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Research Paper

Unveiling the Hidden Risks: Heavy Metal Concentrations in Soil and Vegetables Irrigated with Kalobe Wastewater Stabilization Ponds, Mbeya, Tanzania

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ABSTRACT

This study evaluated the concentrations of heavy metals in wastewater, soil, and tomatoes and Napa cabbage irrigated with effluent from the Kalobe Wastewater Stabilization Pond (KWWSP) in Mbeya, Tanzania. Human health risks were assessed using Chronic Daily Intake (CDI), Target Hazard Quotient (THQ), Hazard Index (HI), and Target Cancer Risk (TCR) indices. The results showed that cadmium (Cd) in all ponds was below the FAO/WHO permissible limits, while lead (Pb) and chromium (Cr) were below detection levels. Heavy metals in soil were found in the order of Pb (5.95 mg/kg) > Cr (0.63 mg/kg) > Cd (0.25 mg/kg), all within FAO/WHO acceptable limits, indicating suitability for agricultural use. Cd levels in Tomatoes (0.14 mg/kg) and Napa cabbage (0.40 mg/kg) exceeded permissible limits. Cr levels in the Tomato and Napa Cabbage were 1.87 and 2.10 mg/kg, respectively, and were close to the safety threshold, suggesting health concerns with long-term consumption. Cd exposure through vegetable intake was within but near acceptable limits, while Cr exposure, particularly for Napa cabbage, exceeded recommended safety thresholds. This resulted in elevated noncarcinogenic risks (THQ and HI > 1) and carcinogenic risks (TCR above the USEPA's acceptable range). These findings suggest that consuming wastewater-irrigated Tomatoes and Napa cabbage may pose human health risks. Continuous monitoring of heavy metals, safe irrigation alternatives, and cropping restrictions using inadequately treated wastewater is essential to safeguard public health and long-term environmental sustainability.

In many parts of the world, particularly in arid and semi-arid regions, increasing water scarcity has become a pressing challenge due to climate change, population growth, pollution, and unsustainable water use practices (Boularbah et al., 2024; Goyal & Kumar, 2021; UNESCO, 2017). The growing demand for freshwater resources has led to an increased reliance on wastewater as a valuable alternative water source (Faragò et al., 2021; Goyal & Kumar, 2021; Silva, 2023; UNESCO, 2017). In developed countries like Israel, treated wastewater is extensively used as a major water resource to address freshwater scarcity (Marin et al., 2017; Shelef, 1991; Tal, 2016). Wastewater is no longer viewed solely as a waste product but is now recognized as a resource for recovering water, energy, and nutrients (Faragò et al., 2021; Silva, 2023; UNESCO, 2017). The emergence of Water Resource Recovery Facilities (WRRFs) exemplifies this transformation, offering integrated solutions that support water security, energy efficiency, and agricultural productivity (Faragò et al., 2021; Guest et al., 2009; UNESCO, 2017). Such innovations are particularly critical in developed countries, where the reuse of treated wastewater alleviates pressure on limited freshwater reserves.

Although wastewater holds great potential as a valuable water resource, it is estimated that over 80% of wastewater globally (over 95% in some developing countries) (UNESCO, 2017) is released into the environment without adequate treatment, severely polluting freshwater and marine ecosystems. In Africa, continuing business as usual in the discharge of insufficiently treated wastewater poses an increasing threat to water bodies, endangering public health, food security, and sustainable development (UNESCO, 2017). While wastewater is a valuable alternative water source, its reuse in agriculture offers

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significant potential. However, in developing countries like Tanzania, inadequate treatment, weak regulation, and low public awareness pose health and environmental risks. For instance, Mwakalukwa et al. (2024) reported the presence of heavy metals in amaranth near the Don Bosco wastewater plant in Iringa, Tanzania, highlighting the risks of unregulated wastewater use in agriculture. The heavy metal contents were also reported in sewage-impacted mangrove-fringed creeks of Kenya, Tanzania, and Mozambique (Kamau et al., 2015). In several developing countries, researchers have reported the presence of heavy metals in treated wastewater, as well as in soils and crops irrigated with such water. For instance, studies have documented heavy metal contamination in Malawi (Malikula et al., 2022), Kenya (Sayo et al., 2020; Tomno et al., 2020), in West African cities (Abdu et al., 2011), Ethiopia (Berihun et al., 2021; Woldetsadik et al., 2017), Zambia (Kapungwe, 2013), and Ghana (Lente et al., 2012). This highlights the potential health and environmental risks associated with the use of inadequately treated wastewater in agriculture. This underscores the need for stricter regulations, improved treatment technologies and increased public awareness in these regions.

In Mbeya City Council, the Kalobe Wastewater Stabilization Pond (KWWSP) is a key wastewater treatment facility in the region. It plays a crucial role in treating domestic, municipal, and institutional wastewater, before discharging them into the environment or potentially being reused in agriculture. However, local communities around the KWWSP use inadequately treated wastewater (field observations) to irrigate vegetables, under the misconception that this wastewater is nutritious and can supplement or reduce the need for industrial fertilizer application. Unfortunately, most farmers pay little attention to the potential health risks their produce may pose to consumers. The motivation for conducting this study arose during an evening walk near the KWWSP, where we observed local farmers using a generator to pump inadequately treated wastewater directly from the stabilization pond to irrigate Tomatoes and Napa cabbage. This alarming scene prompted two critical questions: (1) Are these wastewaters safe for irrigation? and (2) What are the potential health consequences for consumers eating the agricultural produce?. These concerns open a significant gap in awareness and monitoring, particularly regarding the use of untreated wastewater for irrigation around the KWWSP. To the best of our knowledge, no previous research has specifically addressed these issues in the region, underscoring a critical knowledge gap related to the potential health and environmental risks posed by such practices.

Therefore, this study aimed to (a) assess the levels of heavy metals in wastewater, soil, and vegetables irrigated with untreated wastewater from KWWSP; and (b) to evaluate the potential human health risks associated with the consumption of agricultural produce irrigated with such water. This study seeks to uncover and raise awareness of the hidden risks associated with heavy metal contamination in soils and vegetables irrigated with wastewater from the KWWSP.

Materials and methods

Description of the study area. Kalobe Ward is one of the administrative wards within the Mbeya Urban District of the Mbeya Region, located in the southern highlands of Tanzania. Geographically, it lies between longitudes 33°18.0′ and 33°25.8′ East and latitudes 8°55.8′ and 8°54.0′ South (Figs. 1 and 2). The ward covers an area of 4.31 km^2 and has a population of 17,498 people. This population includes 8,257 males and 9,241 females. The population density is approximately 4,060 people per km^2 (Census, 2022). Kalobe is bordered by Nzovwe, Iyunga, Mabatini, Iwambi, Itende, and Itiji wards (Fig. 2). In terms of climate, Mbeya Urban District, including Kalobe Ward, experiences a temperate tropical highland climate. The average annual rainfall ranges from 900 mm to 2,600 mm, with the rainy season occurring from November to May, with peak rainfall typically observed between December and March. The dry season lasts from June to October, characterized by cool and dry weather conditions. Annual temperatures range between 16 °C and 25 °C, with the coolest months being June to August, during which nighttime temperatures drop below 10 °C. The main economic activities in Kalobe ward include agricultural production and business trading. Residents engage in small-scale farming, producing food crops such as maize, beans, vegetables, and livestock keeping. The KWWSP is located at Kalobe Mabwawani Street within the ward (Figs. 1 and 2). These ponds receive wastewater from multiple sources, including industries, hospitals, households, government institutions, urban sanitation facilities, and surface runoff. They are designed to treat wastewater before it is discharged into the environment. However, despite the intended purpose, some local urban farmers illegally use the untreated or partially treated wastewater for irrigating crops (Fig. 3) without taking into consideration the potential human health risks to both growers and consumers.

Sampling and sample preparation. Between October and December 2024, a field investigation was undertaken to assess the quality of wastewater, soil, and vegetables in the vicinity of the KWWSP. In the field, physicochemical parameters including pH, temperature, dissolved oxygen (DO), oxygen saturation, electrical conductivity (EC), and total dissolved solids (TDSs) were measured using a Hanna HI98195 multiparameter meter. A total of sixteen (16) water samples were collected, with four (4) composite samples obtained from each stabilization pond using 200 mL sterilized bottles. The water samples for the heavy metal analysis were filtered and immediately preserved by adding 1 mL of concentrated HNO_3 to reduce the pH to below 2.

For the analysis of heavy metals in the soil, a total of ten (10) composite soil samples were purposefully collected from agricultural fields surrounding the KWWSP (Fig. 2). This study adopted the LUCAS soil sampling method (Fernández-Ugalde et al., 2017), whereby five subsamples were taken from each selected point, one at the center and the other 4 subsamples were collected at a distance of 2 m in the cardinal directions (east, west, south, and north). Each subsample was collected from the topsoil layer (0–20 cm depth) using a spade. The five subsamples were first screened to eliminate vegetation residues, grass, and litter, then homogenized to create a single composite sample. From this homogenate, approximately 500 g was retained for subsequent laboratory analysis. The samples were air-dried at room temperature to constant weight and ground to a uniform particle size to facilitate accurate heavy metal analysis.

For the analysis of heavy metals in edible plant parts, a total of ten (10) composite samples of ripe Tomato fruits and Napa cabbage were collected from agricultural fields irrigated with KWWSP. In this study, we focused on only two crops irrigated with inadequately treated wastewater. However, we acknowledge that the inclusion of additional crops would have strengthened the findings and provided a broader perspective. Therefore, this is a limitation of the present study. Before sample collection, informed consent was obtained from the farmers to allow the collection of Tomato and Napa cabbage samples from their fields. After collection, the samples were immediately sealed in sterilized plastic bags, properly labelled, and transported to the laboratory under cooled conditions within 1 h (Chary et al., 2008) to preserve sample integrity. In the laboratory, the samples were air-dried at room temperature to constant weight to reduce moisture content. The dried samples were then ground to a fine consistency using a mortar and pestle, ensuring thorough homogenization. From each homogenized sample, 200 g were accurately weighed with an analytical balance and retained for subsequent laboratory analysis.

Sample analysis. The analysis of heavy metal concentrations in wastewater, soil, and edible portions of Tomato and Napa cabbage was conducted at the Chemistry Laboratory of Sokoine University of Agriculture. Before analysis, stringent quality control (QC) and quality assurance (QA) procedures were followed to ensure the reliability, reproducibility, and validity of the results. All reagents and solvents

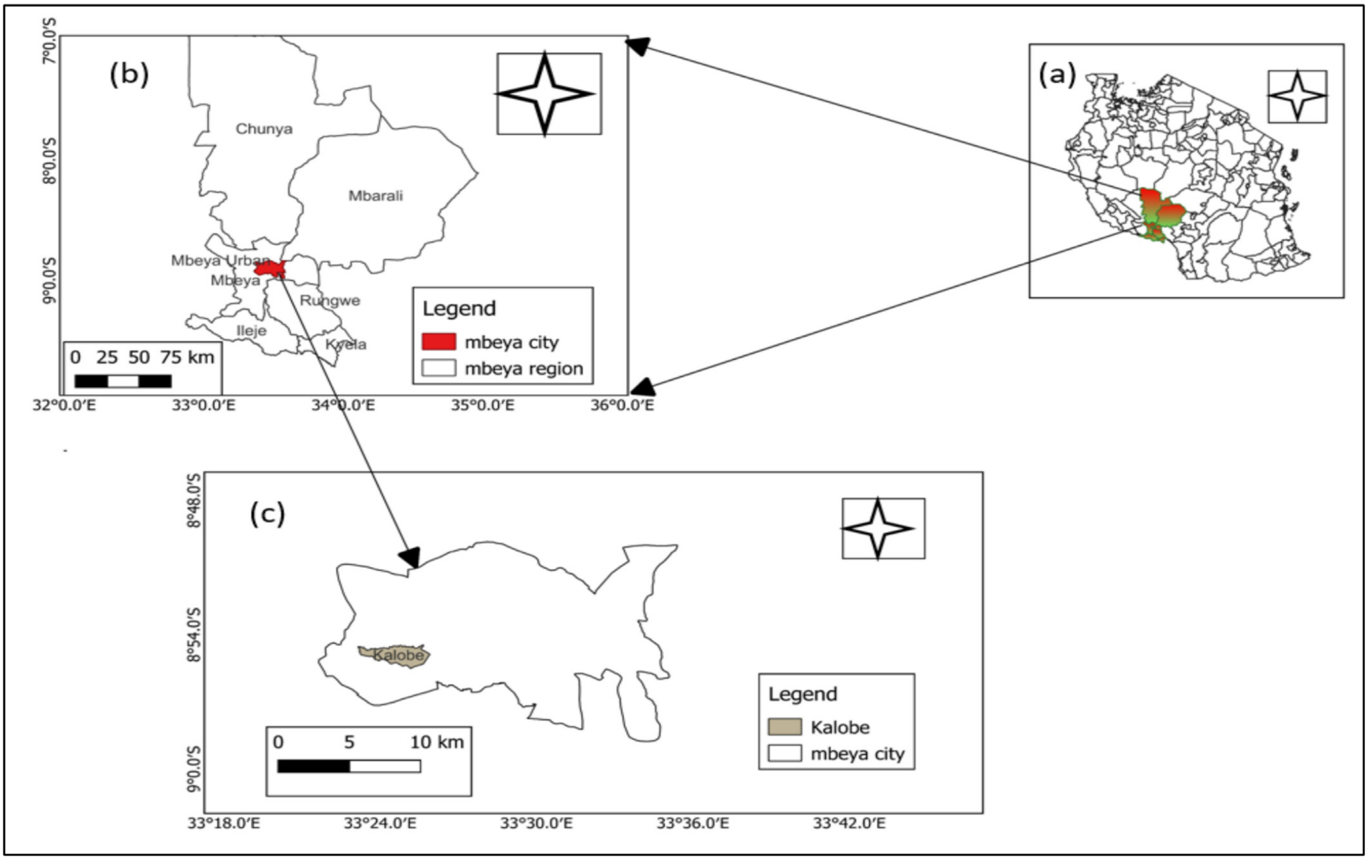

Figure 1. Study area maps showing: (a) the location of Mbeya in Tanzania; (b) the location of the study area within the Mbeya Region; and (c) Kalobe Ward, indicating the site of the Waste Water Stabilization Ponds (WWSP) and adjacent wards.

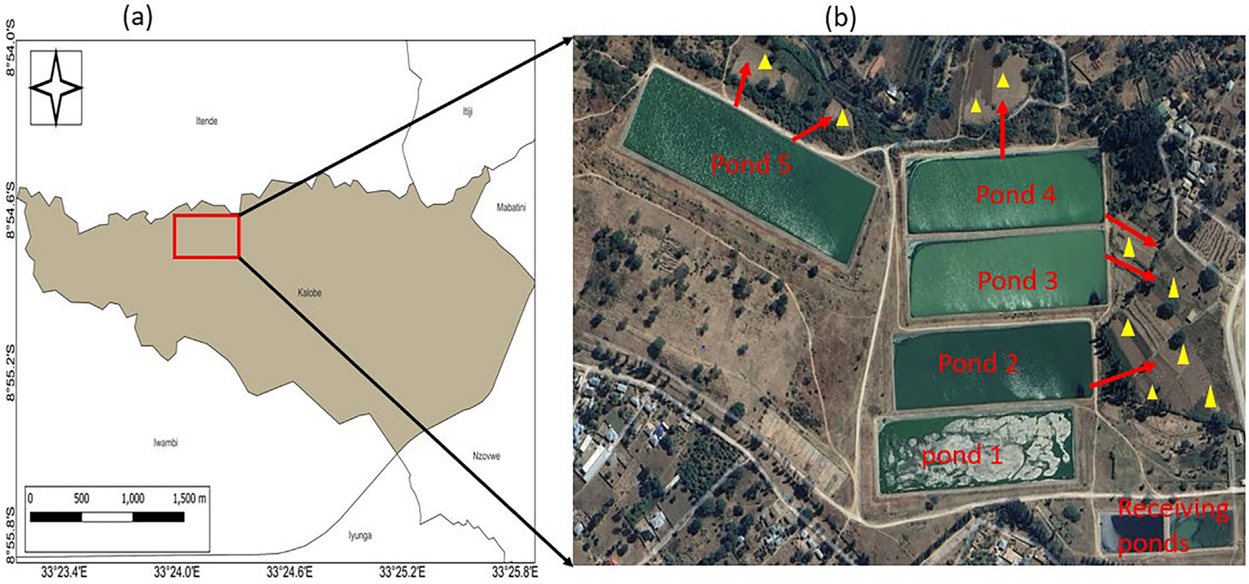

Figure 2. The map shows (a) the location of KWWSP and (b) the KWWSP, which shows the sampling site indicated by the yellow triangle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

used were of analytical grade (GR-grade), with a purity of 99.9% suitable for spectroscopic analysis. Quantification of heavy metals was performed using an Atomic Absorption Spectrophotometer (AAS), model iCE 3000 Series. To prevent contamination, all laboratory glassware (Pyrex) and plastic containers were meticulously cleaned. The cleaning protocol involved soaking in 1% nitric acid (HNO_3), thorough rinsing with double-distilled water, and air drying. Calibration standards and all sample dilutions were prepared using double-distilled water to maintain analytical consistency. The AAS was operated under optimized conditions for each metal. For As, Pb, Cd, and Cr, the wave-

Figure 3. Field observations illustrating wastewater reuse: (a) a generator pumping water from the KWWSP ponds; (b) the drained water from the KWWSP to the Tomato agricultural fields; (c) a farmer fetching water for irrigation of crops; (d) Tomato fields.

lengths were set to 193.7 nm, 283.3 nm, 228.8 nm, and 357.9 nm, respectively, with lamp currents of 6 mA for As, 5 mA (Pb and Cd), and 4 mA (Cr). The limits of detection (LOD) for As, Pb, Cd, and Cr were 0.05 µg/L, 0.01 µg/L, 0.02 µg/L, and 0.05 µg/L, respectively. Standard working solutions were prepared from certified stock solutions (1,000 µg/L), and blank samples were analyzed intermittently to monitor contamination or instrumental drift. Routine washing of instruments between samples further ensured the integrity of results. Each sample was analyzed in triplicate, and mean values were reported to assess precision. The recoveries for As, Pb, Cd, and Cr were 93%, 99%, 96%, and 100%, respectively, indicating high analytical efficiency. Calibration curves demonstrated excellent linearity, with correlation coefficients (R^2) of 0.997 for As, 0.958, Pb, 0.998 for Cd, and 0.996 for Cr. To validate accuracy, certified reference material (NIST SRM-1515, USA) was analyzed under identical conditions. Sample digestion procedures varied according to sample type. Soil samples were digested using a mixture of hydrofluoric acid (HF) and perchloric acid ($HClO_4$), following the protocol described by Chary et al. (2008). For plant samples, including dried edible tissues of Tomato and Napa cabbage, digestion followed the method outlined by Bech et al. (1997), using a combination of nitric acid (HNO_3), perchloric acid ($HClO_4$), and sulfuric acid (H_2SO_4) in a 10:1:1 ratio. Briefly, 0.5 g of dried, powdered plant material was digested in polytetrafluoroethylene vessels using a microwave digestion system (Anton Paar Multiwave Go). Digestion was performed at 180 ˚C and 35 bar pressure, with a ramp time of 5 min and a holding time of 20 min. The software-controlled features of the system enabled precise regulation of temperature, accurate positioning of Hollow Cathode Lamps (HCLs), and fine adjustments of spectral bandwidth, thereby ensuring high sensitivity and accuracy in the quantification of heavy metals.

Statistical analysis. The statistical analysis applied in this study was the Kruskal–Wallis test for Cd and Cr, as the data did not meet the assumption of normality required for a one-way ANOVA. Posthoc pairwise comparisons were subsequently conducted to assess and identify differences in Cd concentrations among Napa cabbage, Tomatoes, and Soil. Posthoc pairwise comparisons (Tukey's HSD test) were applied to determine differences in Cd concentrations among Napa cabbage, Tomatoes, and Soil. For Cr, posthoc analysis was not conducted because the overall group differences were not statistically significant according to the Kruskal–Wallis test.

Heavy metal risk assessment of vegetables. A human health risk assessment of heavy metals (Cd and Cr) in vegetables was conducted using United States Environmental Protection Agency (USEPA) guidelines. Tomato and Napa cabbage, which are commonly irrigated with wastewater from the KWWSPs, were analyzed for dietary exposure risks. The human health risks were assessed in terms of Dietary Exposure Risk, noncarcinogenic and carcinogenic risk indices.

Chronic Daily Intake (CDI). The CDI quantifies the average daily dietary exposure to a contaminant by consuming contaminated food, standardized by body weight and time, and is expressed in mg/kg/day. It was calculated according to (Sharafi et al., 2019) Eq. (1):

$$\mathrm{CDI} = [\mathrm{Cm} \times \mathrm{IR} \times \mathrm{ED} \times \mathrm{EF}] / [\mathrm{BW} \times \mathrm{AT}] \tag{1}$$

Target Hazard Quotients (THQs) and Hazard Indices (HIs). The THQs and HIs were used to qualitatively assess the potential noncarcinogenic risks from regular consumption of contaminated vegetables. THQ and HI values were calculated using Eqs. (2) and (3), respectively (Gebeyehu & Bayissa, 2020; Mekassa et al., 2024). THQ/HI $<$ 1 implies negligible risk, while THQ/HI $\geq$ 1 suggests potential noncarcinogenic effects (Gebeyehu & Bayissa, 2020; Sharafi et al., 2019; USEPA, 2011):

$$\mathrm{THQ} = [\mathrm{CDI}] / [\mathrm{RfDo}] \tag{2}$$

$$\mathrm{HI} = \sum \mathrm{THQs} \tag{3}$$

Target Cancer Risk (TCR). The TCR is a measure of the potential risk of developing cancer from consuming foods that contain heavy metals. In this study, the TCR of heavy metals in the studied vegetables was assessed by Incremental Lifetime Cancer-Risk (ILCR), which represents the probability of excess lifetime cancer risk over the exposed individual. TCR is determined by multiplying CDI by the Oral Cancer slope factor (CSF_o) according to Eq. (4) (Alturiqi et al., 2020; Antoine et al., 2017; Sharafi et al., 2019):

$$\mathrm{TCR} = \mathrm{CDI} \times \mathrm{CSFo} \qquad (4)$$

A description of each input variable used in Eqs. (1)–(4) is given in Table 1.

Results and discussion

Physicochemical parameters and heavy metal concentrations in wastewater. The mean physicochemical parameters and heavy metal concentrations in wastewater samples from KWWSP are summarized in Table 2. The pH values for Ponds 2, 3, 4, and 5 ranged from 8.46 to 8.85, indicating slightly to moderately alkaline conditions within permissible limits set by TBS (6.5–9.0) and FAO (6.5–8) for irrigation water (Dadebo & Gelaw, 2024; FAO, 2004; TBS, 2006). Mean temperatures ranged from 26.29 °C to 26.78 °C, well within the TBS acceptable range of 20–35 °C, supporting stable biological processes essential for wastewater treatment (TBS, 2006). Dissolved oxygen (DO) levels were high (15.4–19.6 mg/L), favoring aerobic microbial activity and treatment efficiency. However, the mean electrical conductivity (EC) values (1,368–1,782 µS/cm) exceeded the recommended limits set by TBS (≤1,000 µS/cm) and FAO (≤700 µS/cm) (Dadebo & Gelaw, 2024; FAO, 2004; TBS, 2006), indicating high salinity that could threaten soil health and crop productivity. Total dissolved solid (TDS) levels (680.3–876 mg/L) also surpassed the TBS and FAO threshold of ≤450 mg/L (Dadebo & Gelaw, 2024; FAO, 2004; TBS, 2006), which could pose risks of soil salinization and negative impacts on sensitive crops when this water is used for irrigation.

The analysis of heavy metal concentrations in the wastewater sample (Table 2) revealed that only Cd was detected across all sampled ponds. The mean concentrations of Cd (in mg/L) were 0.009, 0.008, 0.009, and 0.0073 for ponds 2, 3, 4, and 5, respectively. These values are all below the permissible limit of ≤0.01 mg/L for wastewater reuse for irrigation, as set by the TBS (2006) and FAO (2004), and supported by recent findings (Dadebo & Gelaw, 2024). On the other hand, As, Pb, and Cr were below the detection limits of the analytical instruments used in this study, suggesting their concentrations were negligible or absent in the sampled wastewater. The unusually low heavy metal concentrations reported in this study are consistent with findings from other parts of the world, such as Ghana (Lente et al., 2012) and two cities in India (Singh et al., 2010). The low levels of these heavy metals indicate minimal influence of industrial discharge or anthropogenic input in the effluents entering the KWWSP. Furthermore, the relatively low concentrations of heavy metals could also be attributed to the dynamic nature of the pond system, where the continuous flow and circulation of wastewater potentially prevent the accumulation of con-

Table 1
Description of input variables used in human health risk assessment

Input factors	Description	Unit	Amount	Reference
Cm	Heavy metal concentration	mg/kg	Given in Table 3	
IR	Ingestion rate	kg/person/day	Tomato Adults = 0.024 Children = 0.012 Napa cabbage Adults = 0.100 Children = 0.05	Gebeyehu & Bayissa, 2020; Gupta et al., 2022; Wachirawongsakorn, 2016
ED	Exposure duration	Years	Adults = 70 Children = 6	Adimalla et al., 2020; Ahmad et al., 2021; Feyisa et al., 2025; Gebeyehu & Bayissa, 2020; Mekassa et al., 2024; Sanga & Pius, 2024
EF	Exposure frequency	Days	365	
AT	Average exposure duration	Days	Adults = 25,550 Children = 2,190	
BW	Body weight	kg	Adults = 70 Children = 15	
RfD_o	Oral reference dose	mg/kg/day	Cr = 0.003 Cd = 0.001	
CFS_o	Oral cancer-slope factor	$(mg/kg/day)^{-1}$	Cr = 0.5 Cd = 0.38	

Table 2
The physicochemical characteristics and heavy metal concentrations of the wastewater (Temp (°C), DO (mg/l), EC (µS/cm), TDS (mg/l), Heavy metals (Concentrations (mg/l))

Parameters	Pond 2			Pond 3			Pond 4			Pond 5			[a]TBS	[b]FAO
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max		
pH	8.46	7.68	8.91	8.56	8.37	8.77	8.58	8.41	8.85	8.64	8.20	9.06	6.5–9.0	6.5–8
Temp	26.64	23.17	28.4	26.78	22.99	28.84	26.29	22.73	28.82	26.51	22.45	28.6	20–35	–
DO	19.6	15.36	25.75	16.23	9.72	19.1	15.4	6.11	20.45	17.94	12.57	25.08	–	–
EC	1,782	1,585	1,862	1,622	1,527	1,779	1,369	1,338	1,401	1,574.5	1,516	1,650	≤1,000	≤700
TDS	876	792	970	816	740	890	680.3	617	720	781.5	707	825	≤450	≤450
Pb	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.1	5
Cd	0.009	0.007	0.013	0.008	0.005	0.01	0.009	0.005	0.012	0.0073	0.007	0.008	≤0.01	0.01
Cr	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.1	0.1
As	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	≤0.05	0.01

Note: BDL = Below Detection Limit.

[a] TBS recommended standard (TBS, 2006).

[b] FAO recommended standards (Dadebo & Gelaw, 2024; FAO, 2004).

taminants in the water column. It is also plausible that a significant portion of these metals may have settled into the bottom sludge due to sedimentation processes, which is a common mechanism in stabilization ponds (Bai et al., 2017; Nunes et al., 2021; Yang et al., 2017). However, a key limitation of this study is the lack of sludge analysis, which could provide additional insights into the total heavy metal load within the system. Given that heavy metals often bind to particulate matter and accumulate in sediments, analyzing sludge would offer a more comprehensive assessment of contamination and environmental risk (Bai et al., 2017; Nunes et al., 2021; Yang et al., 2017). Therefore, we recommend that future studies incorporate sludge sampling and analysis to enhance the understanding of heavy metal dynamics in KWWSP. This will help in developing more informed strategies for wastewater reuse in agriculture and in safeguarding both environmental and public health.

Heavy metals in irrigated soil. The descriptive statistics of heavy metal concentrations (mg/kg) for Pb, Cd, and Cr in soils irrigated with wastewater are presented in Table 3, and their visual representation is provided in Figure 4. Although As was not reported in Table 3, as concentrations in the soil samples were below the instrumental detection limit, suggesting that the soils are currently free from As contamination. The results indicated that Pb had the highest concentration among the analyzed heavy metals, with values ranging from 1.21 to 10.01 mg/kg and an overall mean of 5.95 mg/kg, reflecting considerable variation across the sampled sites. Additionally, Cr was the second with concentrations varying between 0.14 and 1.128 mg/kg and a mean value of 0.63 mg/kg**.** On the other hand, Cd recorded the lowest levels, ranging from 0.12 to 0.75 mg/kg, with an average concentration of 0.25 mg/kg. Despite these detections, the concentrations of all analyzed heavy metals were below the WHO/FAO permissible limits for agricultural soils (Codex, 2021; Weldegebriel et al., 2012), as presented in Table 3. This suggests that, under current conditions, the agricultural soil is suitable for crop production, though heavy metal contents warrant ongoing monitoring (Feyisa et al., 2025; Meskelu et al., 2024). However, continuous monitoring is recommended, as prolonged wastewater irrigation can lead to the gradual accumulation of heavy metals over time, potentially exceeding safe thresholds and entering the food chain (Ali & Khan, 2018; Angon et al., 2024; Nkwunonwo et al., 2020; Peralta-Videa et al., 2009).

Heavy metals in vegetables. The mean concentrations (mg/kg) of Pb, Cr, and Cd in the edible portions of the analyzed vegetable samples (Tomatoes and Napa cabbage) are summarized in Table 3, depicted in Figure 4. Although not presented in Table 3 or depicted in Figure 4, As concentrations in both tomato and napa cabbage samples were below the detection limit of the analytical instrument. This indicates that the irrigation with wastewater has not resulted in measurable As accumulation in the studied soils or edible plant tissues. In both Tomatoes and Napa cabbage, Pb concentrations were below the detection limit of the analytical instrument employed in this study, despite the detectable levels observed in the soil samples. This can be attributed to the low

Table 3
The descriptive statistics of Pb, Cd, and Cr in soil, Tomatoes, and Napa cabbage, along with corresponding FAO/WHO permissible limits (concentrations in mg/kg)

Types of samples	Parameters	Concentrations (mg/kg)				
		Mean	Min	Max	FAO/WHO	Reference
Soil	Pb	5.93	1.21	10.01	100	Weldegebriel et al., 2012
	Cd	0.25	0.12	0.76	0–1	Codex, 2021
	Cr	0.63	0.14	1.128	50	Weldegebriel et al., 2012
Tomatoes	Pb	BDL	BDL	BDL	0.1	Codex, 2009
	Cd	0.14	0.02	0.37	0.05	Codex, 2009
	Cr	1.87	0.93	2.43	2.3	Feyisa et al., 2025; Weldegebriel et al., 2012
Napa cabbage	Pb	BDL	BDL	BDL	0.3	Codex, 2009
	Cd	0.4	0.38	0.42	0.2	Codex, 2009
	Cr	2.10	2.06	2.14	2.3	Feyisa et al., 2025; Weldegebriel et al., 2012

BDL = Below Detection Limit.

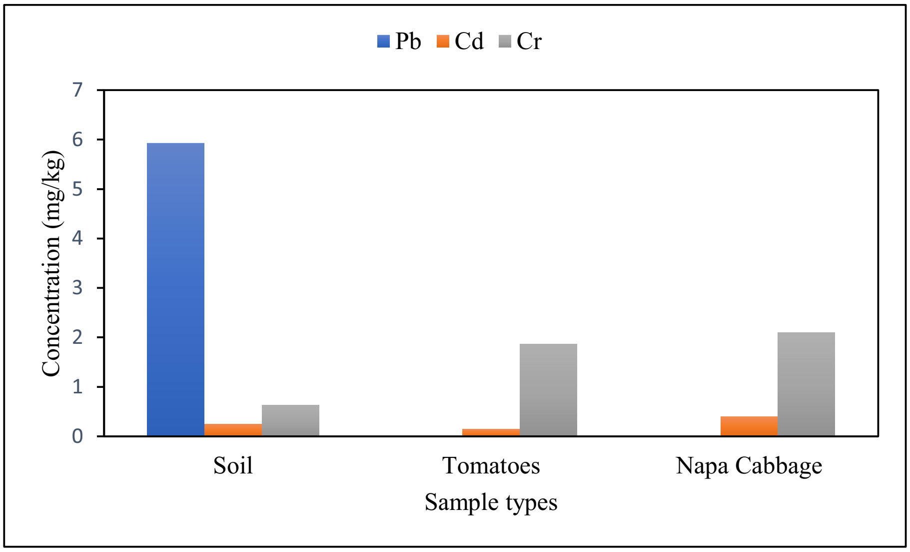

Figure 4. The graphs displaying the Pb, Cd, and Cr in the soil, Tomatoes, and Napa cabbage samples.

bioavailability and limited translocation of Pb from soil to edible plant tissues, as Pb tends to strongly bind to soil particles and organic matter, thereby reducing its mobility and uptake by plants. Similar observations have been reported in previous studies, where Pb was found to accumulate mainly in roots with minimal transfer to shoots or edible parts (Lima et al., 2015; Singh & Kumar, 2006). Heavy metal uptake is also influenced by soil properties, including pH, organic matter, cation exchange capacity (CEC), redox potential, texture, and clay content (Overesch et al., 2007). These findings contrast with those of a recent study conducted in Mbeya City, Tanzania, by Magesa et al. (2025), which reported detectable levels of Pb in Napa cabbage samples collected from various markets. The discrepancy may be attributed to differences in sampling locations, irrigation sources, or environmental conditions influencing Pb uptake. However, this study focused only on the edible portions of the vegetables, limiting insight into overall Pb dynamics in the plant. Comprehensive evaluation of Pb uptake and distribution in other plant tissues, such as leaves, stems, and roots, is suggested in future research.

The results also revealed detectable concentrations (mg/kg) of Cd and Cr in both examined vegetable samples, as seen in Table 3. In Tomatoes, Cd concentrations ranged from 0.02 to 0.37 mg/kg, with a mean value of 0.14 mg/kg, whereas in Napa cabbage, Cd levels varied between 0.38 and 0.42 mg/kg, averaging 0.40 mg/kg. The Kruskal–Wallis test revealed a significant difference in Cd concentrations among soil, tomato, and Napa cabbage samples ($H = 6.32$, $p = 0.042$), as shown in Figure 5. Posthoc pairwise comparisons (Tukey's HSD test) showed that Cd levels in Napa cabbage were significantly higher than those in both soil ($p = 0.048$) and tomato ($p = 0.037$). However, no significant difference was observed between soil and tomato ($p = 0.621$). These findings indicate that Napa cabbage has a greater tendency to accumulate Cd compared to tomato, reflecting crop-specific differences in metal uptake. This may be attributed to differences in the mechanisms of bioaccumulation between the two crops and heavy metal bioavailability for uptake in the soil (Singh & Kumar, 2006). Similar results have been observed in recent studies, for example, a meta-analysis found that leafy vegetables such as Brassica juncea and Brassica pekinensis accumulated significantly more Cd (higher bioconcentration factors) than fruit-vegetable species (Huang et al., 2020). Another study in Dhaka, Bangladesh, showed that cabbage genotypes accumulated more Cd compared to fruit vegetables (Sultana et al., 2022). In this study, we did not assess the uptake and bioaccumulation of Cd between Tomatoes and Napa cabbage, and we acknowledge this omission as one of the limitations of the present study. Future investigations should therefore consider crop-specific variations in metal uptake to provide a more comprehensive understanding of why Cd bioaccumulates in leafy crops. In both Tomato and Napa cabbage, the Cd concentrations exceeded the FAO/WHO food quality threshold value (Codex, 2009; Feyisa et al., 2025; Weldegebriel et al., 2012). The findings are consistent with a recent study conducted in Mbeya City, Tanzania, by Magesa et al. (2025), which reported elevated Cd concentrations in Napa cabbage exceeding the FAO/WHO permissible limit. This finding raises significant concerns for food safety and public health, indicating potential risks associated with the consumption of Tomatoes and Napa cabbage irrigated with wastewater from KWWSP. In this case, raising public awareness and enforcing restrictions on the irrigation of vegetables with inadequately treated wastewater should be prioritized to promote environmental sustainability and protect consumer health.

The concentration of Cr ranges from 0.93 to 2.43 mg/kg, with a mean value of 1.87 mg/kg in Tomato samples, and from 2.06 to 2.14 mg/kg, with a mean value of 2.10 mg/kg in Napa cabbage, as shown in Table 3. Although the mean Cr concentration in Napa cabbage was higher than in Tomatoes, the Kruskal–Wallis test revealed no statistically significant differences in Cr concentrations (Fig. 5) among the groups ($H = 4.30, p = 0.116$). This lack of significant variation suggests that chromium uptake may be influenced more by environmental conditions and soil characteristics than by crop type. However, since the present study did not explore the specific uptake and bioaccumulation mechanisms responsible for these variations, we recognize this as a limitation. We therefore suggest that future studies should explore crop-specific uptake and bioaccumulation mechanisms of heavy metal accumulation. In some Tomato samples, the Cr concentrations exceeded the permissible limit set by FAO/WHO (Feyisa et al., 2025; Weldegebriel et al., 2012), indicating a potential human health risk from consuming Tomatoes irrigated with KWWSP water. In contrast, all Napa cabbage samples had Cr concentrations below the FAO/WHO permissible limit (Feyisa et al., 2025; Weldegebriel et al., 2012); however, values were close to the threshold, suggesting a potential human health risk upon prolonged consumption. Similar studies from other cities in Africa have reported considerably higher Cr concentrations in vegetables irrigated with wastewater, often exceeding the permissible limit. For example, ele-

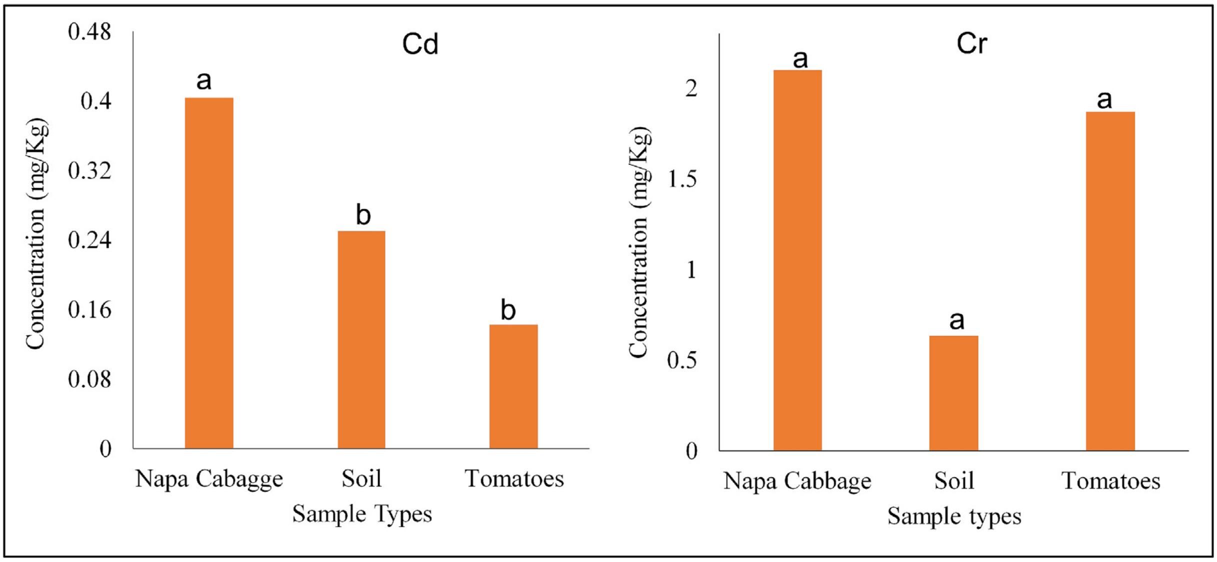

Figure 5. Kruskal–Wallis test results for Cd and Cr concentration (mg kg^{-1}) Napa cabbage, Tomatoes, and irrigated soil. Means followed by the same letters are not significantly different at 5% confidence level.

vated Cr levels (mg/kg) have been documented in vegetables from Gondar City, Ethiopia (Berihun et al., 2021), Machakos municipality, Kenya (Tomno et al., 2020), in Blantyre City, Malawi (Malikula et al., 2022), and in South Cairo Province, Egypt (Galal et al., 2018). These findings highlight that, while the levels in the present study are relatively lower, the proximity to the permissible limit still warrants concern and reinforces the importance of continuous monitoring to safeguard public health.

Dietary exposure risk of consuming vegetables. The results of dietary exposure risk assessment by CDI of heavy metals for adults and children consuming Tomato and Napa cabbage from the study area are presented in Table 4. For adults, the calculated CDI of Cd varied from 5.00×10^{-5} mg/kg/day in tomato to 5.80×10^{-4} mg/kg/day in Napa cabbage, and that of Cr ranged from 5.80×10^{-4} mg/kg/day in tomato to 2.99×10^{-3} mg/kg/day in Napa cabbage. These values were notably lower than the recommended safe intake limit (RfD_o) for Cd (0.001 mg/kg/day) and Cr (0.003 mg/kg/day), signifying limited exposure risks from Cd exposure.

For children, dietary exposure levels were consistently higher than in adults due to their lower body weight relative to consumption rate (Bokkers & Bakker, 2010; Huybrechts et al., 2011). The CDI of Cd in tomato (1.10×10^{-4} mg/kg/day) was within a safe limit (0.001 mg/kg/day); however, in Napa cabbage, the CDI of Cd (9.96×10^{-4} mg/kg/day) approached the safe intake limit, implying borderline exposure risks. Chromium exposure risk from Tomato (CDI = 1.36×10^{-3}) remained moderate, but in Napa cabbage (CDI = 6.98×10^{-3}) exceeded the safe intake limit (0.003 mg/kg/day), suggesting elevated exposure risks. This suggests that regular consumption of Napa cabbage from the study area could pose potential health concerns, particularly for vulnerable groups such as children. Similar observations were reported in Tanzania (Hellen & Othman, 2016) and China (Zhou et al., 2016), where leafy vegetables showed higher chromium accumulation than fruiting vegetables, increasing dietary risk.

Noncarcinogenic health risks. The assessment of noncarcinogenic human health risks using the THQ and HI provides insight into the potential health implications of consuming Cd and Cr contaminated vegetables. In this work, the calculated THQ values range between 0.05 (Cd in Tomato) and 1.00 (Cr in Napa cabbage) for the adults and, from 0.11 to 2.33 for children. According to the USEPA guideline, a THQ or HI > 1 implies a potential of noncarcinogenic risk (Ahmad et al., 2021; Mekassa et al., 2024; USEPA, 2004). For adults, THQ of Cd (0.050 from and Napa cabbage (THQ = 0.58) remained below the noncarcinogenic threshold (THQ < 1), suggesting negligible immediate health effects. The THQ of Cr from Tomato (HQ = 0.19) was below the threshold, while that from Napa cabbage (HQ = 1.00) reached the critical value, suggesting possible noncarcinogenic adverse effects. Similar findings were reported in the Mojo area in Ethiopia (Gebeyehu & Bayissa, 2020) and in Western Nigeria near bitumen deposits (Atikpo et al., 2021), where THQs in cabbage exceeded recommended limits, indicating elevated human health risks for adults consuming these vegetables.

For children, THQ (0.11) Cd exposure from Tomato was below the safe limit, while THQ (0.96) in Napa cabbage approached the safe limit, indicating borderline noncarcinogenic risk. The Cr intake from Tomato (HQ = 0.45) was moderate, while that from Napa cabbage (HQ = 2.33) exceeded the safe limit, highlighting elevated noncarcinogenic risks. Similar findings have been reported in the Msimbazi River in Dar es Salaam, Tanzania (Kihampa & Mwegoha, 2010), indi-

Table 4

Estimated chronic Intakes (CDIs), Target hazard quotient (THQs), and Target cancer risk (TCRs) of Cd and Cr values for adults and children

Vegetable	Metal	CDI	HQ	TCR
I. Adults				
Tomato	Cd	5.00×10^{-5}	0.05	1.85×10^{-5}
	Cr	5.80×10^{-4}	0.19	2.90×10^{-4}
Napa cabbage	Cd	5.80×10^{-4}	0.58	2.19×10^{-4}
	Cr	2.99×10^{-3}	1	1.50×10^{-3}
II. Children				
Tomato	Cd	1.10×10^{-4}	0.11	4.32×10^{-5}
	Cr	1.36×10^{-3}	0.45	6.78×10^{-4}
Napa cabbage	Cd	9.60×10^{-4}	0.96	$3.65\text{E} \times 10^{-4}$
	Cr	6.98×10^{-3}	2.33	3.49×10^{-3}

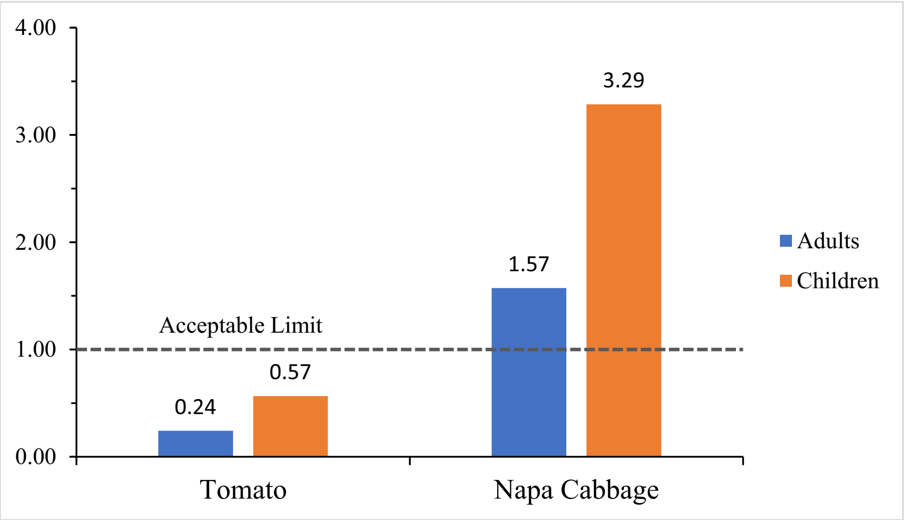

Figure 6. Hazard Index (HI) of vegetables for adults and children.

cating that leafy vegetables, including cabbage, accumulated higher levels of heavy metals compared to fruiting vegetables, leading to increased dietary risks for children. Comparable patterns have also been observed in Ethiopia, where hazard quotients for Cd and Cr in leafy vegetables exceeded safe limits, posing significant human health risks to children (Gebeyehu & Bayissa, 2020).

The corresponding HI values, representing cumulative exposure to both metals, varied from 0.24 in Tomato to 1.57 in Napa cabbage in the case of adults, as displayed in Figure 6. For children, the range was from 0.57 (Tomato) to 3.29 (Napa cabbage). It is worth noting that all THQ and HI values in Napa cabbage exceeded the safe limit (unity) for both age groups, indicating a potential adverse health effect, especially in children. The noticeable difference between adults and children is consistent with prior studies (Sanga & Pius, 2024; Sharma et al., 2016), which attribute the heightened vulnerability of children to their lower body mass, higher food intake per unit body weight, and developing physiological systems (Sanga & Pius, 2024).

Carcinogenic health risk. The carcinogenic risk via consumption of vegetables from the study area was assessed using TCR for adults and children, and the results are presented in Table 4. The study revealed comparatively higher TCR in children than in adults, with Cd ranging from 4.32×10^{-5} (Tomato) to 3.65×10^{-4} (Napa cabbage), and Cr from 6.78×10^{-4} (Tomato) to 3.49×10^{-3} (Napa cabbage). For adults, TCR values of Cd varied from 1.85×10^{-5} (Tomato) to 2.19×10^{-3}, while Cr ranged from 2.90×10^{-5} (Tomato) to 1.50×10^{-5} (Napa cabbage). In both age groups, all TCR values were noticeably above the USEPA acceptable risk range (10^{-6}–10^{-4}), which signifies potential vulnerability to cancer effects from prolonged consumption of vegetables irrigated with effluent from KWWSP.

Moreover, the dominance of Cr over Cd in risk contribution suggests that dietary Cr exposure becomes a critical concern in this context due to concentrations approaching or surpassing the safe intake limit. Chromium, especially in the form of Cr (VI), is recognized as a potent carcinogen (Zhigalenok et al., 2025). Thus, its detection in vegetables at concentrations surpassing established cancer risk thresholds represents a critical public health risk. Similar findings have been reported in previous studies, which also revealed carcinogenic risk in vegetable-wastewater irrigation to heavy metal bioaccumulation (Hassan et al., 2024; Negassa et al., 2025).

Conclusions

This study provides the first assessment of heavy metal contamination and associated human health risks in the soil-wastewater-vegetable system originating from the KWWSP in Mbeya, Tanzania. The nondetectable levels of As in wastewater and plant samples (Tomato and Napa cabbage) indicate that current wastewater-based irrigation practices have not resulted in As enrichment of the soil–plant system. Cd concentrations in irrigation water were below the permissible limits set by the TBS and FAO/WHO, while Pb and chromium Cr were not detected. In soil samples, mean concentrations followed the order Pb > Cr > Cd, with all values remaining below FAO/WHO permissible limits. In both Tomato and Napa cabbage, only Cd concentrations exceeded FAO/WHO limits, indicating a potential human health risk. Cr concentrations in both vegetables were marginally below permissible limits, which may pose human health concerns with regular consumption. The results indicate that daily consumption of vegetables irrigated with KWWSP water could result in carcinogenic and noncarcinogenic human health risks, particularly for children. This is evidenced by the elevated THQ/HI and TCR values. These findings underscore the necessity for regular monitoring of heavy metals and other toxic substances in wastewater-irrigated soils and vegetables. The study also recommends safe irrigation alternatives and cropping restrictions using inadequately treated wastewater. This will help protect public health and support long-term environmental sustainability. Public education initiatives targeting urban farmers and consumers are recommended to increase awareness of the risks associated with consuming wastewater-irrigated vegetables. These initiatives would also help promote safer agricultural practices. Additionally, investment in alternative safe water sources for urban agriculture is essential. Despite providing valuable initial insights, this study's limited sample size necessitates a future large-scale replication study.

CRediT authorship contribution statement

Azaria Stephano Lameck: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Dickson Mlelwa:** Writing – review & editing, Writing – original draft, Conceptualization. **John Chagu:** Writing – review & editing, Formal analysis. **Victor Sanga:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Melkizedeck Hiiti Tsere:** Writing – review & editing. **Gisandu K. Malunguja:** Writing – review & editing. **Alinanuswe Joel Mwakalesi:** Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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