria. Journal of Applied Life Sciences International, 1–12. https://doi.org/10.9734/jalsi/2019/v20i430089.