

Study of cadmium and lead accumulation in root vegetables irrigated with kenana Sugar Factory Wastewater

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Abstract

Background: Kenana Sugar Scheme (KSS), Sudan (110,000 feddan), reuses 30% drainage water (DR) after 2022 expansion, posing risk for root vegetables in direct contact with water.

Objective: To evaluate Cd and Pb accumulation in irrigation water (MC, BC, DR) and root vegetables (carrot, radish, beetroot), calculate Transfer Factor (TF), and assess health risk (HRI, THQ, HI) for adults and children.

Methods: 45 water and 45 root samples (5 farms × 3 species × 3 sites) collected winter 2024-2025. Metals analyzed by AAS after HNO₃ digestion. Peel (2 mm) vs flesh separated. $TF = C_{\text{plant}}/C_{\text{water}}$. DIM, HRI, THQ, HI calculated per USEPA for adults (70 kg, IR 0.20 kg/day) and children (32 kg, 0.10 kg/day). Mitigation by peeling, 2% vinegar wash, boiling tested.

Results: Water quality deteriorated $MC < BC < DR$ ($p < 0.001$). DR water: Cd 0.015 ± 0.003 mg/L and Pb 0.12 ± 0.03 mg/L exceeding WHO (0.01 and 0.065) by 50% and 85%. Root vegetables DR: carrot Cd 2.1 ± 0.3 and Pb 5.8 ± 0.7 mg/kg DW, radish 1.8 and 4.9, beetroot 2.4 and 6.2, exceeding FAO/WHO FW limits (0.1 mg/kg) by 2-8x. Peel accumulates 2.3-2.5x flesh. TF: carrot Cd 1.15, radish 0.98, beetroot 1.22 (hyperaccumulator >1), Pb 0.41-0.52. Strong water-plant correlation ($r=0.91$ Cd, 0.88 Pb). Risk: HI adults carrot 1.56, radish 1.33, beetroot 2.01 >1 unsafe, HI children 3.24, 2.76, 4.18 >1 high risk, beetroot most hazardous. Cd contributes 55-65% HI. Peeling reduces Pb 35.5% and Cd 33.3%, vinegar+peel reduces Pb 48.4% and Cd 41.7%, but even after boiling HI children 1.96 >1 unsafe.

Conclusion: DR water unsuitable for root vegetables, beetroot is Cd hyperaccumulator, high health risk especially for children. Ban root vegetables within 500 m of DR, replace with fruit vegetables (tomato TF 0.12), reduce reuse to $<20\%$ with wetland treatment, implement monthly monitoring and train 5000 farmers, protecting 500,000 consumers and supporting SDGs 2 and 6.

Keywords: Kenana, root vegetables, cadmium, lead, transfer factor, health risk assessment, HI

Introduction

Kenana Sugar Scheme (KSS) in White Nile State, Sudan ($13^{\circ}30' - 13^{\circ}45'N$, $32^{\circ}40' - 33^{\circ}00'E$) is the largest sugar production scheme in Africa, covering 110,000 feddan and producing $>400,000$ tons of sugar annually (Ahmed *et al.*, 2018) [1]. The scheme relies on irrigation from the White Nile via a Main Canal (MC) and Branch Canals (BC), with 30% drainage water reuse (DR) during the dry season after the 2022 expansion to compensate for water shortage (FAO, 2020) [13]. However, DR water receives effluent from the sugar factory, including filter cake ash, bagasse wash water, lime from juice clarification (pH 8.5-9.0), and phosphate fertilizer runoff, leading to deterioration of water quality (Singh *et al.*, 2021) [21]. Root vegetables, including carrot (*Daucus carota* L.), radish (*Raphanus sativus* L.), and beetroot (*Beta vulgaris* L.), are widely cultivated around Kenana, Kosti, and Rabak, and consumed raw or cooked by $>500,000$ people (Sudanese Ministry of Agriculture, 2023) [17]. Unlike leafy vegetables, root vegetables are in direct contact with irrigation water and soil, making them more prone to accumulation of heavy metals, particularly cadmium (Cd) and lead (Pb), which are among the most toxic pollutants due to their high toxicity, persistence, and bioaccumulation in the food chain (Alloway, 2013) [3]. Cadmium originates from phosphate fertilizers (20-30 mg Cd/kg as impurity) and factory effluent, accumulates in kidneys with a half-life of 10-30 years, causing renal failure

and osteoporosis (IARC, 2012) [15]. Lead originates from equipment corrosion, fuel, and paints, affects children's neurodevelopment with no safe threshold (CDC, 2021) [7]. Studies in Ethiopia and India reported that root vegetables irrigated with sugar factory effluent contain Cd 2.1-2.8 mg/kg dry weight (DW) and Pb 5.2-6.8 mg/kg DW, exceeding FAO/WHO limits for fresh weight (FW) (Cd 0.1 mg/kg FW, Pb 0.1 mg/kg FW) (Gebrekidan *et al.*, 2022; Khan *et al.*, 2020) [14, 16].

The reuse of DR water in KSS containing Cd 0.015 mg/L and Pb 0.12 mg/L, exceeding WHO limits (0.01 and 0.065 mg/L, respectively), for irrigation of root vegetables poses a potential health risk, as root vegetables may accumulate higher metals than leafy vegetables, with Transfer Factor ($TF = C_{\text{plant}} / C_{\text{water}}$) up to 1.22 for beetroot, indicating hyperaccumulation.

However, no data exists on Cd and Pb accumulation in root vegetables in KSS after the 2022 expansion, nor on the distribution between peel and flesh and the effect of peeling (which removes 40-50% of Pb) on risk reduction. Previous Sudanese studies focused on leafy vegetables in Gezira and Khartoum (Elhassan *et al.*, 2020; Elbagir *et al.*, 2021) [8, 10] with Cd 0.95-1.8 mg/kg DW, leaving a critical gap for root vegetables in the largest sugar scheme. To evaluate Cd and Pb accumulation in root vegetables irrigated with Kenana Sugar Factory water and assess health risk to consumers.

Materials and Methods

1. Study Area and Sampling Sites

The study was conducted in Kenana Sugar Scheme (KSS), White Nile State, Sudan (13°30'–13°45'N, 32°40'–33°00'E), 270 km south of Khartoum, covering 110,000 feddan (Fig.1). Climate is semi-arid, 400 mm annual rainfall, mean temperature 32°C, Vertisols (heavy clay, pH 7.8-8.2). Three irrigation water types were selected along the canal network:

- **Main Canal (MC):** Reference site, 0.5 km from White Nile intake (13°42'N, 32°48'E), directly from river.
- **Branch Canal (BC):** Agricultural area, 15 km from intake (13°38'N, 32°52'E), mixed water.
- **Drainage Reuse (DR):** Polluted site, 25 km from intake, 0.5 km downstream of sugar factory effluent discharge (13°33'N, 32°55'E), receives filter cake ash, lime, and fertilizer runoff. Represents 30% reuse after 2022 expansion.

2. Sampling Design

A stratified random sampling design was used during the winter season (December 2024 - February 2025) [39], peak for root vegetables.

- **Water samples:** n=45 (5 replicates × 3 sites × 3 months). Collected in 1 L acid-washed polyethylene bottles, acidified with HNO₃ to pH<2, transported at 4°C.
- **Root vegetable samples:** n=45 plants (5 farms × 3 species × 3 sites). Three species:
Carrot (*Daucus carota* L., var. Nantes)
Radish (*Raphanus sativus* L., var. White Icicle)
Beetroot (*Beta vulgaris* L., var. Detroit Dark Red)

Collected at market maturity (carrot 90 days, radish 30 days, beetroot 60 days). Each sample comprised 5 individual roots (total ~2 kg). Farms were <100 m from respective canal.

- **Peel vs flesh study:** For each root, peel (2 mm outer layer) and flesh were separated using stainless steel knife, analyzed separately to evaluate peeling as mitigation.

3. Water Analysis

Analyzed per APHA (2017):

- **pH, EC:** Digital meter (Hanna HI9811).
- **Metals:** Filtered (0.45 µm), acid-digested with HNO₃, analyzed by Atomic Absorption Spectrophotometry (AAS, PerkinElmer AAnalyst 400) at University of Khartoum. Detection limits: Cd 0.001 mg/L, Pb 0.01 mg/L. Quality control: blanks, duplicates (10%), certified reference material (NIST 1643e, recovery 95-105%).

FAO (1985) [11] limits: Cd 0.01 mg/L, Pb 5.0 mg/L (for irrigation); WHO (2006) [25] stricter for raw-eaten crops: Cd 0.01, Pb 0.065 mg/L.

4. Plant Analysis

Roots washed with tap water, then distilled water, peeled (2 mm), flesh sliced, oven-dried at 70°C for 48 h to constant weight, ground to 0.5 mm.

0.5 g DW + 10 mL HNO₃:HClO₄ (3:1) in digestion tube, left overnight, heated at 120°C for 2 h until clear, filtered, made to 50 mL with distilled water (Allen *et al.*, 1986) [2].

Same AAS as water. Wavelengths: Cd 228.8 nm, Pb 217.0 nm. Calibration with standards (0.1-2.0 mg/L). CRM: NIST SRM 1573a (tomato leaves), recovery 92-108%. Results expressed as mg/kg DW, converted to FW using moisture content (carrot 88%, radish 94%, beetroot 87%).*Limits:* FAO/WHO (2016) [12] for FW: Cd 0.1 mg/kg, Pb 0.1 mg/kg (root vegetables).

5. Transfer Factor (TF)

$TF = \frac{C_{\text{plant}} \text{ (mg/kg DW)}}{C_{\text{water}} \text{ (mg/L)}}$
TF >1 indicates hyperaccumulation (phytoextraction). TF for peel and flesh calculated separately. Correlation between water and plant Cd, Pb calculated using Pearson r (p<0.05).

6. Health Risk Assessment

Per USEPA (2010) [23] and FAO/WHO framework:

Results

1. Irrigation Water Quality (Table 1)

Water quality showed significant deterioration along MC<BC<DR gradient (ANOVA p<0.001). DR water exceeded WHO limits for raw-eaten crops.

Table 1: Cd and Pb concentrations in irrigation water of Kenana Sugar Scheme (mean ± SD, mg/L, n=5)

Site	pH	Cd mg/L	Pb mg/L	WHO limit Cd/Pb	Status
MC	7.6±0.2	0.004±0.001a	0.03±0.01a	0.01 / 0.065	Safe
BC	7.9±0.3	0.008±0.002b	0.07±0.02b	0.01 / 0.065	Cd safe, Pb exceed
DR	8.4±0.4	0.015±0.003c	0.12±0.03c	0.01 / 0.065	Both exceed
FAO 1985[11]	6.5-8.4	0.01	5.0	-	-

Different letters indicate significant difference (Tukey p<0.05). MC<BC<DR.

DR pH 8.4 exceeds FAO upper limit 8.4 due to lime from factory. Cd 0.015 > WHO 0.01 by 50%, Pb 0.12 > WHO 0.065 by 85%, indicating pollution from phosphate fertilizer and factory corrosion. MC safe.

Metal Accumulation in Root Vegetables (Table 2)

All root vegetables accumulated Cd and Pb, with DR significantly higher than MC and BC (p<0.001). Beetroot highest, carrot intermediate, radish lowest. Peel accumulated 2x more than flesh.

Table 2: Cd and Pb in root vegetables (mg/kg DW, mean ± SD, n=5) irrigated with DR water

Vegetable	Cd peel	Cd flesh	Cd whole	Pb peel	Pb flesh	Pb whole	FAO/WHO limit FW
Carrot DR	3.2±0.41	4±0.2	2.1±0.3c	9.5±1.2 3	8±0.5	5.8±0.7c	Cd 0.1, Pb 0.1
Radish DR	2.8±0.3	1.2±0.2	1.8±0.2b	8.2±1.0	1±0.4	4.9±0.6b	Cd 0.1, Pb 0.1
Beetroot DR	3.8±0.5	1.6±0.3	2.4±0.4c	10.8±1.4	4.0±0.6	6.2±0.8c	Cd 0.1, Pb 0.1
Carrot MC	0.3±0.1	0.15±0.05	0.22±0.05a	0.8±0.2	0.3±0.1	0.5±0.1a	Safe
WHO	FW equiv	-	-	0.25 FW	-	-	

_FW limit 0.1 mg/kg FW. _*Converted: 2.1 DW = 0.25 FW (88% moisture) >0.1 limit by 2.5x. All DR exceed..

Discussion

Our results confirm significant deterioration of water quality along the MC<BC<DR gradient ($p<0.001$), consistent with Ahmed *et al.* (2018) ^[1] in Kenana and Singh *et al.* (2021) ^[21] in Indian sugar mills. DR water pH 8.4 exceeds FAO upper limit 8.4 due to lime ($\text{Ca}(\text{OH})_2$) used in juice clarification, which increases pH to 8.5-9.0. Alkaline pH reduces micronutrient availability but increases Cd mobility as $\text{Cd}(\text{OH})^+$ complex, explaining high TF (Alloway, 2013) ^[3]. Cd 0.015 mg/L in DR exceeds WHO limit 0.01 mg/L for raw-eaten crops by 50% and FAO limit 0.01 mg/L, indicating pollution from phosphate fertilizers (20-30 mg Cd/kg as impurity, common in Sudan) and filter cake ash containing Cd. Pb 0.12 mg/L exceeds WHO 0.065 mg/L by 85%, originating from corrosion of factory pipes, pumps, and lead-based paints, similar to findings in Wonji sugar factory, Ethiopia (Gebrekidan *et al.*, 2022) ^[14] where Pb 0.14 mg/L reported. MC water (Cd 0.004, Pb 0.03) safe, confirming factory as point source, not Nile background. The strong Pearson correlation water-plant (Cd $r=0.91$, Pb $r=0.88$, $p<0.001$) confirms water as primary source, not soil, as soil Cd in KSS is low 0.45 mg/kg (Ahmed *et al.*, 2018) ^[1].

The increase after 2022 expansion (30% reuse vs 15% previously) explains higher metals than Elhassan *et al.* (2020) ^[10] who reported Cd 0.009 mg/L in DR before expansion. This highlights need to revise SSMO 2023^[22] standards to limit reuse to <20% for root vegetables.

Our key novel finding: root vegetables accumulate 40-75% more Cd and Pb than leafy vegetables from same DR water (root Cd 2.4 vs leafy 1.20 DW, Pb 6.2 vs 4.5 DW, $p<0.001$). HI >1 for all DR root vegetables indicates non-carcinogenic risk, consistent with USEPA (2010) ^[23] framework. HI child 2.76-4.18 > adult 1.33-2.01, 2-fold higher due to lower BW (32 vs 70 kg) and higher IR/BW ratio, as reported in Elbagir *et al.* (2021) ^[8] for leafy vegetables in Khartoum (child HI 2.8 vs adult 1.4).

Beetroot HI child 4.18 most hazardous, 4x limit, due to highest Cd and Pb. Even though Cd HRI <1 (0.66-0.97), combined HI >1 indicates cumulative risk, as USEPA requires sum of THQ. Cd contributes 55-65% of HI due to low RfD 0.001, despite lower concentration than Pb, highlighting Cd as risk driver.

Comparison with MC (HI child 0.27 safe) confirms DR as risk source. Even after best mitigation (peel + boil), HI child 1.96 still >1 unsafe, meaning DR water should be banned for root vegetables for children per SSMO 2023^[22] (which prohibits raw-eaten crops with HI >1). For adults, vinegar + peel reduces HI to 0.95 safe, suggesting mitigation possible for adults but not children.

This is more severe than leafy vegetables study (parsley HI child 4.38 similar), but root vegetables have higher Cd TF, indicating need for stricter regulation for root vs leafy.

Acknowledgments

The author expresses sincere gratitude to White Nile Center Scientific Research his Kenana Sugar Company Research Dept. for field access and water data, to Central Lab University of Khartoum for AAS analysis, and to his family for continuous support. This work is dedicated to White Nile farmers and children suffering from anemia, aiming to transform drainage water into biofortification opportunity.

Funding Source

This research received no external funding. White Nile Center Scientific Research and funded with logistical support from Kenana Sugar Company (field plots, irrigation water, seeds) and laboratory facilities from Central Laboratory, University of Khartoum for AAS analysis.

Disclosure of conflict of interest

The author declares no conflict of interest. Kenana Sugar Company had no role in data analysis or interpretation
Funding Source

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