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Implications of maize fertigation with treated domestic wastewater on soil heavy metal contamination and health risks

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ABSTRACT

Reuse of treated domestic wastewater (TDW) for irrigation offers a sustainable resolution to water scarcity, but its implications for soil quality, crop safety, and public health remain a concern. This study assessed the effect of TDW fertigation on soil contamination, heavy metal concentrations in maize grains, bioaccumulation, and associated health risks. Soil samples and maize grains from treatment and control plots were analyzed in triplicates using Atomic Absorption Spectrophotometry (AAS) to analyze Cr, Pb, Cd, Cu, Zn, and Ni with soil contamination indices, bioaccumulation factors, and risk indices applied for interpretation. Results revealed moderate soil heavy metal enrichment overall, also Cu, Zn, Cd, and Ni, with Pb showing depth-related anomalies, while Igeo classified soils as unpolluted except for chromium, which reached mean concentrations of 6.0 ± 3.6 mg/kg in treatment plots and 4.5 ± 3.4 mg/kg in control plots. In maize grains, Pb (2.21 ± 1.53 mg/kg), Cr (6.0 ± 3.6 mg/kg), and Zn (46.1 ± 8.3 mg/kg) consistently exceeded permissible limits, regardless of irrigation source. Nickel (4.99 ± 3.38 mg/kg) and copper (3.44 ± 1.01 mg/kg) remained within safe thresholds, while cadmium was undetectable. Bioaccumulation factors were <1 for most metals, except Zn, indicating its highest uptake potential, and were in the order of $Pb < Ni < Cr < Cu < Zn$. Risk assessments indicated children as the most vulnerable group, with lead, nickel, and copper contributing to non-carcinogenic risk, and nickel accounting for 55-67% of cumulative carcinogenic risk. TDW fertigation did not significantly ($P > 0.05$) elevate contamination compared to control plots, but systemic background pollution presents food safety and public health challenges, necessitating integrated monitoring, remediation, and child-focused interventions.

Key words:

Heavy metals, fertigation, Maize, pollution index, domestic wastewater, health risks

1.0 Introduction

The rising demand for sustainable farming practices has increased interest in using treated wastewater for irrigation. Reuse of treated domestic wastewater (TDW) in crop farming offers a sustainable solution to water scarcity, but its implications for soil quality, crop safety, and public health remain a concern (Jimenez *et al.*, 2015). Presence of toxic heavy metals like cadmium, copper, lead, nickel, and chromium in wastewater poses significant risks to human health, particularly when used for irrigating staple crops like maize (Kiziloglu *et al.*, 2008; Singh *et al.*, 2010; Mahfuza *et al.*, 2017). About 80% of Tanzanian population use maize as staple food (Mkonda and He, 2017). As a widely consumed food crop, maize contamination can have far-reaching implications for public health (WHO, 2017). The knowledge on whether consumption of maize crops fertigated with treated domestic wastewater pose health risks to populations is essential in informing the public and decision makers on the respective health implications; and the required best practices for safeguarding the ecosystem and public health.

Domestic wastewater is discharged from households in residential areas, and is generated through routine activities such as cooking, cleaning, bathing, washing, and toilet use. It contains a mixture of organic matter, nutrients, pathogens, and traces of pollutants, and is distinct from industrial wastewater sources (Boutin and Eme, 2016; Elgallal *et al.*, 2016). Typically, domestic wastewater is enriched with BOD₅, orthophosphate, ammonia, and nitrates which are nutrients that can support plant growth (Karri *et al.*, 2021). Domestic wastewater contains low concentrations of heavy metals (Elgallal *et al.*, 2016), however, its quality is increasingly influenced by the use of household products, particularly cosmetics and detergents, which introduce undesirable contaminants. Studies show that many cosmetic products contain relatively low amounts of heavy metals such as cadmium (Cd), mercury (Ag), lead (Pb), and arsenic (As), used as colorants, preservatives, or active ingredients; their use and disposal contribute directly to heavy metal loads in wastewater (Safavi *et al.*, 2019). Similarly, Aonghusa and Gray (2002) reported that laundry detergents contribute significant proportions of heavy metals to municipal wastewater, including 31.9% of Cd, 0.3% of zinc (Zn), and 0.24% of copper (Cu). Drozdova *et al.* (2019) reported that domestic wastewater contribute approximately 60% of Cd and 21-35% of zinc (Zn), Cu, and As in municipal wastewater; while its contribution to Pb, Chromium (Cr), iron (Fe), nickel (Ni), and manganese (Mn) is generally below 15%. Conventional secondary wastewater treatment systems are not designed to effectively remove heavy metals; therefore, the reuse or discharge of treated effluents can lead to the contamination of soils with the metals, posing environmental and public health risks.

Application of treated wastewater for irrigation is widely practiced globally for various reasons; mainly the increasing water scarcity and cost of fertilizers (Drechsel *et al.*, 2015a; Kihila, 2015). Hyderabad, India and Haroonabad, Pakistan present few case studies where wastewater is the only dependable irrigation water in the canals during the dry seasons (Keraita *et al.*, 2008). Irrigation with treated wastewater offers water and nutrients for plants, which is described as fertigation; but also protect water bodies from pollution due to inadequate quality of treated wastewater (Bahri *et*

al., 2010; Kihila, 2015). As hinted earlier, water reuse for irrigation is linked to heavy metal contamination in the soil and food chain (Dikinya and Areola, 2010; Rezapour *et al.*, 2019). Soil contamination with heavy metals, including Cd, Pb, Cu, Ni, and Zn in irrigated soil with treated municipal wastewater for short-term has been reported in previous studies (Singh *et al.*, 2010a; Xue *et al.*, 2019; El-hassanin *et al.*, 2020; Jalil *et al.*, 2022). Additionally, the effect of irrigation using treated wastewater on soil heavy metals pollution, plant uptake, and the associated health risks through ingestion of irrigated agricultural produces have been confirmed literature (Khan *et al.*, 2015; Jalil *et al.*, 2022; Rezapour *et al.*, 2019; Angon *et al.*, 2024). Risk assessment studies for crops irrigated with treated wastewater have indicated mixed results for various heavy metals and crops. Ismail *et al.* (2024) reported possible health risks due to Cd and Ni for vegetables irrigated using the treated wastewater from the public sewerage system. On the contrary, Ofori *et al.* (2025) found no possible non-carcinogenic health risk for adults consuming maize irrigated with treated wastewater. While, Jalil *et al.* (2022) reported insignificant health effects to adults and children due to consumption vegetables fertigated with wastewater.

Notably contamination of the soil with heavy metals, bioaccumulation, and health risk depend the source wastewater among others, which influence the levels of heavy metals in the wastewater used for irrigation. Majority of the previous studies evaluated the soil contamination with heavy metals and health risks mainly for municipal wastewater, various industrial wastewater, while others do not specify the source wastewater. However, few studies have specifically explored the contamination of soil with heavy metals and the possible health risk due to fertigation of maize with treated domestic wastewater, especially in regions where maize is a staple crop. This study aims to: (1) determine the levels of heavy metals in the TDW and soil; (2) evaluate soil pollution with heavy metals due to fertigation with TDW using pollution indices; and (3) evaluate the concentrations of heavy metals in the maize grains, bioaccumulation, and the potential human health risks due to intake of maize fertigated with TDW. The findings of the study inform decision makers and stakeholders on the preparation of evidence-based approaches for safe use of TDW for irrigation.

2.0 Materials and methods

2.1 Experimental description

This study was conducted at Ardhi University in Dar es Salaam, Tanzania. It focused on exploring the effect of fertigation with TDW from the residential houses and treated in the anaerobic digester and baffled reactor, on the soil heavy metal contamination, bioaccumulation into the maize grains, and the possible health risks due to ingestion of the maize produced. The experiment involved treatment and control plots, each replicated three times. Treatment plots (PT) received irrigation with TDW, while control plots (CP) were irrigated using clean water. To prevent rainfall from affecting soil heavy metal concentration results, the study was carried out in a greenhouse. A surface drip irrigation system was employed to minimize direct contact with TDW and improve

water use efficiency. Maize seeds were sown in rows spaced 75 cm apart, with plants positioned 25 cm along the drip lines (Frederick *et al.*, 2020).

2.2 Sampling and analysis of irrigation water

Samples of treated domestic wastewater (TDW) and piped water were collected every two months throughout the experiment and analyzed according to standard water and wastewater protocols (Hach Co. and Hach, 1992). The analysis focused on determining concentrations of selected heavy metals namely lead (Pb), copper (Cu), cadmium (Cd), zinc (Zn), chromium (Cr), and nickel (Ni). Metal concentrations were measured using an Atomic Absorption Spectrophotometer (AAnalyst 100, PerkinElmer, USA) following established procedures (Balengayabo *et al.*, 2024; Hach Co. and Hach, 1992).

2.3 Soil sampling, preparation, and analysis for heavy metals

Soil samples were collected from both treatment and control maize plots, with baseline data obtained prior to planting (WHO and UNEP, 2006). Sampling points were selected at irrigated sites where maize was grown. Since soil chemicals typically accumulate within the 0-35 cm root zone (Khaskhoussy *et al.*, 2015), samples were taken from the topsoil (0-20 cm) and the maize root zone (20-40 cm). Results were reported as the mean of triplicate samples for each plot.

Collected soils were air-dried for one week, oven-dried at 105 °C for 24 hours (Hach model 35 GM-2), cooled, ground, and sieved through a 2.0 mm mesh (Hach Kit, Model SIW-1). Heavy metals were extracted using Aqua Regia reagent (HCl:HNO₃, 1:3 v/v). For digestion, 0.5 g of soil was mixed with 2.0 ml Aqua Regia, heated at 100 °C for one hour in a Hach COD digester (DRB 200), cooled, diluted to 10 ml with distilled water, and left overnight before filtration using L-1 Lasman papers.

The analysis targeted zinc (Zn), copper (Cu), lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni), metals of environmental and public health concern frequently reported in treated wastewater (Lu *et al.*, 2015; Khalid *et al.*, 2018). Concentrations were determined using an Atomic Absorption Spectrophotometer (AAnalyst 100, PerkinElmer, USA). To ensure data reliability, blanks and calibration checks were performed throughout, with calibration curves accepted only when correlation coefficients exceeded 0.95. Blank samples were run after each measurement to flush the capillary tube and reduce cross-contamination.

2.4 Assessment of soil pollution levels using indices

The pollution of the irrigated soil with heavy metals was assessed by numerical indices namely the contamination factor (CF), geo-accumulation index (I_{geo}), and pollution load index (PLI) (Ahama *et al.*, 2020).

2.4.1 Contamination factor (CF)

The contamination factor (CF) denotes the degree to which soil is polluted by a specific heavy metal. It highlights metals that may pose a risk of soil contamination and was computed using Equation 1 (Kamanina *et al.*, 2023; Balengayabo *et al.*, 2024; Er, 2025).

$$CF = C_n / C_B \dots \dots \dots \text{Eqn.1}$$

In this study, C_n represents the post-harvest concentration of each heavy metal in the soil, while C_B denotes the baseline concentration established from natural soil levels prior to the experiment. Pollution levels were classified using the contamination factor (CF): values below 1 indicate unpolluted soils; $1 \leq CF < 2$, slightly polluted; $2 \leq CF < 3$, moderately polluted; and $CF > 3$, highly polluted (Kamanina *et al.*, 2023; Balengayabo *et al.*, 2024; Er, 2025).

2.4.2 Pollution load index (PLI)

The Pollution Load Index (PLI) was applied to evaluate the extent of soil quality degradation caused by the accumulation of heavy metals through fertigation with TDW. PLI was calculated as the geometric mean of the contamination factor (CF) values, as outlined in Equation 2 (Kamanina *et al.*, 2023; Balengayabo *et al.*, 2024). In this equation, n denotes the total number of heavy metals analyzed (six heavy metals in this study), while CF values were calculated in Equation 1. The classification of PLI values was as follows: $PLI = 0$, represents background concentrations; $0 < PLI \leq 1$, indicates unpolluted soil; $1 < PLI \leq 2$, moderately polluted soil; and $PLI > 2$, highly polluted soil (Kamanina *et al.*, 2023; Balengayabo *et al.*, 2024; Er, 2025).

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \dots \times CF_n)^{\frac{1}{n}} \dots \dots \dots \text{Eqn. 2}$$

2.4.3 Geo-accumulation Index (Igeo)

The geo-accumulation index (Igeo) is a numerical index used to evaluate accumulation of heavy metal and pollution levels in soils. It accounts for natural background concentrations and the current concentration after the anthropogenic activity such as irrigation using treated wastewater; and is calculated using the formular shown in equation 3 (Ahamad *et al.*, 2020; Yang *et al.*, 2022; Er, 2025).

$$I_{geo} = \log_2 \frac{C_n}{1.5 \times C_b} \dots \dots \dots \text{Eqn.3}$$

The parameter C_n represents the concentration of heavy metals in the samples after maize harvesting, while C_b denotes the background values of the metals; in this study, baseline values were applied. A constant factor of 1.5 is included to account for potential variations in baseline values (Ahamad *et al.*, 2020; Yang *et al.*, 2022). The geo-accumulation index (Igeo) is interpreted as follows: Igeo values ≤ 0 , indicates no pollution, 0-1, no to moderate pollution, 1-2, moderate pollution, 2-3, moderate to heavy pollution, 3-4, heavy pollution, 4-5, heavy to extreme pollution, and >5 extreme pollution (Ahamad *et al.*, 2020; Yang *et al.*, 2022; Er, 2025).

2.5 Analysis of heavy metals in maize grain

The samples of maize grains were sun-dried for one week, and then dried in the oven at 105 °C for 24 hours using a Hach model 35 GM-2 oven to remove moisture. Heavy metals were extracted using Aqua Regia reagent following the standard methods and guidelines, as described in section 2.3. The extracts were analyzed for heavy metals namely lead (Pb), zinc (Zn), chromium (Cr), copper (Cu), nickel (Ni), and cadmium (Cd) using the Atomic Absorption Spectrophotometer (AAnalyst 100, PerkinElmer, USA).

2.6 Bioaccumulation factor

The bioaccumulation factor (BAF) is a widely applied index for quantifying the transfer potential of heavy metals from soil to plants (Zhang *et al.*, 2017; EL-Hassanin *et al.*, 2022; Yang *et al.*, 2022). It is derived by calculating the ratio between the concentration of a given metal in maize grains and its corresponding concentration in the soil, as presented in Equation 4.

$$BAF = \frac{C_m}{C_s} \dots\dots\dots \text{Eqn. 4}$$

In this formula, C_m represents the concentration of heavy metals in maize grains, whereas C_s denotes their concentration in the soil. The resulting ratio provides an index of the degree to which metals present in the soil are translocated and accumulated within the edible portions of maize.

2.7 Evaluation of non-carcinogenic health risk

Non-carcinogenic health risk assessment was performed using the Target Hazard Quotient (THQ) and Total Target Hazard Quotient (TTHQ) tools for versatile evaluation of non-carcinogenic health risk associated with consumption of maize fertigated with treated domestic wastewater. HRI focuses on potential risks through dietary exposure to individual metal in maize crops, while TTHQ covers exposure to all metals in maize crops (Iqbal *et al.*, 2019). The values were calculated using equations 5-7. The non-carcinogenic health risk assessment was conducted based on the concentrations of non-carcinogenic metals identified in maize grain samples. The evaluation employed the United States Environmental Protection Agency (USEPA) human health risk assessment models, as outlined in the subsequent subsections.

2.7.1 Target Hazard Quotient (THQ)

The target hazard quotient (THQ) is employed to assess whether the consumption of food containing heavy metals poses potential health risks. It is determined by comparing the Daily Intake of Metals (DIM) with the Oral Reference Dose (RfD) (Balkhair & Ashraf, 2016; Iqbal *et al.*, 2019; EL-Hassanin *et al.*, 2022; Kokora *et al.*, 2025). The calculation follows Equation 5, with values computed separately for adults and children.

$$THQ = \frac{DIM}{RfD} \dots\dots\dots \text{Eqn. 5}$$

The values of $HRI > 1.0$ indicates potential health risk, implying that consumers may be exposed to metal concentrations above the safe threshold. While, values $HRI < 1.0$ are considered safe, implying that the exposure to hazard level is lower than the reference dose, therefore no expected adverse health effects. According to U.S. Environmental Protection Agency (USEPA), the Oral

Reference Dose (RfD), represents the maximum acceptable daily oral intake of a contaminant that is unlikely to cause harmful effects during a lifetime.

Daily intake of metals (DIM)

The DIM denotes the mount of heavy metal (mg) absorbed by a person per day through ingestion of food crops; and is computed for each metal using equation 3 (Iqbal *et al.*, 2019; Ismail *et al.*, 2024; Kokora *et al.*, 2025).

$$DIM = \frac{C \times IR \times EF \times ED}{BW \times AT} \dots\dots\dots \text{Eqn. 6}$$

The parameters of DIM are defined as follows: C is the concentration of heavy metal in the maize grains, IR is daily consumption of maize (ingestion rate), EF is exposure frequency (365 days), ED is the exposure duration (70 years), BW is the body weight (Kg), which differ for adults and children, and AT is the averaging time. The specific input data into equation 3 are summarized in Table 1.

2.7.2 Total Target health target quotient (TTHQ)

The total target hazard quotient (TTHQ) estimates the collective non-carcinogenic health risk caused by exposure to all metals involved. This index is a sum of the THQ for each individual heavy metal following Equation 4 (Sultana *et al.*, 2017; Iqbal *et al.*, 2019). Like THQ, the values of TTHQ were calculated separately for adults and children.

$$TTHQ = \sum_{i=1}^n THQ \dots\dots\dots \text{Eqn.7}$$

Whereby, *i* represents individual heavy metals for which their hazard quotients were involved in the determination of the TTHQ. The values of TTHQ less than 1.0 indicate that the food has negligible health impact, while the values greater than 1.0 indicates that the food pose harmful health effects to the consumers (Iqbal *et al.*, 2019; Liu *et al.*, 2020).

Table 1. Values of the input parameters used the DIM and THQ models for adults and Children

Parameters	Units	Value	Reference
Average body weight of adults (BW _a)	Kg	62	Leonard and Mkumbo, 2025
Average body weight of children (BW _c)	Kg	30	Leonard and Mkumbo, 2025
Ingestion rate of maize products for adults	Kg/person/day	0.345	El-Hassanin <i>et al.</i> , 2020
Intake rate of maize products for children	Kg/person/day	0.232	El-Hassanin <i>et al.</i> , 2020
Exposure duration (ED)	Years	70	Xue <i>et al.</i> , 2019
Exposure frequency (EF)	Days/year	365	Xue <i>et al.</i> , 2019
Reference doses of heavy metals (RfD)			
Copper (Cu)	mg/Kg/day	0.004	USEPA IRIS, 2000
Lead (Pb)	mg/Kg/day	0.004	
Chromium (Cr)	mg/Kg/day	1.5	
Zinc (Zn)	mg/Kg/day	0.3	
Cadmium (Cd)	mg/Kg/day	0.001	
Nickel (Ni)	mg/Kg/day	0.02	USEPA IRIS, 2015

2.8 Evaluation of carcinogenic health risks

The carcinogenic health risk was assessed for consumption of maize products fertigated with TDW by considering individual heavy metals and cumulative risk associated with all carcinogenic heavy metals detected in the maize grains. Three of the detected heavy metals specifically lead, nickel, and chromium (IV) were considered through their respective oral carcinogenic slope factors (CSF).

2.8.1 Carcinogenic risk for individual metals

The likelihood of cancer risks related to the consumption of maize fertigated with TDM was determined using the Incremental Lifetime Cancer Risk (ILCR) in accordance with previous studies (Cocârță *et al.*, 2016; Mahfuza *et al.*, 2017). Only detected carcinogenic heavy metals in the maize grains were used to estimate the ILCR using equation 8.

$$ILCR = DIM \times SF \dots\dots\dots \text{Eqn.8}$$

DIM is the daily intake of metal in mg/kg BW/day, calculated in Equation 6. It is assumed to be the lifetime mean daily dose of exposure to the carcinogenic heavy metals. SF is the slope factor in mg/kg/day. The slope factors for lead, nickel, and chromium (IV) were 8.50×10^{-3} , 9.10×10^{-1} , and 4.20×10^{-1} respectively (USEPA IRIS, 2000; Cocârță *et al.*, 2016).

2.8.2 Cumulative cancer risk

The cumulative incremental life time cancer risk (CILCR) is due to exposure to multiple carcinogenic heavy metals enriched in maize grains. It is the sum of the individual ILCR of carcinogenic heavy metals detected in maize (lead, nickel, and chromium (IV)) as shown in Equation 9 (Cocârță *et al.*, 2016; Mahfuza *et al.*, 2017; Sultana *et al.*, 2017).

$$CILCR = \sum ILCR_i \dots\dots\dots \text{Eqn.9}$$

i represents the individual carcinogenic heavy metals for which their ILCR were involved in the determination of the CILCR.

2.9 Statistical data analysis

The determination of the effects of fertigation with TDW on heavy metal contamination in the soil, maize grains, and health risks was achieved by using the analysis of variance (ANOVA), notably one-way ANOVA at ($P \leq 0.05$) using GraphPad InStat 3.0 Ink by comparing the mean values from treatment and control plots.

3.0 Results and discussions

3.1 Heavy metal concentrations in irrigation water

The characteristics of irrigation water with respect to heavy metals are summarized in Table 2, which updates the dataset from Balengayabo *et al.* (2024) by including one additional

measurement. Average concentrations of trace metals, including Copper (Cu), Zinc (Zn), Lead (Pb), Cadmium (Cd), Nickel (Ni), and Chromium (Cr) ranged between 0.020 ± 0.013 mg/L and 0.103 ± 0.106 mg/L. Tap water samples consistently showed lower mean values compared to treated domestic wastewater. However, in both cases, the concentrations of heavy metals remained below the permissible thresholds established by WHO and UNEP (2006) for irrigation water classified under slight to moderate restriction categories.

Table 2. Levels of heavy metals in treated domestic wastewater and tap water used for irrigation.

S/N	Parameters	Units	Mean concentrations (n = 13)		FAO standards	P-Values
			Treated wastewater	Tap water		
1	Copper (Cu^{2+})	mg/L	0.007 ± 0.003	0.006 ± 0.005	0.2	≥ 0.05
2	Zinc (Zn^{2+})	mg/L	0.008 ± 0.02	0.005 ± 0.011	2.0	≥ 0.05
3	Lead (Pb^{2+})	mg/L	0.085 ± 0.13	0.066 ± 0.142	2.0	≤ 0.05
4	Cadmium (Cd^{2+})	mg/L	0.020 ± 0.013	0.0036 ± 0.0014	0.01	≥ 0.05
5	Nickel (Ni^{2+})	mg/L	0.0024 ± 0.001	0.013 ± 0.02	0.2	≥ 0.05
6	Chromium (Cr^{3+})	mg/L	0.103 ± 0.106	0.07 ± 0.01	0.1	≤ 0.05

Note. Data adapted from Balengayabo et al. (2024), with one additional dataset.

3.2 Concentration of heavy metals in the soils

The results on average concentrations of heavy metals in the soil experimental plots are presented in Figure 1. At 0-20 cm, copper (Cu) was slightly higher in treatment soils (2.0 ± 0.4 mg/kg) compared to controls (1.8 ± 0.3 mg/kg), though the difference was insignificant ($P > 0.05$). Zinc (Zn) followed a similar pattern, with treatment soils showing elevated values (28.3 ± 5.7 mg/kg) relative to controls (25.5 ± 3.2 mg/kg), again without significant difference ($P > 0.05$). Lead (Pb), however, was markedly higher in treatment soils (1.3 ± 1.9 mg/kg) compared to controls (0.1 ± 0.1 mg/kg), though the difference was insignificant ($P > 0.05$). Chromium (Cr) portrayed similar pattern, as there was insignificant difference between levels in treatment and control ($P > 0.05$). Conversely, cadmium (Cd) and nickel (Ni) concentrations were significantly lower in treatment soils (Cd: 1.2 ± 0.8 mg/kg vs 3.3 ± 0.5 mg/kg; Ni: 4.9 ± 0.5 mg/kg vs 7.6 ± 1.1 mg/kg respectively, $P < 0.05$), suggesting effects of background and natural soil properties.

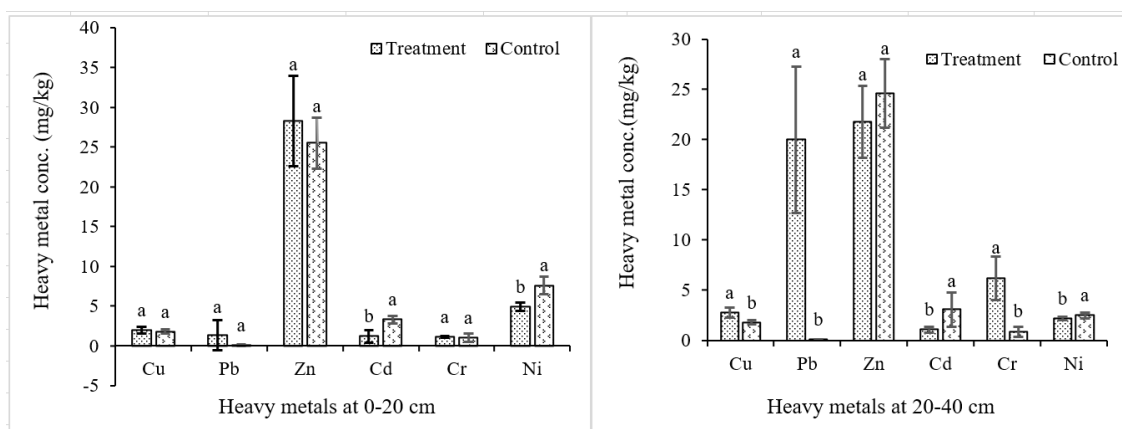


Fig.1 Mean values of soil heavy metal concentrations in the experimental plots (mg/kg) at depths of 0-20 cm and 20-40 cm. *Note:* Letters *a* and *b* above the bars denote the significant difference between mean values of treatment and control plots.

At 20-40 cm, Pb concentrations in treatment soils increased dramatically (20.0 ± 17.3 mg/kg) relative to controls (0.1 ± 0.02 mg/kg), with a highly significant difference ($P < 0.01$). Similarly, Cr was significantly elevated in treatment soils (6.2 ± 7.2 mg/kg) relative to controls (0.9 ± 0.5 mg/kg; $P < 0.05$). In contrast, Cd and Ni remained consistently lower in treatment soils (Cd: 1.1 ± 0.3 mg/kg vs 3.1 ± 1.7 mg/kg; Ni: 2.2 ± 0.2 mg/kg vs 2.5 ± 0.3 mg/kg; respectively, $P < 0.05$). Zn concentrations decreased in treatment soils at depth (21.8 ± 3.6 mg/kg) compared to controls (24.6 ± 3.4 mg/kg), though the difference was not significant ($P > 0.05$).

The findings align, but also contrast with previous studies for various heavy metals studied on some aspects. Wan *et al.* (2024) reported that Zn and Cu often accumulate in surface soils due to agricultural inputs, consistent with the observed elevated mean values in the treatment plots. Xu *et al.* (2022) highlighted spatial variability in heavy metal concentrations with depth linked to anthropogenic activities, which reverberates with the sharp increases observed in deeper treatment soils at 20-40 cm, especially for Pb and Cr. However, the high Pb mean concentration observed at 20-40 cm diverges from the general expectation that Pb accumulates in surface horizons due to limited mobility (Luo *et al.*, 2023). This anomaly may reflect vertical migration facilitated by soil physicochemical conditions or the natural background level. The lower concentration of Cd and Ni in control soils compared to treatment is in conformity with Soleimani *et al.*, (2023), who found higher concentration in soil irrigated with river and well water compared to treated wastewater. On the contrary, the results contrast with previous findings by El-hassanin *et al.* (2020) and Khawla *et al.* (2019) who observed enrichment of these metals under treated wastewater irrigation, suggesting that the treatment applied may have reduced their bioavailability for uptake.

In overall, the enrichment of Zn and Cu in surface soils aligns with established agricultural contamination pathways, while the anomalously high Pb and Cr concentrations at depth, may reflect the site-specific dynamics that warrant further investigation. The consistent reduction of Cd and Ni in treatment soils underscores the importance of localized management practices, which may effectively limit the accumulation of certain toxic metals. The findings emphasize the need for site-specific interpretations of heavy metal behavior in soils, as compared to generalized patterns from previous studies.

3.3 Soil pollution indices

3.3.1 Contamination factor (CF)

The soil pollution indices, including the contamination factor (CF) are summarized in Table 3. The CF values show moderate enrichment in both the treatment and control plots for the majority of metals. Lead (Pb) exhibited a notable anomaly in treatment plots; while the surface soils (0-20 cm) showed low contamination with CF of 1.3 ± 1.9 , the subsurface soils (20-40 cm) displayed extremely high contamination at CF values of 20.0 ± 17.3 , suggesting localized enrichment due to limited leaching. Zinc, copper, and nickel consistently remained within the moderate contamination range of 1-3, with treatment plots indicating slightly higher values for Cu. Furthermore, cadmium (Cd) contamination increased with depth in treatment plots, from low levels (CF, 0.8 ± 0.5) at the surface to moderate levels (CF, 2.8 ± 0.5) at depth of 20-40 cm. Chromium (Cr) portrayed a distinctive contamination levels, that control plots showed significantly larger CF values (5.1 ± 1.8 - 7.5 ± 4.3) than treatment plots (2.0 ± 1.7 - 2.7 ± 2.1), suggesting natural lithogenic sources rather than anthropogenic effects of irrigation activities (Taghipour *et al.*, 2011). The findings are supported by the statistical comparison which indicated insignificant

differences ($P>0.05$) of CF values between treatment and control plots, except for Cu which was significantly higher ($P<0.05$) in treatment plots at the depth of 20-40 cm.

Table 3. Indices for evaluation of soil contamination with heavy metals.

Heavy metals	Experimental Plots	Contamination factor (CF)		Geo-accumulation Index (Igeo)		Pollution load index (PLI)	
		0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm
Cu	Treatment	2.0±0.4	2.8±0.5	0.3±0.4	0.26±0.4	Treatment 1.1± 0.3	Treatment 1.9± 0.9
	Control	1.8±0.3	1.8±0.2	-0.04±0.3	-0.10±0.4		
Pb	Treatment	1.3±1.9	20.0±17.3	-4.0±0.1	-3.3± 0.4		
	Control	0.1±0.1	0.1±0.02	-4.3±0.4	-4.3± 1.1		
Zn	Treatment	2.0±0.4	1.6±0.5	-0.3±0.3	-0.2± 0.4	Control 0.8±0.08	Control 0.9±0.3
	Control	1.8±0.3	1.6±0.4	-0.6±0.4	-0.3± 0.2		
Cd	Treatment	0.8±0.5	2.8±0.5	-2.7±0.5	-2.6± 0.7		
	Control	0.2±0.1	1.8±0.2	-3.1±1.0	-2.6± 0.7		
Cr	Treatment	2.7±2.1	2.0±1.7	2.6±1.0	0.8± 0.7		
	Control	5.1±1.8	7.5±4.3	1.9±1.1	0.4± 0.6		
Ni	Treatment	1.7±0.4	1.3±0.1	-0.03±0.3	-0.6± 0.6		
	Control	1.3±0.3	1.4±0.3	-0.2±0.2	-0.2± 0.2		

3.3.2 Geo-accumulation Index (Igeo)

The geo-accumulation index provides a complementary viewpoint by comparing measured concentrations against background levels. The results in Table 3 indicate that Cu show slightly positive values in treatment plots of 0.30 ± 0.4 and 0.26 ± 0.4 at depths of 0-20 cm and 20-40 cm respectively, indicating unpolluted to moderately polluted soil conditions, while in control soils the values were less than zero. The Igeo values for Pb, Ni, Zn, and Cd in treatment and control soils displayed negative ranging from -0.2 to -4.0, classifying them as unpolluted. The results indicated positive Igeo values for Cr in the range of 0.8-2.6, with slightly higher values in treatment than control plots, indicating soil pollution relative to background concentrations. This reinforces the interpretation that Cr enrichment is geogenic in origin (Taghipour *et al.*, 2011). The values were notable in the surface soil compared to the subsurface soils as indicated by 2.6 ± 1.0 and 1.9 ± 1.1 in treatment and control soils at 0-20 cm, and 0.8 ± 0.7 and 0.4 ± 0.6 in treatment and control at 20-40 cm. Comparison of the Igeo values indicated insignificant differences ($P>0.05$) between treatment and control plots at the sampled depths. The findings imply that based on Igeo values, fertigation with TDW did not pose notable soil contamination with heavy metals (Er, 2025).

3.3.3 Pollution load index (PLI)

The pollution load index (PLI), highlights a cumulative pollution status of all heavy metals involved, as indicated in Table 3. Soils in treatment plots indicated higher PLI values of 1.1 ± 0.3 and 1.9 ± 0.9 , compared to values in control plots with 0.8 ± 0.08 and 0.9 ± 0.3 , at depths of 0-20 and 20-40 cm respectively. The values indicate a moderate pollution in overall pollution load under treatment plots, while signify no pollution load in the control plots in line with Kamanina *et al.*

(2023). However, comparison statistically denoted insignificant difference ($P>0.05$) between PLI values in treatment and control plots.

3.4 Concentration of heavy metals in maize grains

The mean concentrations of heavy metals in maize in grains from the treatment and control plots are presented in Figure 2 (a-f).

Mean concentrations of lead (Pb): In Figure 2 (a), the mean concentrations of Pb in plots irrigated with treated wastewater ranged from 1.23 ± 1.25 to 3.41 ± 1.34 mg/kg. The overall mean concentration was 2.21 ± 1.53 mg/kg (Figure 3f) with a variation coefficient of 69.2%. The grains from the counterpart control plots had mean concentrations ranging from 0.96 ± 1.04 to 3.4 ± 1.42 mg/kg. The respective overall mean concentration was 1.98 ± 1.61 mg/kg with a variation coefficient of 81.3%. Comparison of the mean concentrations between the treatment and the control plots revealed insignificant difference ($P>0.05$). However, the overall mean levels of Pb in grains from both plots exceeded the WHO/FAO (2016) permissible limit of 0.2 mg/kg.

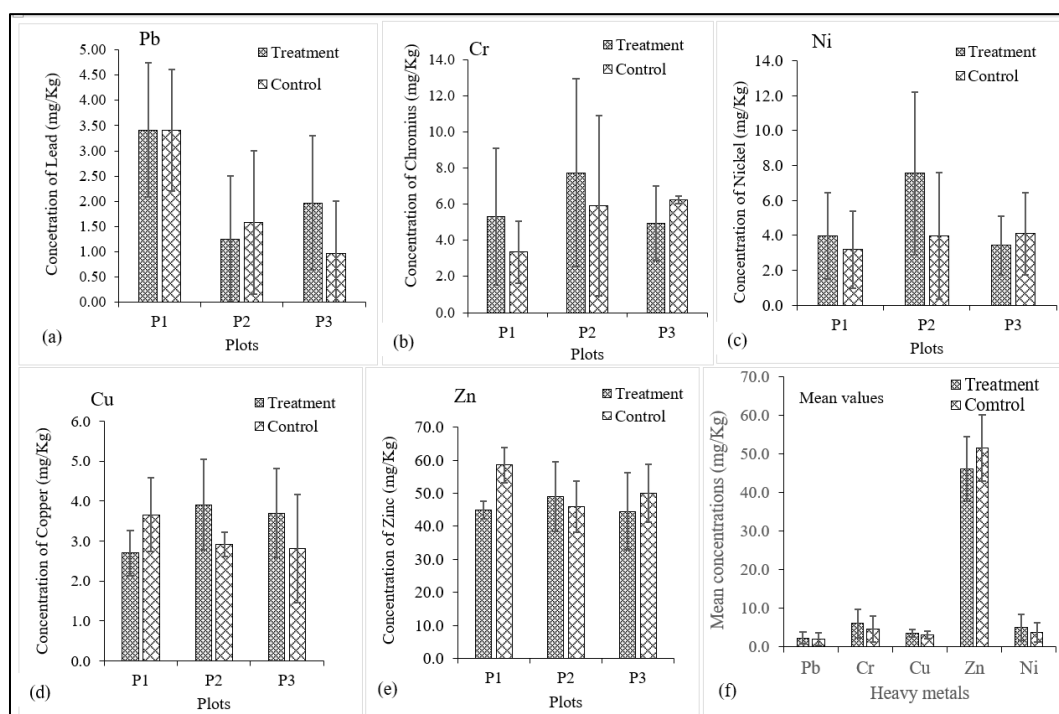


Fig. 2 Mean concentrations of heavy metals in maize grains from plots (P_i) irrigated with treated wastewater (treatment) and tap water (control).

Mean concentrations of Chromium (Cr): In Figure 2 (b), the mean concentrations of Cr in maize grains from plots irrigated with treated wastewater ranged between 4.958 ± 2.06 to 7.744 ± 5.19 mg/kg. The overall mean concentration in these treatment plots was 6.002 ± 3.62 mg/kg, with a coefficient of variation of 60.3%. In the control plots, mean concentrations varied from 3.35 ± 1.71 to 6.25 ± 0.20 mg/kg, yielding an overall mean of 4.51 ± 3.36 mg/kg (Figure 3f) and a coefficient of variation of 74.5%. Statistical analysis showed no significant difference between treatment and control plots ($P>0.05$); however, both exceeded the WHO permissible limit of 1.3 mg/kg. Similar

increases in Cd levels in grains irrigated with treated wastewater have been reported in previous studies (El-Hassanin et al., 2020).

Mean concentrations of Nickel (Ni): In Figure 2 (c), the mean concentrations Ni in maize grains from plots irrigated with treated wastewater ranged from 3.43 ± 1.67 to 7.55 ± 4.67 mg/kg. The overall mean concentration of Ni in the grains from treatment plots was 4.99 ± 3.38 mg/kg with a variation coefficient of 67.7%. In the control plots, the mean concentrations ranged from 3.18 ± 1.68 to 4.09 ± 2.36 mg/kg. The overall mean concentration from the control plots was 3.74 ± 2.46 mg/kg (Figure 3f) with a variation coefficient of 65.8%. The statistical comparison revealed insignificant different ($P > 0.05$) of the overall mean levels of Ni in grains between treatment and control plots; and the mean levels from both plots were within the WHO permissible limit of 10 mg/Kg.

Mean concentrations of Copper (Cu): By referring to Figure 2 (d), the mean concentrations of Cu in plots irrigated with TDW ranged from 2.71 ± 0.57 to 3.91 ± 1.13 mg/kg. The overall mean concentration was 3.44 ± 1.01 mg/kg (Figure 3f) with a variation coefficient of 29.4%. The grains from the counterpart control plots had a mean concentration ranging from 2.82 ± 1.36 to 3.66 ± 0.92 mg/kg. The respective overall mean level was 3.13 ± 0.93 mg/kg with a variation coefficient of 29.7%. Comparison of the mean concentrations between the treatment and the control plots revealed insignificant difference ($P > 0.05$); and the mean concentrations of Cu in the grains from both plots were within the acceptable WHO limit of 10 mg/Kg.

Mean concentrations of Zinc (Zn): In Figure 2 (e), the mean concentrations Zn in maize grains from plots irrigated with treated wastewater ranged from 44.47 ± 11.71 mg/Kg to 48.93 ± 10.58 mg/Kg. The overall mean level of Zn in the grains from treatment plots was 46.09 ± 8.29 mg/Kg with a variation coefficient of 17.9%. In the control plots, the mean concentrations of Zn in the grains ranged from 45.90 ± 7.76 mg/Kg to 58.57 ± 5.36 mg/Kg, with overall mean concentration of 51.49 ± 8.52 mg/Kg (Table 3) and variation coefficient of 16.5%. Statistical comparison revealed that the overall mean concentrations of Zn in the grains from treatment and control plots were insignificantly different ($P > 0.05$); however, the levels were above the permissible WHO limit of 0.6 mg/Kg.

Mean concentrations of Cadmium (Cd): The concentrations of Cd in maize grains from both treatment and control plots were below the detection limit of the AAS Analyst 100. Consequently, Cd levels in the grains were also below the WHO/FAO (2016) permissible threshold of 0.1 mg/kg.

3.4.1 Bioaccumulation factors of heavy metals in maize grains

The bioaccumulation factor (BF) serves as an index to gauge the potential transfer of heavy metals from the soil to the maize grains (Figure 3). The value greater than 1 shows a high possibility of a heavy metal to accumulate in the maize grains, and a value lower than 1 signifies a low possibility. The results in Figure 3 indicates that with the exception of Zinc which had BF of 1.49 ± 0.4 and 1.93 ± 0.7 in treatment and control plots respectively, other heavy metals including Cu, Pb, Cr, and Ni had the BF of less than 1. Additionally, with the exception of Zn the BAF values were slightly higher in control plot than in treatment plots; though the difference was insignificant ($P > 0.05$). This suggests low effect of TDW on bioaccumulation of heavy metals from the irrigated soil to maize grains.

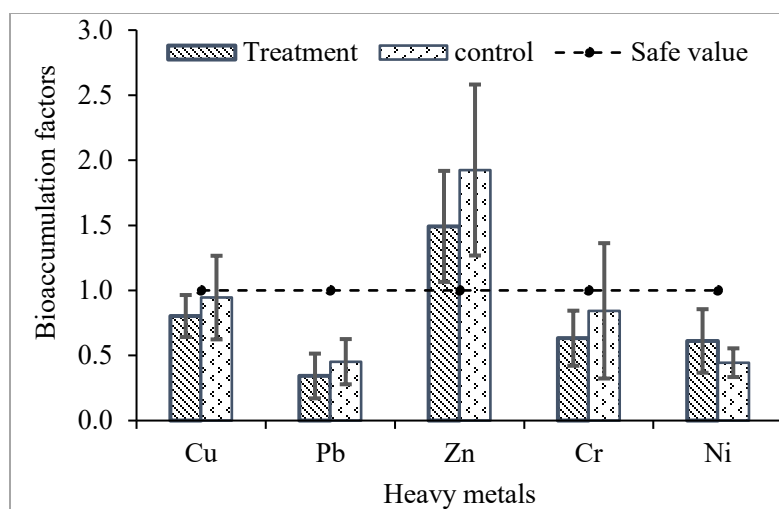


Fig. 3 The mean bioaccumulation factors (BAF) in treatment and control plots

The values of BAF of heavy metals were in the order of $Pb < Ni < Cr < Cu < Zn$. This implies that the bioaccumulation capability of Zn was the highest, while that of Pb was the lowest in conformity with findings from previous studies (Liu *et al.*, 2020). The higher values of BAF for Zn conforms to what was reported by Chaoua *et al.* (2019).

3.5 Health risks associated with intake of maize fertigated with TDW

3.5.1 Non-carcinogenic risks due to intake of maize fertigated with TDW

Daily intake of metals (DIM)

The values of daily intake of metals (DIM) (Table 4) show that children consistently experience higher exposure levels than adults across all metals, reflecting their greater vulnerability associated partly to lower body weight; which translates into higher consumption rate relative to body mass. Zinc recorded the highest DIM values overall, particularly in control plots where children's intake reached 0.543 ± 0.068 compared to 0.318 ± 0.002 in treatment plots. Copper and nickel showed moderate DIM values, with treatment plots slightly elevating adult exposure, while lead intake was similar across treatment and control but consistently higher in children. Chromium displayed the lowest DIM values, suggesting minimal exposure in both adults and children. Comparison of DIM values in maize between treatment and control plots showed insignificant difference ($P > 0.05$) in adults, with values for Pb and Ni being significantly higher ($P < 0.05$) in maize from control than treatment plots. The findings suggest indirect association of maize fertigation with TDW wastewater with DIM through ingestion of fertigated maize, which contrary to what was observed by Chaoua *et al.* (2019). The source of water and soil background levels of metals may be implicated on the observed findings.

Table 4. Non-carcinogenic health risk due to intake of maize fertigated with TDW.

Heavy metals	Experimental Plots	Daily intake of metals (DIM)		Target Hazard Quotient (THQ)		Total Target Hazard Quotient (TTHQ)	
		Adults	children	Adults	children	Adults	children
Cu	Treatment	0.017±0.003	0.024±0.005	0.42±0.079	0.61±0.114	Treatment 4.8±1.1	Treatment 6.9±1.5
	Control	0.015±0.002	0.033±0.005	0.39±0.057	0.83±0.122		
Pb	Treatment	0.011±0.005	0.016±0.008	2.72±1.356	3.92±1.953		
	Control	0.010±0.006	0.021±0.013	2.44±1.569	5.23±3.359		
Zn	Treatment	0.221±0.001	0.318±0.002	0.74±0.004	1.06±0.006	Control 4.6±1.3	Control 9.9±2.8
	Control	0.254±0.032	0.543±0.068	0.85±0.106	1.81±0.227		
Cr	Treatment	0.030±0.007	0.043±0.011	0.02±0.005	0.03±0.007		
	Control	0.026±0.008	0.055±0.017	0.02±0.005	0.04±0.011		
Ni	Treatment	0.019±0.002	0.027±0.002	0.94±0.077	1.35±0.111		
	Control	0.018±0.002	0.039±0.005	0.92±0.121	1.97±0.258		

Target Hazard Quotient (THQ)

The target hazard quotient (THQ) provides insight into potential non-carcinogenic health risks of individual heavy metals, with values greater than 1 indicating possible effects. The results in Table 5 indicate that THQ for copper (Cu) and chromium (Cr) were below the threshold for adults and children, suggesting no possible risk. Zinc (Zn) was particularly below the threshold in adults, but above in children, indicating non-carcinogenic risk to children by eating maize irrigated with TDW and tap water. However, lead (Pb) and nickel (Ni) presented elevated values, with THQ exceeding 1 in both adults and children. Lead (Pb) was particularly concerning, with values ranging from 2.72±1.36 to 5.23±3.36, while nickel showed values close to 1 in adults, but exceeded 1 in children (1.35±0.11-1.97±0.26) indicating possible risk in children. In the control plots, the results highlight lead and nickel as the most problematic metals, especially for children. Comparison of THQ values revealed that there were no significant differences ($P>0.05$) of all heavy metals in treatment and control plots for adults. In children, Zn and Ni were substantially higher ($P<0.05$) in control plots when compared to treatment plots; while Cu, Cr, and Pb did not differ significantly ($P>0.05$) between treatment and control plots. The results indicated that maize fertigation with TDW wastewater did not pose non-carcinogenic risks for individual heavy metals. The potential risk due to Pb and Ni observed may be linked to the source of water and heavy metal background levels in soil rather than TDW, as was supported by lack of significant differences of mean levels in treatment and control plots.

Total target hazard quotient (TTHQ)

The total target quotient (TTHQ) was used to evaluate human health risk linked to exposure to all heavy metals detected in maize grains (Table 4). The results revealed that the values of TTHQ for maize grains from plots irrigated with TDW were 4.8±1.1 for adults and 6.9±1.5 for children. In the plots irrigated with tap water (control), the TTHQ values were 4.6±1.3 for adults and 9.9±2.8 for children. Pb and Ni, were the main contributors into the TTHQ values by 73-77%. In treatment

plots, Pb and Ni contributed 53% and 24% respectively into TTHQ values of adults and children. Similarly, in control plots Pb and Ni contributed 53% and 20% respectively into the TTHQ values of adults and children. Comparison of TTHQ values between maize from treatment and control plots, showed insignificance differences ($P>0.05$) for both adults and children. The results showed $TTHQ>1$ for adults and children implying potential health risk from exposure to multiple heavy metals through intake of maize irrigated with TDW and tap water. The findings are in line with previous studies whereby maize and vegetables irrigated with wastewater effluent and canal water were found to have TTHQ values greater 1, signifying non-carcinogenic risks due to exposure to numerous heavy metals (Iqbal *et al.*, 2019; Iqbal *et al.*, 2024).

3.5.2 Carcinogenic risks associated with intake of maize fertigated with TDW

Incidental Lifetime Cancer Risk (ILCR)

Incidental lifetime cancer risk (ILCR) values reflect the carcinogenic risk associated with individual heavy metal (Table 5). Lead (Pb), show similar risks of about 1.0×10^{-4} in adults and children for maize from treatment plots; while maize from control plots pose slightly higher risks of 2.0×10^{-4} in children. Nickel (Ni) shows much higher ILCR values, with adults at 1.7×10^{-2} in both treatment and control plots, while for children the values range from 2.5×10^{-2} in treatment plots to 3.6×10^{-2} in control plots. Chromium (Cr) follows a similar pattern; adults show risks of 1.2×10^{-2} in treatment plots and 1.0×10^{-2} in control plots, while children the values indicate higher risks of 1.8×10^{-2} and 2.3×10^{-2} , respectively. The values of ILCR for Ni, Pb, and Cr were not significantly different ($P>0.05$) in adults across treatments and controls, while for children, only Nickel was significantly higher ($P<0.05$) in maize from control than treatment plots. Across all metals, children consistently exhibit higher ILCR values than adults, and control plots generally amplify the risks compared to treatment plots. This signify that maize fertigated with TDM are less likely to pose carcinogenic risks due individual heavy metals than those irrigated with tap water.

Table 5. Carcinogenic health risk assessment results associated with intake of maize fertigated with TDW and tap water.

Heavy metals	Experiment al Plots	Incidental life time cancer risk (ILCR)		Cumulative incidental life time cancer risk (CILCR)	
		Adults	children	Adults	children
Pb	Treatment	$1.0\pm 0.5 \text{ E-4}$	$1.0\pm 0.7 \text{ E-4}$	Treatment $3.0\pm 0.4\text{E-2}$	Treatment $4.3\pm 0.6 \text{ E-2}$
	Control	$1.0\pm 0.5 \text{ E-4}$	$2.0\pm 1.1 \text{ E-4}$		
Ni	Treatment	$1.7\pm 0.1 \text{ E-2}$	$2.5\pm 0.2 \text{ E-2}$	Control $2.8\pm 0.5 \text{ E-2}$	Control $5.9\pm 1.2 \text{ E-2}$
	Control	$1.7\pm 0.2 \text{ E-2}$	$3.6\pm 0.5 \text{ E-2}$		
Cr	Treatment	$1.2\pm 0.3 \text{ E-2}$	$1.8\pm 0.5 \text{ E-2}$	Control $2.8\pm 0.5 \text{ E-2}$	Control $5.9\pm 1.2 \text{ E-2}$
	Control	$1.0\pm 0.3 \text{ E-2}$	$2.3\pm 0.7 \text{ E-2}$		

Cumulative Incidental Lifetime Cancer Risk (CILCR)

Cumulative incidental lifetime cancer risk (CILCR) represents the combined risk from all heavy metals together, which offer a more comprehensive assessment of exposure. The values in treatment plots show a cumulative risk of $3.0\pm 0.4\text{E-2}$, while control plots were slightly lower at $2.8\pm 0.5 \text{ E-2}$ for adults, though the difference was insignificant ($P>0.05$). In contrast, children face

much higher cumulative risks of $4.3 \pm 0.6 \text{ E-2}$ for maize from treatment plots and slightly higher at $5.9 \pm 1.2 \text{ E-2}$ in control plots; again, the disparity was insignificant ($P > 0.05$). These values highlight that children are disproportionately affected by cumulative exposure, with control plots presenting the highest overall risk. Ni and Cr contributed up to 97% on average of the values of CILCR, with Ni contributing 55-67% and Cr, 30-50%. The source of water and soil heavy metal background levels may be cited for the observed risks, rather than the TDW. The magnitude of CILCR, especially for children, underscores the importance of interventions to reduce exposure to multiple heavy metals simultaneously.

3.6 Implications of the study findings

The implications of the study suggest that fertigation with treated domestic wastewater (TDW) exerts a complex influence on both soil contamination and human health risks. Soil contamination indices indicate moderate enrichment of Cu, Ni, Zn, and Cd in treatment plots, with Pb showing depth-related anomalies. While the pollution load index (PLI) points to moderate contamination, geo-accumulation indices (Igeo) classify most soils as unpolluted relative to background levels, except for chromium, which consistently emerges as a pollutant due to lithogenic enrichment. Thus, soils may be considered moderately impacted overall, with localized anomalies particularly Cr requiring further investigation.

From a health perspective, non-carcinogenic risk assessments reveal that children are the most vulnerable group, consistently exhibiting higher daily intake (DIM), hazard risk index (HRI), and total hazard quotient (TTHQ) values. Lead and nickel pose the greatest concern, while copper, though individually within safe limits, contributes substantially to cumulative hazard loads. Importantly, risks are higher in control plots than in TDW-treated plots, underscoring that background soil contamination and water source quality, rather than TDW itself, are the primary drivers of exposure. Carcinogenic risk analysis further highlights nickel and chromium as significant contributors to incremental lifetime cancer risk (ILCR), particularly for children, with nickel accounting for 55-67% of cumulative cancer risk (CILCR). Although lead's carcinogenic risk is comparatively lower, it remains noteworthy. The consistent pattern across all metals confirms that children are disproportionately vulnerable, and maize from control plots carries higher risks than that from TDW-treated plots.

The findings imply that TDW fertigation does not inherently exacerbate contamination or health risks; instead, the critical determinants are the quality of water sources and the natural background levels of heavy metals in soils. The study underscores the need for systematic monitoring of water quality and soil contamination, with targeted interventions to mitigate exposure to nickel, chromium, and lead. Special attention should be directed toward safeguarding children, who represent the most sensitive population group.

4.0 Conclusion

The study demonstrates that fertigation with treated domestic wastewater (TDW) exerts a complex influence on soil and maize contamination dynamics. While contamination factors indicated moderate enrichment of certain metals, geo-accumulation indices largely classified soils as unpolluted, with chromium standing out as a lithogenic anomaly requiring closer scrutiny. In maize grains, however, systemic contamination was evident, with Pb, Cr, and Zn consistently exceeding WHO/FAO permissible limits irrespective of irrigation source, underscoring broader environmental pollution pathways beyond wastewater use. Bioaccumulation factors revealed

limited transfer of most metals from soil to maize, except for zinc, which showed the highest uptake potential. Risk assessments further highlighted children as the most vulnerable group, with lead, nickel, and copper contributing significantly to non-carcinogenic hazards, and nickel and chromium posing long-term carcinogenic risks. Collectively, these findings emphasize that while TDW fertigation itself does not markedly elevate contamination compared to control plots, the prevailing background pollution and systemic heavy metal presence in soils and grains present serious food safety and public health challenges. Addressing these risks requires integrated monitoring of water and soil quality, targeted remediation strategies, and community-level interventions, with particular attention to safeguarding children from cumulative exposure.

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Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request

Declarations

Clinical trial number: Not applicable.

Ethics and Consent to Participate

Collection of maize (*Zea mays*) plants and plant parts complied with national regulations of the Tanzania Official Seed Certification Institute (TOSCI) and internationally recognized USDA ARS agronomic protocols. Maize plants were cultivated under controlled field conditions, and there were no applicable permissions and licenses for maize seed use in experimental trials.

Competing of interest

The authors have no relevant financial or non-financial interests to disclose.

5.0 References

- Ahamad, M. I., Song, J., Sun, H., Wang, X., Mehmood, M. S., Sajid, M., ... & Khan, A. J. (2020). Contamination level, ecological risk, and source identification of heavy metals in the hyporheic zone of the Weihe River, China. *International journal of environmental research and public health*, 17(3), 1070. DOI: <https://doi.org/10.3390/ijerph17031070>.
- Angon, P. B., Islam, M. S., Das, A., Anjum, N., Poudel, A., & Suchi, S. A. (2024). Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. *Heliyon*, 10(7). DOI: <https://doi.org/10.1016/j.heliyon.2024.e28357>
- Aonghusa, C. N., & Gray, N. F. (2002). Laundry detergents as a source of heavy metals in Irish domestic wastewater. *Journal of Environmental Science and Health, Part A*, 37(1), 1-6.

- Bahri, A., Drechsel, P., & Brissaud, F. (2010). Water reuse in Africa: challenges and opportunities. September, 1-16.
- Balengayabo, J. G., Kassenga, G. R., Mgana, S. M., & Salukele, F. (2024). Impact of recurring irrigation with treated domestic wastewater on heavy metal accumulation in the soil. *Agricultural Water Management*, 297, 108814. DOI: <https://doi.org/10.1016/j.agwat.2024.108814>
- Balkhair, K. S., & Ashraf, M. A. (2016). Field accumulation risks of heavy metals in soil and vegetable crop irrigated with sewage water in western region of Saudi Arabia. *Saudi journal of biological sciences*, 23(1), S32-S44. DOI: <https://doi.org/10.1016/j.sjbs.2015.09.023>
- Boutin, C., and Eme, C. (2016). Domestic wastewater characterization by emission source. In 13eme congress spécialisé IWA on Small Water and wastewater Systems (pp. 8-p). DOI: <https://hal.science/hal-01469077v1>
- Cocârță, D. M., Neamțu, S., & Reșetar Deac, A. M. (2016). Carcinogenic risk evaluation for human health risk assessment from soils contaminated with heavy metals. *International Journal of Environmental Science and Technology*, 13(8), 2025-2036. DOI: <https://doi.org/10.1007/s13762-016-1031-2>.
- Chaoua, S., Boussaa, S., El Gharmali, A., & Boumezzough, A. (2019). Impact of irrigation with wastewater on accumulation of heavy metals in soil and crops in the region of Marrakech in Morocco. *Journal of the Saudi Society of Agricultural Sciences*, 18(4), 429-436. DOI: <https://doi.org/10.1016/j.jssas.2018.02.003>
- Dikinya, O., & Areola, O. (2010). Comparative analysis of heavy metal concentration in secondary treated wastewater irrigated soils cultivated by different crops. *International Journal of Environmental Science and Technology*, 7(2), 337-346. DOI: <https://doi.org/10.1007/BF03326143>
- Drechsel, P., Qadir, M., & Wichelns, D. (2015a). Wastewater: Economic asset in an urbanizing world. *Wastewater: Economic Asset in an Urbanizing World*, 1-282. DOI: <https://doi.org/10.1007/978-94-017-9545-6>
- Drozdova, J., Raclavska, H., Raclavsky, K., & Skrobankova, H. (2019). Heavy metals in domestic wastewater with respect to urban population in Ostrava, Czech Republic. *Water and Environment Journal*, 33(1), 77-85. DOI: <https://doi.org/10.1111/wej.12371>
- Elgallal, M., Fletcher, L., & Evans, B. (2016). Assessment of potential risks associated with chemicals in wastewater used for irrigation in arid and semiarid zones: A review. *Agricultural Water Management*, 177, 419–431. DOI: <https://doi.org/10.1016/j.agwat.2016.08.027>
- El-hassanin, A. S., Samak, M. R., Abdel-rahman, G. N., Abu-sree, Y. H., & Saleh, E. M. (2020). Risk assessment of human exposure to lead and cadmium in maize grains cultivated in soils

- irrigated either with low-quality water or freshwater. *Toxicology Reports*, 7(June 2019), 10–15. DOI: <https://doi.org/10.1016/j.toxrep.2019.11.018>
- EL-Hassanin, A. S., Samak, M. R., Saleh, E. M., Abu-Sree, Y. H., Abdel-Rahman, G. N., & Ahmed, M. B. M. (2022). Bioaccumulation of heavy metals in the different parts of maize cultivated in soils irrigated with different quality of water. *Egyptian Journal of Chemistry*, 65(9), 625–638. DOI: <https://doi.org/10.21608/EJCHEM.2022.115735.5254>.
- Er, H. (2025). Effect of long-term use of treated wastewater and clean water mixtures on soil heavy metal accumulation: An assessment using pollution indices. *PloS one*, 20(12), e0337424. DOI: <https://doi.org/10.1371/journal.pone.0337424>
- Frederick, B., Sabula, L., Mruma, S., Mzee, F., Mtoka, E., Masigo, J., Ndunguru, A., & Swai, E. (2020). *Maize production manual for smallholder farmers in Tanzania*. 32.
- Safavi, S., Najarian, R., Rasouli-Azad, M. O. R. A. D., Masoumzadeh, S., Ghaderi, A., & Eghtesadi, R. A. Z. I. E. (2019). A narrative review of heavy metals in cosmetics; health risks. *International Journal of Pharmaceutical Research*, 11(4), 182-190. DOI: <https://doi.org/10.31838/ijpr/2019.11.04.031>
- Hach Co, & Hach (1992). Siw-1 Soil and Irrigation Water Manual Table of Contents. Test.
- Ismail, M., Khan, S., Zahid, N., Khan, M. I., Gul, S., Din, A., & Khan, M. A. (2024). Toxicity and Daily Intake of Heavy Metals to Adults and Children in Vegetables Irrigated by Different Water Sources. *South African Journal of Chemistry*, 78, 162-169. DOI: <https://doi.org/10.17159/0379-4350/2024/v78a22>
- Iqbal, Z., Abbas, F., Ibrahim, M., Ayyaz, M. M., Ali, S., & Mahmood, A. (2019). Surveillance of heavy metals in maize grown with wastewater and their impacts on animal health in peri-urban areas of Multan, Pakistan. *Pakistan Journal of Agricultural Sciences*, Vol. 56(2), 321-328. DOI: <https://doi.org/10.21162/PAKJAS/19.8133>
- Iqbal, Z., Abbas, F., Raza, M., Gul, M., & Haider, R. (2024). Heavy Metal Contamination in Vegetable Grown with Wastewater in Peri Urban Areas of Multan City, Pakistan: A Health Risk Assessment. *Pakistan Journal of Science*, 76(4), 688-701.
- Jalil, H. M., Rezapour, S., Nouri, A., & Joshi, N. (2022). Assessing the ecological and health implications of soil heavy metals in vegetable irrigated with wastewater in calcareous environments. *Agricultural Water Management*, 272, 107848. DOI: <https://doi.org/10.1016/j.agwat.2022.107848>
- Jimenez, B., & Asano, T. (2015). Water Reuse: An International Survey of current practice, issues and needs. *Water Intelligence Online*, 7(0), 9781780401881–9781780401881. DOI: <https://doi.org/10.2166/9781780401881>

Kamanina, I. Z., Badawy, W. M., Kaplina, S. P., Makarov, O. A., & Mamikhin, S. V. (2023). Assessment of soil potentially toxic metal pollution in Kolchugino town, Russia: characteristics and pollution. *Land*, 12(2), 439. DOI: <https://doi.org/10.3390/land12020439>

Karri, R. R., Ravindran, G., & Dehghani, M. H. (2021). Wastewater-sources, toxicity, and their consequences to human health. In *Soft computing techniques in solid waste and wastewater management* (pp. 3-33). Elsevier. DOI: <http://dx.doi.org/10.1016/B978-0-12-824463-0.00001-X>

Keraita, B., Jimenez, B., & Drechsel, P. (2008). Extent and implications of agricultural reuse of untreated, partly treated and diluted wastewater in developing countries. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, 3(January). DOI: <https://doi.org/10.1079/PAVSNNR20083058>

Khan, A., Khan, S., Khan, M. A., Qamar, Z., & Waqas, M. (2015). The uptake and bioaccumulation of heavy metals by food plants, their effects on plants nutrients, and associated health risk: a review. *Environmental science and pollution research*, 22(18), 13772-13799. DOI: <https://doi.org/10.1007/s11356-015-4881-0>

Khalid, S., Shahid, M., Natsha, Bibi, I., Sarwar, T., Shah, A. H., & Niazi, N. K. (2018). A review of environmental contamination and health risk assessment of wastewater use for crop irrigation with a focus on low and high-income countries. *International journal of environmental research and public health*, 15(5), 895. DOI: <https://doi.org/10.3390/ijerph15050895>

Khaskhoussy, K., Kahlaoui, B., Messoudi Nefzi, B., Jozdan, O., Dakheel, A., & Hachicha, M. (2015). Effect of Treated Wastewater Irrigation on Heavy Metals Distribution in a Tunisian Soil. *Engineering, Technology & Applied Science Research*, 5(3), 805–810. DOI: <https://doi.org/10.48084/etasr.563>

Khawla, K., Bisma, K., Enrique, M., & Mohamed, H. (2019). Accumulation of trace elements by corn (*Zea mays*) under irrigation with treated wastewater using different irrigation methods. *Ecotoxicology and Environmental Safety*, 170 (December 2018), 530–537. DOI: <https://doi.org/10.1016/j.ecoenv.2018.12.025>

Kihila, J. (2015). A review of the challenges and opportunities for water reuse in irrigation with a focus on its prospects in Tanzania. *Library*, 7(2), 110–130. DOI: <https://doi.org/10.1017/S000748530002229X>

Kiziloglu, I., Turan, M., Sahin, U., Kusvuran, S., & Erman, M. (2008). Trace elements in wastewater irrigated soils and plants. *Journal of Environmental Science and Health, Part B*, 43(2), 169-176.

Kokora, A. F., Konan, K. G., Meite, L., & Camara, Y. S. (2025). Assessment of the contamination of *Lactuca sativa* by metal trace elements, Vol. 19(11), pp. 390-396. DOI: <https://doi.org/10.5897/AJEST2025.3397>

Leonard, L. S., & Mkumbo, S. K. (2025). Health risk evaluation of heavy metal-contaminated

- groundwater in unplanned settlements of Dar es Salaam, Tanzania. *Journal of Water and Health*, 23(10), 1152-1162. DOI: <https://doi.org/10.2166/wh.2025.381>
- Liu, P., Zhang, Y., Feng, N., Zhu, M., & Tian, J. (2020). Potentially toxic element (PTE) levels in maize, soil, and irrigation water and health risks through maize consumption in northern Ningxia, China. *BMC Public Health*, 20(1), 1729. DOI: <https://doi.org/10.1186/s12889-020-09845-5>
- Luo, Y., Wang, Z., Zhang, Y. D., Zhang, J. Q., Zeng, Q. P., Zhang, Z. L., and Chen, L. (2024). Vertical migration behavior simulation and prediction of Pb and Cd in co-contaminated soil around Pb-Zn smelting slag site. *Journal of Hazardous Materials*, 469, 133990. DOI: <https://doi.org/10.1016/j.jhazmat.2024.133990>.
- Lu, Y., Yao, H., Shan, D., Jiang, Y., Zhang, S., & Yang, J. (2015). Heavy Metal Residues in Soil and Accumulation in Maize at Long-Term Wastewater Irrigation Area in Tongliao, China. *Journal of Chemistry*, 2015(1), 628280. DOI: <https://doi.org/10.1155/2015/628280>
- Mahfuza S. Sultana, S. Rana, S. Yamazaki, T. Aono & S. Yoshida | (2017). Health risk assessment for carcinogenic and non-carcinogenic heavy metal exposures from vegetables and fruits of Bangladesh, *Cogent Environmental Science*, 3:1, 1291107, DOI: [10.1080/23311843.2017.1291107](https://doi.org/10.1080/23311843.2017.1291107)
- Mkonda, M. Y., & He, X. (2017). Yields of the major food crops: Implications to food security and policy in Tanzania's semi-arid agro-ecological zone. *Sustainability (Switzerland)*, 9(8). <https://doi.org/10.3390/su9081490>
- Ofori, S., Di Leto, Y., Smrčková, Š., Marin, M. A. L., Gallo, G., Růžicková, I., & Wanner, J. (2025). Treated wastewater reuse for crop irrigation: a comprehensive health risk assessment. *Environmental Science: Advances*, 4(2), 252-269. DOI: <https://doi.org/10.1039/d4va00274a>
- Othman, O. (2001). Heavy metals in green vegetables and soils from vegetable gardens in Dar es Salaam, Tanzania. In *Tanzania Journal of Science* (Vol. 27, Issue 1). DOI: <https://doi.org/10.4314/tjs.v27i1.18334>
- Rezapour, S., Atashpaz, B., Moghaddam, S. S., & Damalas, C. A. (2019). Heavy metal bioavailability and accumulation in winter wheat (*Triticum aestivum* L.) irrigated with treated wastewater in calcareous soils. *Science of the Total Environment*, 656, 261-269. DOI: <https://doi.org/10.1016/j.scitotenv.2018.11.288>
- Singh, A., Sharma, R. K., Agrawal, M., & Marshall, F. M. (2010). Health risk assessment of heavy metals via dietary intake of foodstuffs from the wastewater irrigated site of a dry tropical area of India. *Food and Chemical Toxicology*, 48(2), 611-619. <https://doi.org/10.1016/j.fct.2009.11.041>
- Singh, A., Sharma, R. K., Agrawal, M., & Marshall, F. M. (2010). Health risk assessment of heavy metals via dietary intake of foodstuffs from the wastewater irrigated site of a rapidly growing urban area of India. *Ecotoxicology and Environmental Safety*, 73(5), 903-911.

- Soleimani, H., Mansouri, B., Kiani, A., Omer, A. K., Tazik, M., Ebrahimzadeh, G., & Sharafi, K. (2023). Ecological risk assessment and heavy metals accumulation in agriculture soils irrigated with treated wastewater effluent, river water, and well water combined with chemical fertilizers. *Heliyon*, 9(3). DOI: <https://doi.org/10.1016/j.heliyon.2023.e14580>
- Sultana, M. S., Rana, S., Yamazaki, S., Aono, T., & Yoshida, S. (2017). Health risk assessment for carcinogenic and non-carcinogenic heavy metal exposures from vegetables and fruits of Bangladesh. *Cogent Environmental Science*, 3(1), 1291107. DOI: <https://doi.org/10.1080/23311843.2017.1291107>.
- Taghipour, M., Ayoubi, S., & Khademi, H. (2011). Contribution of lithologic and anthropogenic factors to surface soil heavy metals in western Iran using multivariate geostatistical analyses. *Soil and Sediment Contamination: An International Journal*, 20(8), 921-937. DOI: <https://doi.org/10.1080/15320383.2011.620045>
- U.S. Environmental Protection Agency. (2000). Integrated Risk Information System (IRIS). Washington, DC: National Center for Environmental Assessment, Office of Research and Development. Retrieved from <https://www.epa.gov/iris>
- U.S. Environmental Protection Agency. (2015). *Integrated Risk Information System (IRIS)*. Washington, DC: USEPA. Retrieved from <https://www.epa.gov/iris>
- Wan, Y., Liu, J., Zhuang, Z., Wang, Q., and Li, H. (2024). Heavy metals in agricultural soils: Sources, influencing factors, and remediation strategies. *Toxics*, 12(1), 63. DOI: <https://doi.org/10.3390/toxics12010063>
- WHO (2017). Guidelines for Drinking-water Quality, 4th edition incorporating the first addendum. World Health Organization.
- WHO, & UNEP. (2006). *Safe use wastewater, excreta and greywater. VOL1 policy and regulatory aspects. I*, 114.
- World Health Organization & Food and Agriculture Organization of the United Nations (2016). *Permissible limits of heavy metals in food crops*. Geneva/Rome: WHO/FAO.
- Xu, J., Wang, S., Yao, T., She, X., & Gan, Z. (2022). Vertical distributions and bioavailabilities of heavy metals in soil in an-tea plantations in Qimen county, China. *Processes*, 10(4), 664. DOI: <https://doi.org/10.3390/pr10040664>
- Xue, P., Zhao, Q., Sun, H., Geng, L., Yang, Z., & Liu, W. (2019). Characteristics of heavy metals in soils and grains of wheat and maize from farmland irrigated with sewage. *Environmental Science and Pollution Research*, 26(6), 5554–5563. DOI: <https://doi.org/10.1007/s11356-018-3997-4>
- Yang X., Cheng B., Gao Y., Zhang H., and Liu, L. (2022) Heavy metal contamination assessment and probabilistic health risks in soil and maize near coal mines. *Front. Public Health*

10:1004579. DOI: <https://doi.org/10.3389/fpubh.2022.1004579>

Zhang, S., Yao, H., Lu, Y., Yu, X., Wang, J., Sun, S., ... & Zhang, D. (2017). Uptake and translocation of polycyclic aromatic hydrocarbons (PAHs) and heavy metals by maize from soil irrigated with wastewater. *Scientific reports*, 7(1), 12165. DOI: <https://doi.org/10.1038/s41598-017-12437-w>

Statements and Declarations

Competing of interest: The authors have no relevant financial or non-financial interests to disclose

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