



Quality assessment of tomato and okra irrigated with Kenana Sugar Factory effluent: Balancing Fe and Zn biofortification vs Cd and Cr contamination and food safety implication

Dr. Gamar Eldawla Abdelmotalib Ahmed¹, Dr. Masheir Ibrahim Baleil Ibrahim², Dr. Mohammed Salem Abd Elfadil³

¹ Associate Professor, Department of Plant Nutrition, College of Education, University of White Nile, kosti, Sudan

² Assistant Professor White Nile Center Scientific Research, (WNCSR), kosti, Sudan

³ Associate Professor, Department of Chemistry, College of Education, University of Imam Mahdi, kosti, Sudan

Abstract

Background: Kenana Sugar Scheme reuses 30% drainage water (DR) containing both nutrients (Fe 3.5, Zn 2.8 mg/L) and contaminants (Cd 0.015, Cr 0.08 mg/L). Root vegetables in DR show unsafe HI 4.18, but fruit vegetables hypothesized to achieve positive balance via selective uptake.

Methods: Tomato and okra irrigated with Main Canal (MC), Branch Canal (BC), and DR waters in RCB (n=4) during 2024-25 winter. Water, soil DTPA, and fruits (peel/pulp) analyzed for Fe, Zn, Cd, Cr by AAS. TF, %RDA, THQ, HI, and novel Benefit-Risk Ratio BRR = (%RDA Fe+Zn)/HI calculated.

Results: DR soil DTPA Fe 28.5, Zn 5.6, Cd 0.32, Cr 1.10 mg/kg, 2-3x MC. Tomato DR accumulated Fe 110, Zn 42 mg/kg DW (2.4x MC) providing 11% Fe and 5% Zn RDA per 200 g adult (6.6% and 5% for child 100 g), with low Cd 0.32 DW (0.019 FW) and Cr 0.45 DW (0.027 FW) below FAO limits (0.1, 0.5). TF Fe 0.18, Zn 0.22 vs TF Cd 0.10, Cr 0.08, 2x selective. HI adult 0.093 tomato, 0.183 okra, child 0.19-0.38 <1 safe vs beetroot 4.18 unsafe. BRR 172 adult tomato, 61 child, 128 and 45 okra >>1 positive, beetroot child 0.95 negative.

Conclusion: Fruit vegetables achieve positive quality balance: Fe/Zn biofortification (11-15% RDA) with Cd/Cr safety (HI <1), BRR 45-172, ideal for DR zones, replacing root vegetables, supporting SDG 2,3,6.

Keywords: Biofortification, benefit-risk ratio, tomato, okra, Kenana, food safety

Introduction

The world faces a dual crisis: water scarcity and micronutrient deficiency. According to FAO 2023, 40% of agricultural lands suffer water shortage, while 2 billion people suffer from iron and zinc deficiency (WHO 2021). In Sudan, Kenana Sugar Scheme (KSS) is the largest in Africa (110,000 feddan, 450,000 tons sugar/year), consuming 1.2 billion m³ water annually and reusing 30% drainage water (DR) after expansion of treatment plant in 2022 [14] to cope with White Nile water shortage (Ministry of Irrigation Sudan, 2023). Kenana industrial effluent is not merely a pollutant but a *complex mixture*: it contains contaminants such as cadmium Cd (0.015 mg/L) from phosphatic fertilizers used for sugarcane, and chromium Cr (0.08 mg/L) from corrosion of factory equipment made of stainless steel (Ahmed *et al.*, 2018; Gebrekidan *et al.*, 2022) [1, 8], and at the same time contains essential micronutrients such as iron Fe (3.5 mg/L) and zinc Zn (2.8 mg/L) resulting from cane washing and groundwater rich in Fe in Kenana area (Elhassan *et al.*, 2020) [5]. According to WHO 2011, Fe and Zn are the most deficient nutrients in Sudan, where 40% of children in White Nile State suffer iron-deficiency anemia and 35% zinc deficiency causing stunting (WHO Sudan Nutrition Survey 2021) [23]. This duality creates a novel scientific question not studied in Sudan: Can wastewater be transformed from a pollution problem into a biofortification opportunity? Biofortification is increasing crop nutrient content via irrigation or fertilization, a strategy adopted by FAO and HarvestPlus to combat hidden hunger (FAO, 2020). Vegetables are classified by edible part and contact with irrigation water into three groups: root vegetables directly contacting water (carrot, beetroot) with high TF

1.22 hazardous, leafy vegetables contacting spray (rocket, lettuce) TF medium 0.65, and fruit vegetables distant from water (tomato, okra, eggplant) TF low 0.12 safe (Rattan *et al.*, 2005; Singh *et al.*, 2021) [16, 19]. The first study in Kenana proved root vegetables unsafe HI 4.18 for children, therefore an alternative safe and nutritious crop in same water must be sought. Fruit vegetables possess a unique physiological mechanism called *Selective Uptake*: Roots absorb all elements, but sequester 80% of contaminants (Cd, Cr) in vacuoles via phytochelatins and metallothioneins, while translocating beneficial nutrients (Fe, Zn) via specialized transporters: IRT1 and YSL for Fe, ZIP family for Zn, to fruits via xylem and phloem (Alloway, 2013; Clemens *et al.*, 2013) [2, 3]. This means fruit benefits from Fe, Zn and avoids Cd, Cr naturally, achieving a *Positive Balance* between benefit and risk. Studies in India (Sharma *et al.*, 2019) [17] on tomato irrigated with sugar mill effluent similar to Kenana found Fe 95 and Zn 38 mg/kg DW with Cd only 0.32 (TF Fe 0.18, TF Cd 0.11) and HI 0.38 safe, providing 20% of child RDA Fe. In Egypt (Elbagir *et al.*, 2021) [4] okra irrigated with wastewater contained Zn 35 mg/kg with HI 0.52 safe. In Ethiopia (Gebrekidan *et al.*, 2022) [8] same result: fruit vegetables safe even in contaminated DR water. Despite importance of Kenana, no single study in Sudan evaluated the balance between nutritious and contaminant in same crop and same water after 2022 [14] expansion. Previous studies (Ahmed *et al.*, 2018; Elhassan *et al.*, 2020) [1, 5] focused only on pollution (Cd, Pb) in root and leafy vegetables, did not study nutritional benefit (Fe, Zn) nor compare fruit vegetables as solution. According to SSMO 2023, Sudanese standard allows fruit vegetables in reuse water if HI <1 even if Cd

exceeds, but no data exists to apply it in Kenana. Therefore this study aims to fill the gap: evaluate quality of tomato and okra irrigated with Kenana three waters (MC, BC, DR) via balancing biofortification with Fe, Zn (benefit) versus Cd, Cr accumulation (risk), calculate Benefit-Risk Ratio (BRR), and provide sustainable cropping model that converts DR water from problem to opportunity to combat anemia in White Nile.

Materials and Methods

1. Study Area

Kenana Sugar Scheme (KSS) is located in White Nile State, Sudan (13°45'N, 32°45'E), 250 km south of Khartoum. The scheme covers 110,000 feddan (46,200 ha) and produces 450,000 tons sugar annually. Three irrigation water sources were selected:

- **Main Canal (MC):** Fresh Nile water, control, located at Kilo 0, EC 0.45 dS/m
- **Branch Canal (BC):** Mixed water (70% MC + 30% drainage), Kilo 25, EC 1.2 dS/m - *Drainage Reuse (DR):* 100% treated industrial effluent, 0-500 m from factory outfall, EC 2.8 dS/m, pH 7.8

Climate: semi-arid, mean temp 32°C, rainfall 150 mm/year,

Soil: Vertisols (clay 60%), pH 7.9, OM 0.8%.

2. Experimental Design

Randomized Complete Block Design (RCBD) with 3 water treatments × 2 crops × 4 replications = 24 plots. Each plot 4m × 5m = 20 m², with 1m buffer.

- Tomato (*Solanum lycopersicum*_ L.) cv. Castle Rock - most cultivated in Sudan, 120 days
- Okra (*Abelmoschus esculentus*_ L.) cv. Clemson Spineless - 90 days

Sowing date: 15 November 2024 (winter season), harvest: February-March 2025.

Irrigation: flood irrigation every 10 days, total 12 irrigations, 8000 m³/feddan.

Fertilization: NPK 100:50:50 kg/feddan as per KSS recommendation, no micronutrient fertilizer to avoid interference.

3. Sampling

3.1 Water Sampling

Water samples collected 5 times during season (at planting, vegetative, flowering, fruiting, harvest) from MC, BC, DR. 1L plastic bottles acid-washed, preserved with 2 mL conc. HNO₃ to pH<2, stored at 4°C.

3.2 Soil Sampling

Soil samples collected before planting and after harvest from 0-30 cm depth, 5 cores per plot mixed, air-dried, and sieved 2 mm.

3.3 Plant Sampling

Fruit samples collected at commercial maturity: tomato red stage, okra 6-8 cm length. 10 fruits per plot randomly. Washed: - Unwashed: direct analysis

- **Washed:** tap water 30 sec + distilled water to assess surface contamination

Separated into peel (1 mm) and pulp for distribution analysis. Oven-dried at 70°C for 72h, ground.

4. Analytical Methods 1 .Water Analysis

- **pH:** pH meter (Jenway 3505)
- **EC:** EC meter (Hanna HI9811)
- **Fe, Zn, Cd, Cr:** Atomic Absorption Spectrophotometer (AAS, Shimadzu AA-7000) after filtration 0.45 µm and acid digestion. Detection limits: Fe 0.01, Zn 0.005, Cd 0.001, Cr 0.002 mg/L.

2. Soil Analysis

- pH (1:2.5 soil:water), EC (1:5), OM (Walkley-Black), texture (pipette)
- Total Fe, Zn, Cd, Cr: aqua regia digestion (3:1 HCl:HNO₃) + AAS - DTPA-extractable (bioavailable): Lindsay and Norvell 1978 ^[13] method + AAS

3. Plant Analysis

- **Dry ashing:** 0.5 g plant powder ashed at 550°C 4h, dissolved in 5 mL 2N HCl
- **Fe, Zn, Cd, Cr:** AAS, calibrated with standards (Merck). QA/QC: blank every 10 samples, duplicate 20%, recovery 95-105% using CRM (NIST 1573a tomato leaves).

4. Calculations

TF = C_{plant} (mg/kg DW) / C_{soil} DTPA (mg/kg)

Interpretation: TF <0.2 low, 0.2-0.5 medium, >0.5 high (Rattan *et al.*, 200

Results and Discussion

1. Physico-chemical Properties of Irrigation Water

Water quality significantly differed (p<0.05) among sites. DR water showed highest EC and metals.

Table 1: Water quality (mean ± SD, n=5)

Parameter	MC	BC	DR	WHO Limit (2011)	Status DR
pH	7.2±0.2a	7.5±0.3b	7.8±0.3c	6.5-8.5	Safe
EC dS/m	0.45±0.05a	1.20±0.1b	2.80±0.2c	3.0	Safe
Fe mg/L	0.45±0.05a	1.20±0.1b	3.50±0.3c	5.0	Safe, high beneficial
Zn mg/L	0.90±0.1a	1.80±0.2b	2.80±0.25c	2.0	Slightly exceed, beneficial
Cd mg/L	0.004±0.001a	0.008±0.001b	0.015±0.002c	0.01	Exceed 60%
Cr mg/L	0.020±0.005a	0.045±0.008b	0.080±0.01c	0.05	Exceed 60%

_Different letters significant p<0.05. DR: 3x Fe and Zn vs MC, beneficial but also Cd, Cr polluted._DR water is *dual nature*: rich in Fe, Zn (beneficial for biofortification) but also contaminated with Cd, Cr (risk). Zn 2.8 exceeds WHO 2.0 but still beneficial as micronutrient, not toxic at this level.

2. Soil Contamination

DTPA-extractable (bioavailable) metals in DR soil significantly higher (p<0.01).

Table 2: DTPA-extractable metals in soil 0-30 cm (mg/kg, n=4)

Metal	MC soil	BC soil	DR soil	Background	Cf DR	Status
Fe	12.5±1.2a	18.3±1.5b	3.50±0.3c	15	1.9	Moderate
Zn	1.2±0.2a	2.8±0.3b	5.6±0.5c	1.5	3.7	High beneficial
Cd	0.08±0.02a	0.18±0.03b	0.32±0.04c	0.1	3.0	High pollution
Cr	0.25±0.05a	0.55±0.08b	1.10±0.12c	0.3	3.6	High pollution

_Background = MC soil as baseline. Cf = contamination factor. DR soil enriched 2-3x in all metals vs MC. Fe, Zn beneficial enrichment; Cd, Cr pollution.

3. Metal Accumulation in Tomato and Okra Fruits - Core Result

Table 3: Metal concentration in fruits (mg/kg DW, mean ± SD, n=4) - DR vs MC

Crop-Site	Fe DW	Zn DW	Cd DW	Cr DW	Fe FW	Zn FW	Cd FW	Cr FW	FAO Limit
Tomato DR	110±12c	42±5c	0.32±0.04c	0.45±0.06c	6.60	2.52	0.019	0.027	Cd 0.1, Cr 0.5
Tomato MC	45±5a	18±2a	0.08±0.02a	0.12±0.02a	2.70	1.08	0.005	0.007	Safe
Okra DR	95±10b	38±4b	0.38±0.05c	0.52±0.07c	9.50	3.80	0.038	0.052	Cd 0.1, Cr 0.5
Okra MC	38±4a	15±2a	0.10±0.02a	0.15±0.03a	3.80	1.50	0.010	0.015	Safe
Beetroot DR (prev study)	85	28	2.40	3.20	11.0	3.64	0.31	0.41	Exceed 3x

_FW conversion: tomato 6% DW (94% moisture), okra 10% DW (90% moisture). *_FAO/WHO 2011 limits for fruit veg: Cd 0.1, Cr 0.5 mg/kg FW.

- Soil DTPA Fe vs fruit Fe $r=0.85$ $p<0.01$ positive - biofortification works
- Soil DTPA Cd vs fruit Cd $r=0.42$ $p<0.05$ weak - fruit avoids Cd
- Fe vs Cd in fruit $r=-0.32$ negative (competition) - Fe inhibits Cd uptake via IRT1 competition DR water contains Fe 3.5, Zn 2.8 (beneficial) and Cd 0.015, Cr 0.08 (polluted). Tomato DR accumulated Fe 110, Zn 42 mg/kg DW (2.4x MC) providing 11-15% RDA, with low Cd 0.32 DW (0.019 FW) and Cr 0.45 DW, TF Fe 0.18 vs TF Cd 0.10 (selective), HI 0.093 adult and 0.19 child safe vs beetroot 4.18 unsafe. BRR 61-172 >1 highly positive, proving fruit vegetables achieve positive balance: biofortification with safety, ideal for DR zones.

Our results confirm DR water has dual character: Fe 3.5 mg/L and Zn 2.8 mg/L, 3.2x and 3.1x higher than MC (1.1 and 0.9 mg/L), respectively, due to groundwater Fe and Zn from cane washing (Elhassan *et al.*, 2020) [5]. At same time, Cd 0.015 mg/L exceeds WHO 0.01 by 50% from phosphatic fertilizers, and Cr 0.08 mg/L exceeds WHO 0.05 by 60% from stainless steel equipment corrosion (Ahmed *et al.*, 2018) [1]. This duality is common in sugar effluents worldwide: Gebrekidan *et al.* (2022) [8] Ethiopia found Fe 4.1, Zn 3.2, Cd 0.018, Cr 0.09 mg/L, similar to Kenana. Unlike previous Sudan studies focusing only on pollution (Ahmed *et al.*, 2018) [1], we highlight beneficial aspect: Fe and Zn at these levels are not toxic (WHO limit Fe 5.0 mg/L) but beneficial for biofortification, addressing Fe deficiency anemia affecting 40% children in White Nile (WHO Sudan 2021) [23].

The core finding is selective transfer: TF Fe 0.18 and Zn 0.22 in tomato DR vs TF Cd 0.10 and Cr 0.08 (Table 4). This 2x difference is due to physiological mechanisms: roots sequester Cd and Cr via phytochelatins (PCs) and metallothioneins in vacuoles (Clemens *et al.*, 2013) [3], while ZIP family (ZRT-IRT-like proteins) and IRT1 (Iron-Regulated Transporter 1) actively translocate Fe and Zn to fruits via xylem/phloem (Alloway, 2013) [2]. Competition also plays role: Fe^{2+} competes with Cd^{2+} for IRT1, $r = -0.32$ between Fe and Cd in fruit (negative correlation), so high Fe

in DR water inhibits Cd uptake, as reported by Khan *et al.* (2020) [12].

In contrast, beetroot root directly contacts water, lacks this barrier, and uses NRAMP5 transporter non-selectively, leading to TF Cd 1.22 hyperaccumulator, 12x higher than tomato (0.10). Rattan *et al.* (2005) [16] classified TF >0.5 as high, TF <0.2 as low; our fruit TF 0.08-0.22 confirms low accumulator safe, root TF 1.22 high unsafe. This explains why fruit FW Cd 0.019 mg/kg (safe <0.1) vs root 0.31 mg/kg (3x exceed).

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

References

1. Ahmed ME, Elhag AM, Hassan AB. Assessment of heavy metals in sugar industry effluent of Kenana Sugar Scheme, Sudan. *Journal of Environmental Science and Technology*, 2018;11(3):145-153.
2. Alloway BJ. Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability (3rd ed.). Springer, 2013. <https://doi.org/10.1007/978-94-007-4470-7>
3. Clemens S, Aarts MGM, Thomine S, Verbruggen N. Plant science: The key to preventing slow cadmium poisoning. *Trends in Plant Science*, 2013;18(2):92-99. <https://doi.org/10.1016/j.tplants.2012.08.003>

4. Elbagir HM, Hassan MK, Ibrahim S. Accumulation of heavy metals in okra irrigated with wastewater in Egypt: Food safety and nutritional quality. *Food Chemistry*,2021;345:128734. <https://doi.org/10.1016/j.foodchem.2020.128734>
5. Elhassan AM, Osman AK, Mohammed HI. Groundwater geochemistry and iron enrichment in Kenana area, White Nile State, Sudan. *Sudanese Journal of Agricultural Sciences*,2020;21(2):88-97.
6. FAO. Biofortification: A food systems solution. Food and Agriculture Organization, 2020. <https://www.fao.org/documents/card/en/c/CB2001EN/>
7. FAO/WHO. Codex Alimentarius: General standard for contaminants and toxins in food and feed (CODEX STAN 193-1995). FAO, 2011.
8. Gebrekidan A, Gebresellasie T, Ambelu A. Heavy metals in sugar factory effluent and irrigated vegetables in Wonji, Ethiopia: Health risk assessment. *Environmental Monitoring and Assessment*,2022;194(5):321. <https://doi.org/10.1007/s10661-022-09987-4>
9. HarvestPlus. Biofortification progress brief: Iron and zinc crops. International Food Policy Research Institute, 2022.
10. Kabata-Pendias A. Trace elements in soils and plants (4th ed.). CRC Press, 2011.
11. Khan MA, Khan S, Khan A, Alam M. Soil contamination with cadmium, consequences and remediation using organic amendments. *Science of the Total Environment*,2017;601:1591-1605. <https://doi.org/10.1016/j.scitotenv.2017.06.030>
12. Khan ZI, Ahmad K, Ashraf M. Iron-cadmium interaction and its effect on biofortification and toxicity in vegetables. *Journal of Plant Nutrition*,2020;43(12):1789-1802. <https://doi.org/10.1080/01904167.2020.1750645>
13. Lindsay WL, Norvell WA. Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal*,1978;42(3):421-428. <https://doi.org/10.2136/sssaj1978.03615995004200030009x>
14. Ministry of Irrigation and Water Resources, Sudan. Kenana Sugar Scheme expansion and drainage reuse report 2022-2023. Khartoum, 2023.
15. Muchuweti M, Birkett JW, Chinyanga E, Zvauya R, Scrimshaw MD, Lester JN. Heavy metal content of vegetables irrigated with mixtures of wastewater and sewage sludge in Zimbabwe. *Agriculture, Ecosystems & Environment*,2006;112(1):41-48. <https://doi.org/10.1016/j.agee.2005.04.028>
16. Rattan RK, Datta SP, Chhonkar PK, Suribabu K, Singh AK. Long-term impact of irrigation with sewage effluents on heavy metal content in soils, crops and groundwater. *Agriculture, Ecosystems & Environment*,2005;109(3-4):310-322. <https://doi.org/10.1016/j.agee.2005.02.025>
17. Sharma S, Nagpal AK, Kaur I. Heavy metal contamination in soil and vegetables irrigated with sugar mill effluent and health risk assessment. *Environmental Monitoring and Assessment*,2019;191(6):364. <https://doi.org/10.1007/s10661-019-7511-5>
18. Singh A, Sharma RK, Agrawal M, Marshall FM. Risk assessment of heavy metal toxicity through contaminated vegetables from waste water irrigated area of Varanasi, India. *Tropical Ecology*,2010;51(2S):375-387.
19. Singh S, Yadav R, Singh A. Selective uptake and translocation of heavy metals in fruit vegetables irrigated with wastewater: Implications for food safety. *Scientia Horticulturae*,2021;285:110165. <https://doi.org/10.1016/j.scienta.2021.110165>
20. SSMO. Sudanese standard for reuse of treated industrial wastewater in agriculture No. 184/2023. Sudanese Standards and Metrology Organization, Khartoum, 2023.
21. USEPA. Integrated Risk Information System (IRIS): Reference doses for cadmium and chromium. U.S. Environmental Protection Agency, 2022.
22. WHO. Guidelines for drinking-water quality (4th ed.). World Health Organization, 2011.
23. WHO. Sudan nutrition survey 2021: Prevalence of anemia and zinc deficiency in White Nile State. WHO Sudan Office, 2021.
24. WHO/FAO. Recommended dietary allowances (RDA) for iron and zinc. World Health Organization, 2021.