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Assessment of soil and crop contamination along El-Qalyubia Drain, Egypt, based on contamination indices

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Abstract

Purpose – This study aims to investigate the spatial distribution and seasonal dynamics of toxic metals in water, soil and edible crops cultivated near the El-Qalyubia Drain, Egypt. Where irrigation sources may include reused agricultural drainage water. It aims to identify contamination hotspots, assess ecological risks and evaluate the food safety implications of drainage water reuse.

Design/methodology/approach – Soil, drainage water and edible plant samples were collected from eight sites during summer and winter. Ecological risks were evaluated using the contamination factor, ecological risk factor, potential ecological risk index and pollution load index. Crop contamination was assessed in accordance with the Codex Alimentarius maximum permissible limits for food safety.

Findings – Drainage water met Egyptian standards; however, certain soils and crops exhibited elevated contamination, particularly with copper, manganese, cadmium and lead. Wheat, turnip and molokheya frequently exceeded Codex limits for cadmium and lead. Copper enrichment was most pronounced in winter ($Cf > 40$). The ecological risk index indicated low risk in summer ($RI = 33.38$) but moderate in winter ($RI = 173.42$).

Research limitations/implications – The study covered one major drain and two seasons, limiting extrapolation to other systems or longer timescales. Broader multi-drain and multi-year studies across diverse agro-ecological zones are needed to strengthen generalizability.

Practical implications – Findings underscore the need for soil remediation, crop monitoring and regulatory control to restrict high-accumulating crops in contaminated areas.

Originality/value – This is the first integrated, seasonally resolved assessment linking water, soil and crop contamination, revealing inconsistencies between water quality standards and actual food safety outcomes in reuse-based agriculture.

Keywords Contamination factor, Ecological risk index, Food safety, Heavy metals, Nile Delta, Reuse of drainage water in Egypt

Paper type Research article

1. Introduction

Soil and water are essential to agricultural sustainability, yet they are increasingly threatened by industrial activity, water contamination, and poor waste management practices. One major

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challenge in arid and semi-arid regions is the use of untreated or inadequately treated wastewater for irrigation, driven by chronic water scarcity. While this practice offers short-term agricultural benefits, such as improved soil moisture and increased crop yield under water scarcity, it introduces a mix of physical, chemical, and biological pollutants into soils, altering their structure and threatening long-term productivity (Abd El-Aziz, El-Ghannam, Amin, & Abd El-Al, 2025; Jabbarov *et al.*, 2025).

Agricultural drainage canals often serve as conduits for these pollutants, particularly toxic metals that bioaccumulate and biomagnify in living systems, causing significant ecological and health risks (Soliman, Abdullah, & El-Sherpiny, 2024; Jabbarov *et al.*, 2025). Their presence in soil is typically linked to industrial effluents, urban runoff, agrochemical residues, and untreated domestic wastewater, which are frequently discharged into drains (Adnan *et al.*, 2024; Soliman *et al.*, 2024). Over time, repeated irrigation with such contaminated waters elevates metal concentrations in soils and increases the likelihood of plant uptake, threatening food safety (World Bank, 2024; Wang *et al.*, 2025).

In addition to anthropogenic inputs, natural geogenic processes also contribute to background metal concentrations. These include volcanic activity, dust deposition, and the weathering of mineral-rich rocks, which naturally release trace elements into soils. Such sources must be differentiated from human-induced enrichment to accurately interpret contamination patterns (Adewumi & Ogundele, 2024; Xiao *et al.*, 2024). Natural geogenic processes also contribute, such as volcanic activity, dust deposition, and weathering of mineral-rich rocks (Wan, Liu, Zhuang, Wang, & Li, 2024). In Egypt, a prime example is the El-Qalyubia Drain, which spans El-Qalyubia and El-Sharkiya governorates. It receives mixed industrial and domestic wastewater that is subsequently reused for irrigation due to freshwater scarcity in the Nile Delta (Abd El-Aziz *et al.*, 2025). While this supports agriculture, it poses significant ecological risks, including soil contamination and crop pollution.

Toxic metals in soil disrupt microbial processes, reduce fertility, and exert phytotoxic effects. Their accumulation in edible plant tissues leads to biomagnification across trophic levels, with eventual impacts on animals and humans. Chronic exposure to elevated levels has been linked to renal dysfunction, neurological disorders, and carcinogenesis (Aboukila, 2022). A recent study on the Bahr El-Baqar drain reported hazard index values of 8.8 for adults and 7.5 for children, well above safety thresholds, illustrating the risks of using untreated drainage water in agriculture (Romeh, Negm, & Elhelbawy, 2025). These findings underscore the potential for comparable health and ecological risks in other major drainage systems of the Nile Delta, including the El-Qalyubia Drain, where mixed industrial and domestic discharges are similarly reused for irrigation.

To assess such risks, researchers employ standardized indices that account for both contamination levels and toxicity. These include the Contamination Factor (Cf_i), Ecological Risk Factor (Er_i), Potential Ecological Risk Index (RI), Pollution Load Index (PLI), and Bioconcentration Factor (BCF), which collectively enable hotspot detection and ecological and health risk estimation (Rostami, Kamani, Shahsavani, & Hoseini, 2021).

This study investigates the seasonal and spatial variability of potentially toxic metals (Fe, Mn, Cd, Co, Zn, Cu, Pb, Ni, and Cr) in soils, drainage water, and edible crops around the El-Qalyubia Drain. It applies multiple indices, Cf_i, Er_i, RI, and PLI, to evaluate contamination patterns and associated risks. The research represents the first seasonally resolved, multi-matrix investigation along this major drain, integrating water, soil, and crop data. Unlike earlier studies that focused only on individual media or regulatory water compliance, this holistic approach identifies critical mismatches between permissible water quality and actual food safety and ecological hazards. The outcomes provide a robust basis for site-specific interventions aimed at managing pollution hotspots and safeguarding environmental and human health in wastewater-irrigated agriculture of the Nile Delta.

2. Materials and methods

This study represents the first seasonally resolved, multi-matrix investigation along this major drain, integrating water, soil, and crop data. Unlike earlier studies that focused on single environmental media or relied solely on regulatory water compliance, this approach combines contamination and ecological risk indices to reveal inter-matrix relationships and identify pollution hotspots more effectively.

2.1 Study area

The investigation was conducted along the El-Qalyubia Drain, the longest drainage canal in Egypt, extending over 72 km across El-Qalyubia and El-Sharkiya governorates. Eight representative sampling sites were selected along a 47 km section of the drain (30.259017°–30.482531° N; 31.147517°–31.350109° E). The 47 km segment was selected because it encompasses the most agriculturally active portion of the El-Qalyubia Drain, where drainage water is most frequently reused for irrigation and where upstream-to-downstream variation in contamination intensity is most pronounced. At each site, soil samples were collected within 100 m of the main canal, with three replicates per site to ensure reliability. Edible plant samples were simultaneously collected from the same locations to directly compare environmental contamination with crop uptake. The overall workflow consisted of field sampling (water, soil, and plants), laboratory analyses for toxic metals, and application of multiple ecological risk indices (Contamination Factor (Cf), Ecological Risk Factor (Er_i), Potential Ecological Risk Index (RI), and Pollution Load Index (PLI)) for comprehensive assessment.

2.2 Water sampling and analytical procedures

Irrigation water samples were collected from eight predefined stations along the El-Qalyubia Drain during the summer of 2023 and the winter of 2024. At each site, three replicate samples were obtained using pre-cleaned 100 mL high-density polyethylene (HDPE) containers. The pH was measured promptly in the field with portable sensors (WTWMulti 350i multimeter). Analytical procedures for metal parameters were performed as per standardized APHA (2017) protocols. To preserve metal integrity and prevent surface adsorption of ions onto container walls, 1 mL of concentrated nitric acid (HNO_3) was added to each sample immediately post-collection. Separate sets of samples were designated for different analyses: acidified samples were preserved for trace metal determination, while non-acidified samples were retained for complementary water quality parameters, such as pH, all in sterilized HDPE bottles. All samples were stored in insulated iceboxes at 4 ± 1 °C until they were analyzed in the laboratory. All metal measurements were carried out using an ICP-OES instrument (Agilent 5,110, Agilent Technologies, USA).

2.3 Soil sampling and analytical procedures

Surface soil (0–30 cm) was collected using a stainless-steel auger and stored in labeled polyethylene bags. In the laboratory, samples were air-dried, homogenized, and sieved (<0.2 mm). Available fractions of Fe, Mn, Cd, Cr, Co, Zn, Cu, Pb, and Ni were determined using the DTPA extraction method (Soltanpour & Schwab, 1991), which is widely applied for estimating plant-available metals (Lei, Liao, Zeng, Qin, & Khan, 2008).

2.4 Plant sampling and analytical procedures

Representative edible plant parts were harvested at all sites during both seasons: leaves (leafy vegetables), grains/seeds (cereals), bulbs (onion/garlic), and roots (turnip). Samples were washed thoroughly with tap water and rinsed with deionized water to remove soil residues. Plant tissues were oven-dried at 70 °C until constant weight, ground into fine powder, and digested (0.5 g) with H_2SO_4–$HClO_4$ The digestion procedure followed the protocols of Jones (2001) for plant nutrient analysis, while sample preparation and chemical extraction were adapted from the classical methods described by Jackson (2005) to ensure consistency with standard agronomic practices. The digests were analyzed for heavy metals using ICP-OES.

2.5 Contamination and risk assessment indices

2.5.1 Contamination factor (Cf_i). Contamination factor (Cf_i) is a standard index used to quantify the concentration of metal in the soil compared to the natural concentration of this metal in the soil. It is computed from Equation (1):

$$\mathbf{Cf_i = Cf_i / C_{ri}} \tag{1}$$

Where

(1) C_i = Measured concentration of metal *i* in the soil sample (mg/kg)

(2) C_{ri} = Reference/background concentration of metal *i* in the soil (mg/kg)

Håkanson (1980) stressed that background values for heavy metals should reflect pre-industrial conditions of the specific study area, rather than relying on universal values. Researchers use different references for these values, such as national standards, global average shale, or average crustal concentrations. Egypt, however, has no established national baseline for heavy metals in soils. Because the Nile Valley and Delta have long been influenced by human activities, their soils cannot be considered pristine. Moreover, their alluvial origins differ from the rock-derived soils found elsewhere in Egypt. In the absence of national guidelines, heavy metal concentrations in Egyptian soils are usually assessed against international references, including global soil averages and European Union limits for agricultural soils (Khalifa & Gad, 2018). The background concentrations adopted from Alloway (2013) were selected because they represent globally accepted average values for agricultural soils and are commonly used in Egyptian and regional studies in the absence of national baselines, allowing for cross-study comparability as follows: Fe (5.00), Mn (1.00), Zn (1.50), Cu (0.05), Cd (0.50), Co (0.01), Pb (1.00), Ni (5.00), and Cr (0.01) mg/kg.

The Cf_i index provides insights into the anthropogenic influence on soil metal content. It enables site-specific risk evaluation by revealing deviations from natural geochemical baselines shaped by geological and atmospheric inputs. *Interpretation of Contamination Factor (Cf_i) values* (Wang, Deng, Yin, & Tang, 2018).

(1) $Cf_i < 1 \rightarrow$ Low or no contamination

(2) $1 \le Cf_i < 3 \rightarrow$ Moderate contamination

(3) $3 \le Cf_i < 6 \rightarrow$ Considerable contamination

(4) $Cf_i \ge 6 \rightarrow$ Very high contamination

2.5.2 Ecological risk factor (Er_i). Er_i is the ratio of a predicted or measured environmental concentration of a metal to its ecologically safe level. It is given by Equation (2):

$$\mathbf{Er_i = Tr_i \times Cf_i} \tag{2}$$

Where.

(1) Tr_i = Toxicity response factor for metal *i*

(2) Cf_i = Contamination factor of metal *i*

Toxicity factors (Tr_i) were adopted from Liu, Wang, Yu, Gao, and Xu (2021): Fe (1), Mn (1), Zn (1), Cu (5), Cd (30), Co (5), Pb (5), Ni (5), and Cr (2).

Higher Er_i values represent more ecologically toxic metals. Cadmium, for example, is 30 times more toxic to the environment than zinc. *Thresholds for interpreting Ecological Risk Factor (Er_i)* (Miranzadeh Mahabadi, Ramroudi, Asgharipour, Rahmani, & Afyuni, 2020; Rostami *et al*., 2021).

(1) $Er_i < 40 \rightarrow$ Low ecological risk

(2) $40 \leq Er_i < 80 \rightarrow$ Moderate ecological risk

(3) $80 \leq Er_i < 160 \rightarrow$ Considerable ecological risk

(4) $160 \leq Er_i < 320 \rightarrow$ High ecological risk

2.5.3 Potential ecological risk index (RI). For cumulative ecological risk estimation, the potential ecological risk index (RI) adds up the individual ecological risk factors of all the metals in question (Equation 3):

$$RI = \sum Er_i \tag{3}$$

This index enables a comprehensive assessment of the cumulative ecological load. *Risk classification based on the Potential Ecological Risk Index (RI)* (Håkanson, 1980).

(1) $RI < 150 \rightarrow$ Low ecological risk

(2) $150 \leq RI < 300 \rightarrow$ Moderate ecological risk

(3) $300 \leq RI < 600 \rightarrow$ Considerable ecological risk

(4) $RI \geq 600 \rightarrow$ Very high ecological risk

2.5.4 Pollution Load Index (PLI). Pollution Load Index (PLI) is a composite index to estimate the overall level of heavy metal pollution in the soil (Equation 4):

$$\mathbf{PLI} = (\mathbf{Cf_1} \times \mathbf{Cf_2} \times \ldots \times \mathbf{Cf_n})\hat{}(\mathbf{1}/\mathbf{n}) \tag{4}$$

Where n is the number of metals analyzed. PLI is a brief measure of overall contamination. *Classification of Pollution Load Index (PLI) values* (Lu, Wang, Lei, Huang, & Zhai, 2009).

(1) $PLI = 0 \rightarrow$ No pollution

(2) $0 < PLI \leq 1 \rightarrow$ Low or background level

(3) $1 < PLI \leq 2 \rightarrow$ Moderate pollution

(4) $2 < PLI \leq 3 \rightarrow$ High pollution

(5) $PLI > 3 \rightarrow$ Very high pollution

2.5.5 Statistical analysis. Data were statistically analyzed using SAS 13.1 software (SAS Institute, 2013). Analysis of variance (ANOVA) was conducted via the General Linear Model (PROC GLM). Mean differences were evaluated using the Student-Newman-Keuls (SNK) test, with significance accepted at $p < 0.05$. The Student–Newman–Keuls (SNK) test was selected as the post hoc procedure due to its suitability for detecting pairwise differences among multiple treatments while balancing Type I error control and statistical power in environmental data with moderate replication.

3. Results

3.1 Available micronutrients and toxic metals in the El-Qalyubia drain

Water samples collected from eight monitoring stations during summer and winter were analyzed for pH and the concentrations of micronutrients and potentially toxic metals, including Cu, Fe, Mn, Zn, Co, Pb, Cd, Ni, and Cr (Table 1).

pH values ranged from 7.70 to 7.99 across all sites and seasons, remaining within the Egyptian legal standard (6.5–8.5). These slightly alkaline conditions favor the mobility of metals in drainage waters. Among the analyzed elements, Fe recorded the highest concentrations, peaking at 0.846 and 0.981 at the summer and winter seasons mg/L at Sites 1, though still below the permissible limit of 3 mg/L. Mn showed a similar pattern, with a maximum of 0.825 and 0.908 mg/L at the same site, under the limit of 2 mg/L. Zn varied across stations, reaching 0.221 and 0.392 mg/L at Site 2, which is well below the allowable 2 mg/L threshold.

Cu was consistently detected at low levels (0.006–0.092 mg/L), significantly under the 1 mg/L limit. Cd was only detected at Site 4 in winter (0.002 mg/L), remaining below the standard of 0.03 mg/L. Pb, Ni, Co, and Cr were either absent or present at trace levels, with measurable concentrations only at Site 4 in winter: 0.007 mg/L Pb, 0.003 mg/L Ni, and 0.002 mg/L Cr.

The seasonal differences in metal concentrations along El-Qalyubia Drain can be understood as the outcome of several opposing processes that operate at the same time. In winter, farmers apply far smaller quantities of fertilizers, which would normally suggest lower

Table 1. Metals of El-Qalyubia drain, during the summer and winter seasons

Site	pH	Cu	Fe	Mn	Zn	Cd	Co	Pb	Ni	Cr
	Summer season									
1	7.80	0.053	0.846	0.825	0.042	Nd*	Nd	Nd	Nd	Nd
2	7.70	0.013	0.789	0.479	0.221	Nd	Nd	Nd	Nd	Nd
3	7.80	0.048	0.743	0.458	0.207	Nd	Nd	Nd	Nd	Nd
4	7.90	0.034	0.553	0.360	0.108	Nd	Nd	Nd	Nd	Nd
5	7.80	0.013	0.719	0.179	0.007	Nd	Nd	Nd	Nd	Nd
6	7.80	0.011	0.684	0.305	0.008	Nd	Nd	Nd	Nd	Nd
7	7.80	0.080	0.641	0.306	0.006	Nd	Nd	Nd	Nd	Nd
8	7.90	0.006	0.404	0.228	Nd	Nd	Nd	Nd	Nd	Nd
*Limit**	*6.5–8.5*	*1*	*3*	*2*	*2*	*0.03*	-	*0.1*	*0.1*	-

Site	pH	Cu	Fe	Mn	Zn	Cd	Co	Pb	Ni	Cr
	Winter season									
1	7.99	0.074	0.981	0.908	0.134	Nd	Nd	Nd	Nd	Nd
2	7.80	0.043	0.865	0.604	0.392	Nd	Nd	Nd	Nd	Nd
3	7.87	0.068	0.923	0.694	0.403	Nd	Nd	Nd	Nd	Nd
4	7.80	0.056	0.693	0.591	0.316	0.002	Nd	0.007	0.003	0.002
5	7.83	0.033	0.689	0.299	0.294	Nd	Nd	Nd	Nd	Nd
6	7.90	0.031	0.899	0.579	0.209	Nd	Nd	Nd	Nd	Nd
7	7.79	0.092	0.905	0.569	0.118	Nd	Nd	Nd	Nd	Nd
8	7.86	0.029	0.404	0.465	Nd	Nd	Nd	Nd	Nd	Nd
*Limit**	*6.5–8.5*	*1*	*3*	*2*	*2*	*0.03*	-	*0.1*	*0.1*	-

Note(s): *Limit according to Egyptian Ministerial Decree No. 92 of 2013 amending the Ministerial Decree No. 8 of 1982 on the executive Regulations of Law No. 48 of 1982 concerning the Protection of the Nile River and water channels from pollution

Nd** = not detectable. The detection limits are Fe (0.01 mg/L), Mn (0.002 mg/L), Zn (0.002 mg/L), Cu (0.001 mg/L), Cd (0.0005 mg/L), Co (0.0005 mg/L), Pb (0.001 mg/L), Ni (0.001 mg/L), Cr (0.0005 mg/L)

All values represent the average of three replicates metal inputs from agricultural fields. However, winter crops such as *wheat and alfalfa* also consume much less irrigation water than summer crops like *rice and corn*, and this directly reduces the amount of drainage water reaching the canal. With a lower discharge, the drain's ability to dilute incoming contaminants declines noticeably (Chapman & Kimstach, 1996), so even limited metal inputs may result in higher measured concentrations. In summer, the situation is reversed: high evaporation rates tend to concentrate dissolved constituents, but this effect is moderated by the larger volumes of irrigation water and the greater return flows associated with summer cultivation. As a result, the seasonal pattern of metal concentrations reflects a balance between reduced contaminant loading but limited dilution in winter, and increased inputs but higher dilution capacity in summer (Hassan, Ferdoushi, Rana, & Alam, 2024; Shetaia *et al.*, 2025).

Despite these seasonal fluctuations, all concentrations complied with Egyptian Regulation No. 92 (2013), which governs Nile water protection (Egyptian Ministry of Water Resources and Irrigation, 2013). Overall, while metal levels in the El-Qalyubia Drain remain within national safety limits, this underscores the importance of continuous monitoring to ensure safe reuse of drainage water in irrigation and to prevent long-term ecological and health risks.

3.2 Contamination factor (Cf_i)

The contamination factor (CF) values of heavy metals were analyzed across eight sampling stations along the El-Qalyubia Drain during both summer and winter to evaluate pollution levels (Figure 1). Iron (Fe) consistently showed CF values above 3 at all locations, with a maximum of 4.42 at Site 8 in summer, indicating considerable contamination linked to industrial effluents or agricultural inputs.

Manganese (Mn) presented the most critical results, recording very high contamination ($CF \geq 6$) at several sites. Values ranged from 7.31 to 9.79 in summer at Sites 2, 6, 7, and 8, suggesting fertilizer leaching and enhanced solubility under slightly alkaline conditions.

Zinc (Zn) generally exhibited moderate contamination (CF = 1.03–1.37), though Site 4 in winter showed a marked increase (CF = 3.87), shifting it into the considerable contamination category.

Copper (Cu) displayed pronounced seasonal variation: while moderate during summer, winter values surged dramatically, with Site 4 reaching CF = 41.32. Such very high levels point to intense localized anthropogenic input, likely from industrial discharges or other point sources.

Cadmium (Cd), though found at lower concentrations, still presented ecological risks. At Site 4 in summer, CF reached 1.02, close to moderate contamination, while most other sites remained in low to moderate ranges.

Cobalt (Co) was generally low but registered moderate levels in summer at Sites 1 and 6 (CF up to 1.19), before declining in winter. Lead (Pb) contamination was moderate at Site 1 in summer (CF = 2.16) but sharply increased at Site 8 in winter (CF = 7.01), classifying it as very high contamination and raising localized concern.

Nickel (Ni) and Chromium (Cr) both remained at low levels throughout, with CF ranges of 0.21–0.63 and 0.02–0.13, respectively, indicating little or no contamination.

A general classification of sites confirmed that all locations fell under **"very high contamination"**, as at least one metal exceeded the CF threshold of 6 (Wang *et al.*, 2018). Copper dominated winter contamination across all sites (CF 19.91–41.32), followed by Mn. Additional risks were evident at Site 8 due to Pb enrichment. Sites 4, 6, and 8 were designated as contamination hotspots based on two combined criteria: (1) at least one metal exhibiting $Cf \geq 6$ (very high contamination) during both seasons, and (2) co-occurrence of multiple metals classified within moderate to high contamination ranges ($1 \leq Cf < 6$). These combined indicators reflect cumulative multi-metal enrichment and justify prioritizing these sites for targeted management.

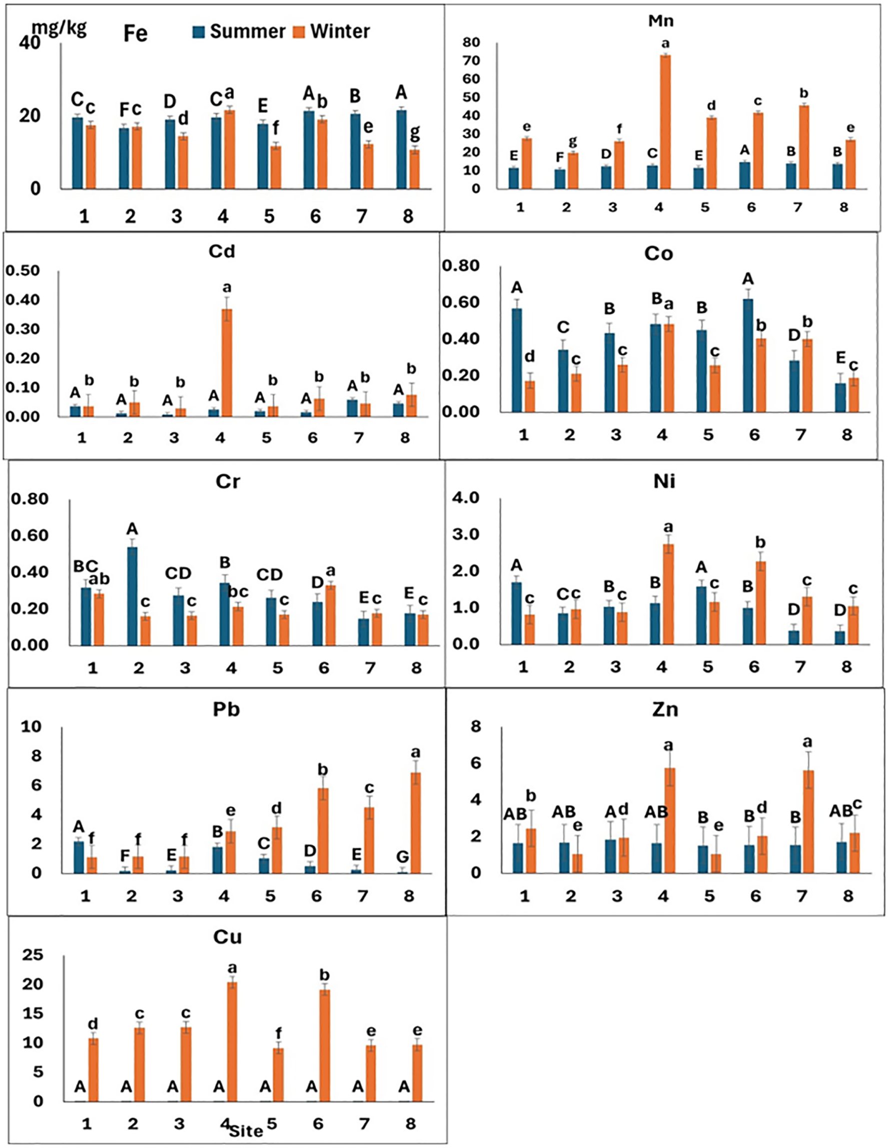

Figure 1. Contamination factor (CF) values across sampling sites during the summer and winter seasons, expressed as mean ± standard deviation. Different letters above the columns indicate statistically significant differences between values at the 0.05 significance level

3.3 Ecological risk factor (Er_i)

Table 2 shows the ecological risk factor (Er) values for different heavy metals at each location along the El-Qalyubia Drain in the summer and winter seasons. These values can be used to evaluate the possible ecological risk of a single metal in soil or sediment. Based on the adopted classification criteria of Er.

In summer, all Er values of the monitored metals were well less than 40, indicating low ecological hazard at all locations. Even normally hazardous metals such as Cd, Pb, and Cu were within tolerable limits during this period. The highest Er for Cu (10.00) was at Sites 5 and 6 and for Cd (2.35) at Site 1. These values, although considerable, are still in the low-risk category and represent a low ecological impact in summer.

The ecological risk values during winter were substantially higher for Cu across all sampling sites, whereas Mn posed an elevated risk only at one site, with the other metals being all less than 40 and therefore having very low ecological risk in all areas.

Site 4 recorded the most problematic results, with Cu (206.80) recording levels that were characteristic of high ecological risk. Manganese at site 4 had a score Er = 48.84, which represented moderate risk.

3.4 Potential ecological risk index (RI)

The Potential Ecological Risk Index (RI) offers a comprehensive assessment of the combined ecological threat posed by multiple heavy metals at each sampling site. The results in Table 3 show clear seasonal variations and spatial disparities in ecological risk levels across the El-Qalyubia Drain system.

During the summer season, all investigated stations recorded RI values below 40, which, according to established classification criteria, falls within the "low ecological risk" range. The highest RI in summer was recorded at Station 1 (RI = 39.15), followed closely by Stations 6 and 5, while Station 8 recorded the lowest RI (27.64). This general low-risk profile suggests

Table 2. Ecological risk factor (Er) for the investigated locations

Sites	Er Fe	Mn	Zn	Cu	Cd	Co	Pb	Ni	Cr
Summer season									
1	3.91 B	7.64 G	1.17 B	7.96 C	2.35 A	5.70 B	8.55 A	1.70 A	0.08 B
2	3.36 C	7.03 H	1.11 B	8.96 B	0.01 E	3.20 E	4.30 E	0.85 E	0.14 A
3	3.81 B	8.31 E	1.25 A	7.94 C	0.63 D	4.50 D	5.20 D	1.05 C	0.06 B
4	3.93 B	8.57 D	1.13 B	7.01 D	0.73 D	4.80 C	5.55 C	1.10 C	0.08 B
5	3.56 C	7.79 F	1.05 B	10.00 A	1.80 B	4.70 C	7.40 B	1.50 B	0.08 B
6	4.28 A	9.83 A	1.09 B	10.00 A	1.23 C	6.30 A	5.05 D	1.00 D	0.06 B
7	4.11 A	9.31 B	1.03 B	9.00 B	0.53 D	3.10 E	1.55 G	0.30 G	0.04 C
8	4.33 A	9.11 C	1.11 B	7.95 C	1.37 C	1.70 F	1.80 F	0.35 F	0.04 C
Aver	*3.91*	*7.64*	*1.17*	*8.00*	*2.40*	*5.70*	*8.55*	*1.70*	*0.08*
Winter Season									
1	3.39 c	17.92 f	1.62 c	107.40 e	1.77 c	1.79 d	8.55 a	0.85 c	0.06 ab
2	3.47 c	13.24 h	0.71 f	126.00 d	1.14 e	2.25 cd	4.30 e	0.96 c	0.04 b
3	2.90 d	17.88 g	1.33 e	127.60 c	1.77 c	2.27 cd	5.20 d	1.00 c	0.04 b
4	4.36 a	48.84 a	3.88 a	206.80 a	6.00 a	5.20 a	5.55 c	3.00 a	0.06 ab
5	2.39 e	26.08 d	0.71 f	94.10 h	1.20 d	2.69 c	7.40 b	1.15 c	0.04 b
6	3.84 b	27.84 c	1.33 e	193.20 b	4.82 b	4.00 b	5.05 d	2.35 b	0.08 a
7	2.47 e	30.52 b	3.75 b	96.60 g	1.22 d	3.92 b	1.55 g	1.00 c	0.06 ab
8	2.15 e	18.07 e	1.43 d	99.90 f	1.77 c	2.07 d	1.80 f	1.05 c	0.04 b
Aver	*3.39*	*27.31*	*2.02*	*143.94*	*2.70*	*3.34*	*5.15*	*1.56*	*0.06*

Note(s): Within columns, values followed by different letters are significantly different at $\alpha = 0.05$

Table 3. Potential ecological risk index (RI) for the investigated locations

Sites	Summer season RI value	Overall ecological risk level	Winter season RI value	Overall ecological risk level
1	39.15 A	Low ecological risk	143.39 e	Low ecological risk
2	28.99 AB	Low ecological risk	152.26 d	Moderate ecological risk
3	32.78 AB	Low ecological risk	160.35 c	Moderate ecological risk
4	32.76 AB	Low ecological risk	283.69 a	Moderate ecological risk
5	37.88 B	Low ecological risk	135.77 g	Low ecological risk
6	38.81 A	Low ecological risk	242.49 b	Moderate ecological risk
7	29.04 AB	Low ecological risk	141.03 f	Low ecological risk
8	27.64 AB	Low ecological risk	128.34 h	Low ecological risk
Average	*33.38*	*Low ecological risk*	*173.42*	*Moderate ecological risk*

Note(s): Within columns, values followed by different letters are significantly different at $\alpha = 0.05$

that summer metal pollution is likely to be decreased through increased dilution and sedimentation rates due to increased water flow.

In contrast, the winter season showed a more heterogeneous pattern of risk. While Site 4 exhibited the highest RI value (283.69), revealing a moderate degree of toxic metal accumulation. The elevated Cu risks observed at Site 4 are likely linked to industrial discharges and small-scale metal workshops in the surrounding area. There existed other sites (Sites 2, 3, and 6) with high RI values ranging from 152 to 242, which qualified them as "moderate ecological risk" zones.

Despite these peaks, Sites 1, 5, 7, and 8 had low ecological risk even in winter. The mean value of RI across all sites shifted from 33.38 in summer (low risk) to 173.42 in winter, which places the system as a whole under moderate ecological stress during the winter season.

Clear seasonal and spatial differences were observed. Summer values consistently fell within the low-risk category, reflecting reduced metal concentrations associated with higher irrigation return flow, increased water volume. Similar seasonal dilution patterns have been reported for Nile Delta drains, where elevated summer discharge reduces metal accumulation in the water column (Hassan *et al.*, 2024; Shetaia *et al.*, 2025). In contrast, winter RI values increased markedly, driven by higher Cu and Mn contamination, lower hydrological flushing, and greater metal retention in sediments.

These findings emphasize the necessity of seasonal monitoring; specifically winter sampling should be prioritized due to higher ecological vulnerability. Site-specific management actions should be directed at Sites 4 and 6, where ecological risk approaches or exceeds the level at which regulatory action is indicated.

3.5 Pollution Load Index (PLI)

The Pollution Load Index (PLI) provides the collective expression of the overall heavy metal pollution at each station. It is the integrated impact of multiple contaminants compared with the background level. The threshold or baseline is expressed by a PLI value of 1, while values below 1 imply low pollution, and values above 1 reflect multi-metal buildup that may impair soil quality, pose risks to crop uptake, and increase ecological stress.

During summer, all the stations except Station 4 had PLI values below 1, indicating low pollution. The highest summer value was obtained at Station 4 (1.03), which just registered as moderate pollution (Table 4). We clarified that near-threshold values may indicate early-stage contamination trends and could signal the need for enhanced monitoring to prevent future exceedances.

During winter, the level of pollution was raised at various sites. Three sites, Site 4 (1.43), Site 6 (1.68), and Site 7 (1.48), exceeded the threshold point of 1, denoting moderate

Table 4. Pollution load index (PLI) for the investigated locations

Sites	Summer season PLI value	Pollution level	Winter season PLI value	Pollution level
1	0.77 A	Low pollution	0.89 c	Low pollution
2	0.48 F	Low pollution	0.76 g	Low pollution
3	0.54 E	Low pollution	0.91 d	Low pollution
4	1.03 D	Moderate pollution	1.43 a	Moderate pollution
5	0.69 B	Low pollution	0.94 f	Low pollution
6	0.63 C	Low pollution	1.68 b	Moderate pollution
7	0.47 G	Low pollution	1.48 e	Moderate pollution
8	0.41 G	Low pollution	1.00 h	Low pollution
Average	*0.63*	*Low pollution*	*1.14*	*Moderate pollution*

Note(s): Within columns, values followed by different letters are significantly different at $\alpha = 0.05$

contamination. In the meantime, Sites 1, 2, 3, 5, and 8 had PLI values less than 1, although some were close to the boundary threshold (Table 4).

3.6 Seasonal variation of cadmium and lead concentrations in edible plants compared to Codex Alimentarius limits

This sub-section provides the levels of Cadmium (Cd) and Lead (Pb) in edible crops collected from different agricultural fields during summer and winter seasons (Table 5). The results are compared to the Maximum Allowable Limits (MLs) established by the FAO/WHO Codex Alimentarius (CODEX STAN 193–1995) to establish food safety.

Cadmium (Cd) concentration patterns: Cd concentrations in plant material varied by site and season. Exceedances of the Codex MLs were large in the summer season. Cd in maize stalks, for instance, was up to 1.20 mg/kg, much beyond the safety levels recommended. Rice grains in Site 6 contained 0.60 mg/kg of Cd, above the Codex ML of 0.4 mg/kg. Additionally, molokheya leaves and sesame seeds contained Cd concentrations of 0.44 mg/kg and 0.28 mg/kg, respectively, both above their corresponding Codex levels.

Table 5. Cadmium (Cd) and Lead (Pb) concentrations (mg/kg) in edible plants from the study area: Seasonal variation (summer vs. winter) vs. FAO/WHO Codex maximum levels (MLs)

Sites	Summer season Plant	Cd	Limits*	Pb	Limits	Winter season Plant	Cd	Limits	Pb	Limits
1	Maize stalks	1.20	–	6.90	–	Wheat grains	0.30	0.2	6.70	0.2
2	Maize grains	0.06	0.1	0.66	0.2	Onion bulb	0.56	0.1	5.30	0.1
3	Eggplant fruits	0.14	0.05	6.76	0.1	Clover	0.30	–	6.50	–
4	Sesame plant	0.28	0.1	4.38	0.2	Onion bulb	0.60	0.1	5.70	0.1
5	Molokheya leaves	0.44	0.2	6.60	0.3	Wheat grains	0.30	0.2	7.40	0.2
6	Rice grains	0.60	0.4	4.80	0.2	Turnip plant	1.00	0.2	8.3	0.1
7	Maize grains	0.31	0.1	2.80	0.2	Cabbage leaves	0.30	0.2	1.10	0.3
8	Rice grains	0.24	0.4	5.90	0.2	Beans grains	0.30	0.1	5.90	0.2

Note(s): *Maximum allowable limits (Maximum Levels, MLs) for Heavy Metals in Food Crops based on the FAO/WHO Codex Alimentarius (General Standard for Contaminants and Toxins in Food and Feed, CODEX STAN 193–1995). These limits apply to key heavy metals of concern: Lead (Pb), Cadmium (Cd), Arsenic (As), and Mercury (Hg). The FAO/WHO Codex Alimentarius does not set international Maximum Levels (MLs) for Fe, Mn, Zn, Cu, Co, Ni, or Cr in food crops due to scientific, nutritional, and risk-based principles

In the winter seasons, high concentrations of Cd were seen to persist. Turnip contained a concentration of Cd of 1.00 mg/kg, which is five times the safety threshold of 0.2 mg/kg. Onion bulbs at other locations contained Cd concentrations ranging between 0.56 and 0.60 mg/kg, well above the safety threshold of 0.1 mg/kg. Even crops like clover, wheat, cabbage, and beans, commonly consumed in the region, registered Cd concentrations at or above the permissible thresholds.

Lead (Pb) concentration trends: Lead contamination was consistently higher than Codex MLs in all tested plant samples across both seasons. Maize stalks have 6.90 mg/kg of Pb in summer, while eggplant fruits have 6.76 mg/kg, both of which were far more than the general Codex Pb level of 0.1 to 0.3 mg/kg. The same trend was observed in sesame (4.38 mg Pb/kg), molokheya (6.60 mg Pb/kg), and rice grains (4.80:5.90 mg Pb/kg).

In winter, Pb levels were far beyond the safety threshold. Turnip plants were the most contaminated with Pb at 8.30 mg/kg. Other plants, including wheat (7.40 mg/kg), onion (5.70 mg/kg), clover (6.50 mg/kg), and beans (5.90 mg/kg), were also highly contaminated. Even plants with relatively lower values of Pb, like cabbage leaves (1.10 mg/kg), exceeded the Codex ML of 0.3 mg/kg.

Summary of contamination level: None of the edible plants analyzed during the two seasons met complete compliance with the Codex Alimentarius MLs for Cd and Pb. Cd contamination was the highest in root and leafy vegetables during winter, but Pb contamination was elevated throughout the year and in all categories of plants and seasons. The widespread exceedance of Codex levels is suggestive of widespread and systemic contamination in the study area.

4. Discussion

4.1 Soil contamination despite acceptable drain water quality

The observation that heavy metal concentrations in El-Qalyubia Drain water comply with Egyptian standards (Decree No. 92/2013), while soil samples reveal elevated contamination, underscores a major limitation in conventional monitoring. Sole reliance on water quality does not capture the cumulative and long-term risks associated with reusing drainage water for irrigation. This study, together with previous research, highlights several mechanisms driving the observed accumulation.

First, *persistent accumulation from repeated reuse* plays a central role. Even trace concentrations in irrigation water can build up in soils over time due to the absence of removal pathways. In arid and semi-arid regions, this effect is amplified by frequent reuse and high evaporation, which concentrate salts and metals in the surface horizons (Elsokkary & Aboukila, 2020; Abuzaid *et al.*, 2021; Rattan, Datta, Chhonkar, Suribabu, & Singh, 2005).

Second, *soil adsorption processes* enhance retention. Metals such as Cu and Mn readily bind to clay minerals and organic matter, particularly in neutral to alkaline soils, leading to reduced mobility but increased long-term accumulation (Kabata-Pendias & Mukherjee, 2007; Alloway, 2013). While adsorption processes enhance metal retention in soil, they also offer opportunities for remediation through soil amendments such as biochar, organic matter enrichment, and lime application, which can immobilize metals and reduce their bioavailability.

Third, *anthropogenic inputs beyond irrigation water* contribute substantially. Fertilizers, pesticides, sewage sludge, and animal manures frequently contain trace metals that add to soil burdens. Additionally, atmospheric deposition from industrial emissions and vehicle exhaust further intensifies contamination. Among anthropogenic sources, industrial effluents and municipal wastewater were identified as dominant contributors to Cu, Pb, and Cd enrichment. At the same time, agrochemical inputs, including phosphate fertilizers and pesticides, contributed to secondary but persistent sources of Zn and Mn. Atmospheric deposition from traffic emissions and open burning added diffuse background loads (Sharma & Agrawal, 2005; Adewumi & Ogundele, 2024; Xiao *et al.*, 2024). Effective risk assessments must therefore account for multiple human-driven pathways.

Fourth, *geological sources* provide background concentrations. Weathering of mineral-rich parent rocks, volcanic activity, and dust deposition establish baseline metal levels, which should be distinguished from anthropogenic enrichment (Wan *et al.*, 2024). The El-Qalyubia region is underlain by alluvial deposits derived from Nile sediments rather than mineral-rich parent rocks, suggesting relatively low natural metal background levels. Therefore, most observed metal enrichment likely reflects anthropogenic rather than geogenic origins.

Finally, *seasonal dynamics* shape contamination patterns. Higher temperatures and evapotranspiration during summer enhance evapoconcentration, driving salts and metals to accumulate in upper soil layers. Elevated summer temperatures accelerate evapotranspiration, thereby concentrating on solutes in the soil solution. Simultaneously, higher soil respiration and microbial activity can alter redox conditions, enhancing the mobility of redox-sensitive metals such as Mn and Fe. Conversely, during cooler winter months, reduced microbial turnover and lower evaporation slow metal diffusion, favoring adsorption and localized accumulation in topsoil (Rattan *et al.*, 2005). This explains seasonal fluctuations observed in contamination indices.

These findings highlight the need for an integrated monitoring framework that combines water, soil, and crop assessments within a unified reporting system. Such a framework should involve coordination between the Ministry of Water Resources and Irrigation, the Ministry of Agriculture, and environmental agencies to establish early-warning indicators, seasonal sampling protocols, and site-specific mitigation plans.

4.2 Elevated Cd and Pb in plants despite low water levels

Winter-grown crops in the El-Qalyubia region contained unusually high concentrations of cadmium (Cd) and lead (Pb) in edible tissues, even though drainage water samples showed minimal levels of these metals. This apparent contradiction reflects the complexity of soil–plant interactions. Metals often persist in soils as latent reserves, bound to minerals or organic matter, and are mobilized when environmental conditions, such as low temperature, waterlogging, and redox shifts, alter soil chemistry. Once released, these metals become more bioavailable, enabling plants to absorb them, particularly under seasonal physiological states that enhance uptake.

Several mechanisms explain this phenomenon. First, highly bioavailable soil fractions of Cd and Pb were detected at considerable to very high levels, allowing roots direct access to absorbable forms (Singh, Singh, Madheshiya, Khare, & Tiwari, 2024). Second, crop-specific uptake efficiency plays a key role. Onion, turnip, and molokheya are recognized as efficient accumulators due to root morphology and physiology. Traits such as large root surface area, shallow rooting that contacts topsoil, exudate secretion that solubilizes metals, and transport proteins that mistake Cd and Pb for essential nutrients (Zn, Ca, Fe) increase their uptake capacity. Many of these plants also tolerate toxic loads without obvious damage, sustaining accumulation (Khan, Rehman, Khan, Khan, & Shah, 2015).

Traits such as enhanced root surface area, secretion of organic acids and phytochelatins, and the expression of metal transport proteins that mistakenly absorb Cd^{2+} and Pb^{2+} in place of Zn^{2+} or Ca^{2+} have been demonstrated in leafy and root vegetables (Clemens, 2006; Li, Ma, van der Kuijp, Yuan, & Huang, 2014; Narayanan & Ma, 2023) . These physiological features explain the high accumulation capacity observed in crops such as onion, turnip, and molokheya.

Third, historical contamination of soils contributes. Pb, in particular, binds strongly to organic matter and clay, remaining in the topsoil from past fertilizer applications and continuing to pose risk regardless of current irrigation water quality (Miretzky & Fernandez-Cirelli, 2008; Singh, Sharma, Agrawal, & Marshall, 2010). The persistence of Cd and Pb in topsoil, even decades after their initial introduction, underscores the need for long-term soil management. Strategies such as phytoremediation using metal-tolerant species or application of immobilizing amendments (e.g. biochar and phosphate compounds) can progressively reduce metal bioavailability and limit crop uptake over time.

Fourth, because industrial or wastewater discharges often occur sporadically, periodic grab sampling may fail to capture peak contamination events. Incorporating time-integrated sampling techniques, such as real-time water monitoring stations, would provide a more accurate representation of temporal contamination variability (Saeed & Shaker, 2008; Ali, Khan, & Sajad, 2013).

Finally, metal mobility differs between water and soil. Cd and Pb are relatively immobile in surface water but accumulate effectively in roots and edible tissues, making water testing alone an unreliable predictor of crop contamination (Wang *et al.*, 2021). Cd and Pb have low solubility and strong soil adsorption under neutral to alkaline pH, and they are often undetectable in surface water despite significant accumulation in plant tissues. This uncoupling highlights the inadequacy of water-only monitoring systems and reinforces the requirement of integrated assessments monitoring soil and crop matrices.

These findings stress that monitoring must extend beyond irrigation water to include soils and crops to ensure accurate assessment of food safety risks.

4.3 Interpretation and relevance of pollution indices

To interpret the ecological impacts of metal accumulation in soils, four indices were applied: the Contamination Factor (Cf_i), Ecological Risk Factor (Er_i), Potential Ecological Risk Index (RI), and Pollution Load Index (PLI). Each offers a distinct perspective, moving beyond concentration data to provide decision-makers with tools for prioritizing risks.

The Contamination Factor (Cf_i) quantifies enrichment relative to background values. In this study, Cu, Mn, and Cd displayed particularly elevated Cf_i levels, especially at Sites 4 and 6, indicating substantial buildup far above natural concentrations.

The Ecological Risk Factor (Er_i) extends the analysis by weighing ecological sensitivity. High Er_i values for Cu during winter signaled notable ecological risks, emphasizing that some elements pose greater biological hazards than their concentrations alone suggest.

The Potential Ecological Risk Index (RI) integrates all Er_i values at a site to provide a cumulative risk profile. While most locations fell into the low-risk category during summer, several shifted into moderate or considerable risk ranges in winter. Again, Sites 4 and 6 emerged as hotspots, with seasonal changes driving sharp increases in risk levels.

The Pollution Load Index (PLI) synthesizes Cf_i values into a single measure of overall site quality. A PLI >1 denotes deteriorating environmental conditions. In winter, Sites 4, 6, and 7 exceeded this threshold, marking them as moderately polluted and confirming the cumulative impact of multiple metals.

Collectively, these indices reveal both the intensity and ecological significance of contamination, as well as its seasonal variability. While Cf_i and PLI capture pollution intensity, Er_i and RI highlight ecological risk, together forming a comprehensive framework for monitoring. Their combined application underscores the necessity of adaptive, year-round strategies rather than static assessments to support sustainable agricultural management under drainage water reuse.

The combined application of Cf_i, Er_i, RI, and PLI not only characterizes contamination intensity and ecological risk but also provides a quantitative framework for regulation and management. When Cf_i and PLI exceed 3, local authorities can initiate mitigation actions, such as soil treatment or restriction of sensitive crops. When RI overtake 150 indicates the need for enhanced ecological monitoring, time it passes 300 warrants direct remediation under established environmental risk assessment frameworks (Håkanson, 1980; Rostami *et al.*, 2021). These values offer thresholds that can help the prioritization of polluted sites.

5. Conclusion and policy recommendations

This study assessed the seasonal and spatial distribution of Cu, Fe, Mn, Zn, Cd, Co, Pb, Ni, and Cr in drainage water, agricultural soils, and edible plant tissues from El-Qalyubia. While drainage water samples generally met Egyptian regulatory standards, the application of indices such as Contamination Factor (Cf_i), Ecological Risk Factor (Er_i), Potential Ecological Risk Index (RI), and Pollution Load Index (PLI) revealed clear evidence of accumulation and ecological risks not reflected in water analyses alone.

Copper and manganese showed particularly elevated contamination factors, with Cu reaching values above 40 at Site 4 during winter and Mn exceeding the very high contamination threshold across multiple sites. Although Cd and Pb displayed low to moderate soil index values, their concentrations in edible plant tissues, especially in winter-grown crops, consistently surpassed Codex Alimentarius limits, highlighting a critical food safety concern. This discrepancy underscores the limitations of short-term water quality assessments and emphasizes the importance of soil–plant monitoring. Persistent soil accumulation and crop uptake of toxic metals pose direct risks to human health, particularly where crops are consumed fresh or raw.

Long-term intake of cadmium and lead through vegetables and grains irrigated with polluted water can progressively harm organs such as the kidneys and liver, disturb neurological development, and increase the risk of cancer. Even in small quantities, long-term exposure can disrupt the micronutrient balance and lead to changes in immunity, posing an unrecognized health risk to individuals involved with drainage-irrigated crops (Kabir, Abdullah, Alam, & Anik, 2025). Surplus copper in the soil can interfere with useful microbes, preventing decomposition of organic matter and ultimately depleting nutrient cycling by lowering overall soil health (Giller, Witter, & McGrath, 1998).

Crops cultivated under raised copper concentrations typically exhibit shortened roots and reduced chlorophyll, resulting in weaker growth and lower yields (Nagajyoti, Lee, & Sreekanth, 2010). When copper enters aquatic ecosystems, it impedes algal productivity and inflicts gill injury on invertebrates and fish, consequences that can propagate through food webs and lead to biodiversity losses. (Jaishankar, Tseten, Anbalagan, Mathew, & Beeregowda, 2014; Giller *et al.*, 1998). Over time, the propensity of heavy metals to bioaccumulate in living species exacerbates ecological stress and jeopardizes the long-term stability of both terrestrial and aquatic ecosystems.

5.1 Policy recommendations

(1) *Integrated Monitoring:* Establish monitoring programs that extend beyond water to include soils and crops, capturing both seasonal and cumulative contamination risks.

(2) *Site-Specific Management:* Implement targeted strategies in hotspots such as Sites 4, 6, and 7, including crop rotation, phytoremediation, and alternative land use.

(3) *Crop Restrictions:* Limit the cultivation of high-accumulating vegetables in contaminated areas, particularly near industrial discharge zones, to reduce dietary exposure to Cd and Pb.

(4) *Farmer Capacity Building:* Provide training on safe reuse practices, encourage planting of crops with low metal uptake, and promote soil amendments to reduce bioavailability.

(5) *Institutional Collaboration:* Foster coordinated action between water, agricultural, and public health sectors to develop integrated policies for sustainable water reuse and food safety.

(6) *Remediation Strategies* in wastewater-irrigated regions, such as the use of constructed wetland filtration systems in northern Egypt. Lake Manzala engineered wetland (LMEW), Egypt, is situated in the northeast frontier of the Nile Delta, Egypt. It was designed to treat a section of the Bahr El-Baqar drain (a mixture of secondary and primary treated wastewater from Cairo agro-drainage discharged at Lake Manzala) to

address Lake Manzala's water quality problem (Aboukila & Elhawary, 2022) and has demonstrated measurable reductions in Cd and Pb levels. Localized, low-cost approaches could yield similar benefits in the El-Qalyubia basin.

(7) *Crop restrictions* should spotlight high-accumulating crops, for instance, turnip, molokheya, wheat, and onion, which exhibited Cd and Pb concentrations substantially exceeding Codex Alimentarius limits. The substitution of low-uptake alternatives such as maize, barley, or okra in contaminated zones can reduce dietary exposure risks.

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