



Effects of Irrigation Water Sources on Soil Fertility, Heavy Metal Accumulation in both Soil and Rice (*Oryza sativa* L.)

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Abstract

Aims This study assessed the comparative impact of irrigation with sewage wastewater (SWW) and mixed sewage-industrial wastewater (SIWW) on soil fertility indicators and heavy metal accumulation in clayey soils and rice grains, using Nile water (NW) irrigation as a control.

Materials and Methods Samples were collected from 21 sites in Dakahlia Governorate, Egypt, representing three irrigation sources: seven sites each irrigated by SWW, SIWW, and NW.

Results Soils and rice grains from wastewater-irrigated sites showed significantly elevated levels of salinity, nutrients, organic matter, and bioavailable

heavy metals compared to the Nile water control. Soil pH was the sole exception, showing no significant difference. SWW sources exhibited the highest levels of salinity, biochemical oxygen demand, nutrients, and heavy metals. This directly corresponded with elevated levels of these constituents in the soil and, subsequently, in rice grains, demonstrating a clear source-pathway-receptor linkage. Evaluation of soil fertility using the Applied System for Land Evaluation software classified into two classes: good-C2 under, and fair-C3 under. Heavy metal levels in soil, water, and plants were within safe limits. The contamination factor values followed the order: $Ni > Cd > Cu > Pb > Zn$. The pollution load index of soils under SWW was higher than that of soils under SIWW.

Conclusions Wastewater is a valuable source of nutrients that significantly improves soil fertility. However, the associated accumulation of soluble salts and bioavailable cadmium, which entered the food chain, necessitates immediate, targeted monitoring and source control to ensure long-term agricultural sustainability.

Keywords Soil fertility · Heavy metals · Wastewater irrigation · Contamination factor

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Introduction

Water quality, determined by its physical and chemical properties, is typically evaluated against a set

of standardized criteria to assess its suitability for a given use. Therefore, water quality is the paramount factor determining the success and sustainability of wastewater reuse systems. The pathogen concentration, salinity, specific ion toxicity, trace elements, and nutrients are the primary water quality parameters that affect whether recycled water is suitable for irrigation (Ertuđ and Mirza 2010). Egypt faces a limited freshwater supply against growing agricultural demands. To bridge this deficit, the use of drain water is imperative; however, its quality must be rigorously assessed before use (El-Agrodi et al. 2018; Hashem and Qi 2021; Pedrero et al. 2010). The country is predominantly dependent on the Nile River, which fulfills approximately 97% of its agricultural water needs. This reliance is threatened by transboundary water challenges, notably the construction of the Ethiopian Renaissance Dam, which risks reducing flow into Lake Nasser and exacerbating water shortages. Such shortages could jeopardize millions of hectares of cultivated land (Omran and Negm 2020). Compounding this scarcity, Egypt contends with an annual water deficit of approximately 7 billion cubic meters. Furthermore, many of its water bodies are polluted by indiscriminate waste disposal, degrading their quality for both potable and irrigation uses (Hassanain et al. 2021). In this context, the annual collection of about 5 billion m³ of sewage water represents a significant potential resource. Effectively treated, this wastewater could offset a substantial portion of the national water deficit (Hashem and Qi 2021).

This practice is widespread; in many developing regions, a significant proportion of irrigation water is sourced from polluted streams, as farmers opt for these low-cost alternatives (Ibrahim and Salmon 1992; Mara and Cairncross 1989). Global drivers, including population growth and climate change, are exacerbating water scarcity and disrupting hydrological cycles. Concurrently, urbanization and industrialization are increasing the volume and complexity of wastewater generated (Bodin et al. 2019). The widespread use of untreated wastewater is frequently driven by the prohibitive cost and inadequate infrastructure for formal treatment (Ofori et al. 2021). Consequently, both treated and untreated wastewater, including industrial effluents, are increasingly used for irrigation globally to alleviate freshwater pressure, despite associated risks such as heavy metal contamination (Abbas et al. 2020; Ali et al. 2025; Carpanez

et al. 2024; Heyde et al. 2025; Soliman et al. 2024). Global food production is decreasing because of land degradation and cultivation problems brought on by a number of factors, including unpredictable climate change, expanding mining and industrial sectors, pesticide use, and an increasing reliance on wastewater for farming (Singh et al. 2025).

Water is an important factor in introducing nutrients and mineral salts to the plant to grow. Irrigation with polluted water poses significant risks: direct phytotoxicity, accumulation of contaminants in the food chain harming animals and human health, and long-term degradation of soil structure and fertility. These risks underscore the critical need for comprehensive irrigation water quality assessment (El-Hassanin et al. 2020; Hamilton et al. 2007; Hossain and Ahmed 1999). Furthermore, long-term wastewater irrigation can alter fundamental soil physico-chemical properties, which may either enhance or degrade soil fertility depending on the water's composition and management (Gatta et al. 2015). Therefore, to mitigate these risks and advance sustainable agriculture, rigorous and continuous monitoring of irrigation water is essential to determine its suitability (Akhtar et al. 2018). Utilizing wastewater in agriculture presents specific long-term risks, notably the accumulation of heavy metals in soils and crops, and soil salinization (an increase in sodium relative to other cations). The severity of these risks depends on the wastewater source, degree of treatment, and inherent soil properties (Abd-Elwahed 2018; Ganjegunte et al. 2018). Studies confirm that soils under long-term wastewater irrigation typically exhibit higher concentrations of heavy metals, including more bioavailable forms of toxic elements like lead and cadmium, compared to those irrigated with fresh water (Alnaimy et al. 2021).

Conversely, wastewater, particularly sewage, can be a nutrient-rich resource. Its content of nitrogen, phosphorus, and potassium can reduce dependence on and expenditure for synthetic fertilizers (Becerra-Castro et al. 2015; Corcoran et al. 2010; De Carlo et al. 2020). Additionally, it supplies organic matter and essential micronutrients like Zn, Fe, and Cu, potentially enhancing overall soil fertility (Chen et al. 2014; Ganjegunte et al. 2018; Khan et al. 2011; Ofori et al. 2021). Wastewater irrigation reuse has the potential to deliver notable amounts of plant-available nitrogen, phosphorus, and organic matter, commonly reducing farmers' reliance on conventional fertilizers

while serving circular-economy aims and greenhouse-gas mitigation associated with fertilizer manufacturing. These potential agronomic and environmental benefits, in addition to rising water demand under climate change, have excited renewed scientific and policy attention for the agricultural reuse of wastewater (Carpanez et al. 2024; Heyde et al. 2025).

The impact of wastewater on soil is highly variable. For instance, studies on sandy soils have reported significant changes in pH, salinity, and organic matter content following irrigation with treated effluent (Bedbabis et al. 2014; Shakir et al. 2017). Compliance with water quality guidelines, such as those from the Food and Agriculture Organization (FAO) and national standards like Egyptian Code of Practice 501/2015 (ECP 501/2015), is a key determinant of reuse safety, though parameters like nitrate and specific metals often approach or exceed limits in drain waters (Abbas et al. 2020). Many published studies focus narrowly on single indicator classes (for example, nutrients or heavy metals), whereas decision-relevant soil quality assessments require simultaneous measurement of nutrients, salinity, heavy metals, microplastics, and emerging organic contaminants together with key biological and functional indicators. Regional studies frequently report heavy metal concentrations in drainage water exceeding permissible limits, leading to significant bioaccumulation in irrigated crops, as indicated by elevated bioaccumulation factors (Ahmed et al. 2023; Soliman et al. 2024; Yalin et al. 2023).

Sewage irrigated soil contained much higher concentrations of Cd, Cu, Pb, Zn, Ni, Cr, As, and Hg compared to clean water irrigated soil (Meng et al. 2016). In Egypt, contamination from wastewater irrigation is documented across multiple regions. Studies in El-Minia, Giza, and elsewhere report elevated levels of heavy metals and other pollutants in soils and waters used for irrigation, linked to industrial and municipal discharges (Alnaimy et al. 2021; Hussein et al. 2022; Salman et al. 2018). To guarantee its safe use for irrigation, it is now mandatory to periodically evaluate the water quality in this area. Based on the FAO classification, the collected waters had salinities ranging from medium to high. B, Mg, or sodicity risks were not found in any of the water samples. However, all the water samples under study were categorized as extremely hard water. While Cd toxicity was found in nearly all water samples, the concentrations of Co and

Pb in all water samples were within allowable limits (Alnaimy et al. 2021; Hussein et al. 2022). Additionally, soil samples were taken from areas close to water supplies. Even though the potentially toxic elements were below the allowable limits in every soil location, the principal component analyses show that practically all soils had low, medium, and high-risk pollution levels with potentially toxic elements (PTEs) based on the pollution load index calculations (Abu El Ella et al. 2017; Hussein et al. 2022; Salman et al. 2018). Reuse of wastewater for irrigation in Egypt and neighboring areas of the MENA region is common in peri-urban as well as some rural areas and is associated with both agronomic benefits and documented locations of contamination. Current Egyptian case studies and regional assessments record long-term accumulation of heavy metals in drain-irrigated soils, excessive burden of microplastics, and site-specific incidents of industrial pollutants, identifying the need for local monitoring and management on a drain and effluent source basis. These findings imply that national and local reuse standards must be informed by empirical, site-specific soil quality evaluations on a chemical, physical, and biological basis (Alnaimy et al. 2021; Gad et al. 2025; Romeh et al. 2025).

According to ECP 501/2015, Group B crops (such as dry cereal crops, cooked and processed vegetables, fruit crops, and medicinal plants) should be irrigated with Nile freshwater, while Group D crops (such as timber trees, bio-charcoal crops, bio-diesel fuel crops, and cellulose production crops) should be irrigated with agricultural drainage water and mixed wastewater (Abbas et al. 2020).

Rice (*Oryza sativa* L.), a staple for over half the world's population, is also one of the most water-intensive crops, with consumptive use reaching approximately 6187 m³ per feddan in Egypt (Ministry of Agriculture and Land Reclamation 2007; Ministry of Agriculture and Land Reclamation 2007). Furthermore, rice is known to accumulate potentially toxic elements (PTEs); studies show that concentrations of Cd, Pb, and Cu in rice grains can exceed safety thresholds, posing a health risk, a situation exacerbated by industrial pollution (Hang et al. 2009). Given its high-water demand, rice is frequently irrigated with wastewater. This pragmatic solution, however, carries the distinct disadvantage of introducing heavy metals into the soil-rice system, with consequent risks to the ecosystem and human health

(Martínez-Cortijo and Ruiz-Canales 2018). Despite documented risks, integrated field studies comparing the dual effects of distinct wastewater types on soil fertility and heavy metal accumulation in rice, particularly in the clayey soils of the Northern Nile Delta, remain limited. Therefore, this study was conducted across multiple sites in Dakahlia Governorate, Egypt, to evaluate the comparative impact of sewage wastewater (SWW) and mixed sewage-industrial wastewater (SIWW) irrigation on soil properties, fertility, and heavy metal transfer in the soil-rice system, using Nile water irrigation as a control.

Materials and methods

The study was conducted in the Dakahlia Governorate during the 2023 summer rice season. Twenty-one fields were selected: seven each irrigated exclusively with water from i) sewage wastewater (SWW), ii) mixed sewage-industrial wastewater (SIWW), and iii) the Nile River (NW, control). From each field, a composite water sample (from the irrigation source), a composite soil (0–30 cm), and a mature rice grain sample were collected, yielding 21 sets of paired samples (Fig. 1).

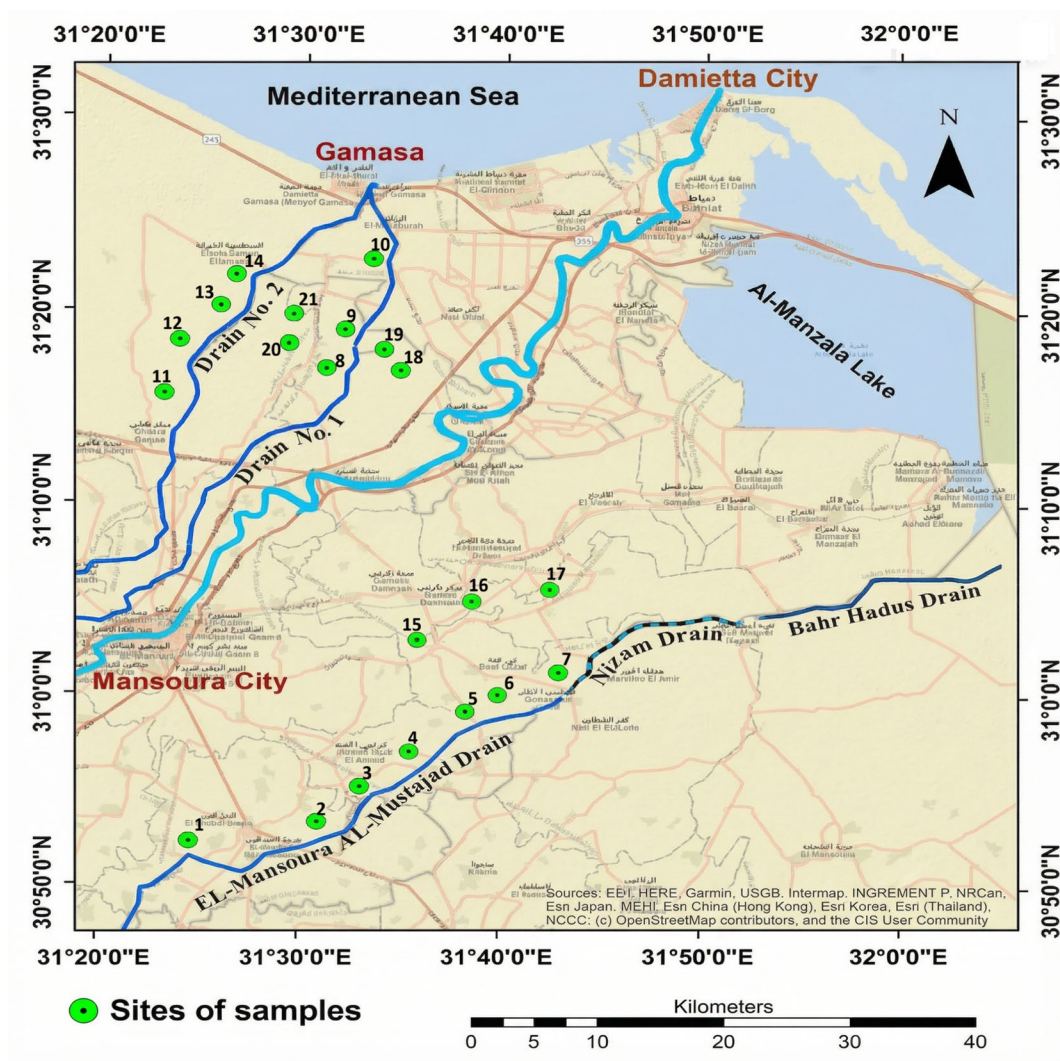


Fig. 1 Location of the study area and sampling

Preparation, analysis, and quality assessment of water samples

According to American Public Health Association (1999),

Fourteen water samples were collected, prepared and analyzed, water samples were collected from the middle of the canals used as an irrigation source and before conducting the chemical analyses required to evaluate water quality, samples were prepared as follows: The sampling bottles were treated with nitric acid (HNO_3 , 10%) for 48 h then rinsed with distilled water to measure accurately heavy metal concentration. A few drops of toluene were added to stop biological activities. After that, the measurements were performed as follows: chemical oxygen demand (COD, milligrams per liter (mg L^{-1})) by oxidation with potassium dichromate. The biochemical oxygen demand (BOD, mg L^{-1}) was determined by the dilution and seeding method. Ammoniacal nitrogen (N-NH_4^+ , mg L^{-1}) and nitrate nitrogen (N-NO_3^- , mg L^{-1}) were measured by deep-freezing at -5°C and determined calorimetrically using a spectrophotometer at 425 nm. Total phosphorus (P, mg L^{-1}) was measured calorimetrically by the stannous chloride method (690 nm). The total contents of heavy metals (mg L^{-1}) in samples were digested by nitric acid and measured using atomic absorption spectroscopy

according to Page et al. (1982). While electrical conductivity (EC, deciSiemens per meter (dSm^{-1})) was measured according to Jackson (1958). The pH was measured as described by Klute (1986). Total dissolved solids (TDS, mg L^{-1}) were determined using a conductivity bridge meter as described by the United States Department of Agriculture (1969). Sodium adsorption ratio (SAR) was calculated using the equation (Richard 1954). The quality of water samples was assessed as per the guidelines of the Food and Agriculture Organization 1985; United States Environmental Protection Agency 2012) (Table 1.).

Preparation, analysis, and fertility assessment of soil samples

The surface soil samples (0–30 cm) were collected, air-dried, ground, passed through a 2 mm sieve, and kept for analysis. Mechanical analysis carried out by the international pipette method (Piper 1950). Soil reaction (pH) was measured in the soil suspension 1:2.5 using the pH meter (Jenway AD 1030) as described by Klute (1986). Electrical conductivity (EC, dSm^{-1}) was measured in the soil paste extract using the EC-meter (Jenco 3173) according to Singh (2024). Exchangeable Sodium Percentage (ESP) was calculated at clayey soil according to the formula: $\text{ESP} = 1.8667 + 0.9228 (\text{SAR}) + 0.001$

Table 1. Guidelines for the quality of irrigation water

Indicator	Unit	Degree of restriction on use			Reference
		None	Slight to moderate	Severe	
EC	dSm^{-1}	< 0.7	0.7–3	> 3	(FAO 1985)
SAR		< 3	3–9	> 9	
TDS	parts per million (Ppm)	< 450	450–2000	> 2000	
$\text{NO}_3 - \text{N}$	Ppm	< 5	5–30	> 30	(USEPA 2012) (USEPA 2012) (FAO 1985)
$\text{NH}_4 - \text{N}$	Ppm	usual range 0–5			
$\text{PO}_4 - \text{P}$	Ppm	usual range 0–2			
pH	-	normal range 6.5–8.4			
BOD	Ppm	must not exceed 30			
COD	Ppm	must not exceed 60			
Trace elements and heavy metals	Ppm	Recommended maximum concentration 0.20			
	Ppm	Recommended maximum concentration 2.0			
	Ppm	Recommended maximum concentration 0.01			
	Ppm	Recommended maximum concentration 0.20			
	Ppm	Recommended maximum concentration 5.00			

(SAR)² (Gazia et al. 2008). Organic matter content (OM, %) was measured using the Walkley and Black method as described by Singh (2024). Total calcium carbonate (CaCO₃, %) was measured using Collins' calcimeter as described by Piper (1966). Particle size distribution was measured by the international Pipette method according to Piper (1966). Available nitrogen (N, milligrams per kilogram (mg Kg⁻¹)) was extracted using 2.0 M KCl and determined by micro-Kjeldahl apparatus as described by Hesse (1971). Available phosphorus (P, mg Kg⁻¹) was extracted using sodium bicarbonate (0.5 N, pH 8.5) and determined calorimetrically using the spectrophotometer (PD-303S) at a wavelength of 660 nm (Singh 2024). Available heavy metal concentrations (mg kg⁻¹) in soil samples were extracted using 1.0 M ammonium acetate (NH₄CH₃CO₂, pH 7.0). The extracted solutions were analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES; Thermo Scientific iCAP 7400) following the method described by Cottenie et al. (1982). The limits of detection (LOD) for the analyzed metals were obtained from the instrument specifications and were lower than the measured concentrations. Soil fertility was evaluated using ASLE software (Applied System for Land Evaluation), which was developed by Ismail and Morsi (2001) to calculate the fertility index value. The quality of soil was assessed according to the studied indicators presented in Table 2.

Preparation and analysis of plant samples

Approximately 0.2 g oven-dried ground rice was digested by 4 ml of sulphuric acid (H₂SO₄) and perchloric acid (HClO₄) mixture (1 sulphuric acid:1 perchloric acid) on a hot plate at 120–150 °C for 2–3 h until a clear solution was obtained. After cooling, the digested samples were filtered and diluted with distilled water according to Chapman and Pratt (1961). Then, the N, P, and K content was measured in the extract, as was done in the soil analysis. Heavy metals were determined using inductively coupled plasma optical emission spectrometry (ICP-OES; Thermo Scientific iCAP 7400) following the method described by Cottenie et al. (1982). The limits of detection (LOD) were obtained from the instrument

specifications and were lower than the detected concentrations.

Pollution quantification

The contamination factor (CF) and pollution load index (PLI) were calculated (Hakanson 1980; Varol 2011). The mean heavy metal concentrations from the seven Nile water-irrigated (control) sites were used as the local background values (C_{background}): Cu=1.14, Zn=5.14, Cd=0.03, Ni=0.11, Pb=1.06 mg kg⁻¹.

$$CF = C_{\text{soil}} / C_{\text{background}}$$

According to Hakanson (1980), the values of Cf < 1 indicate low contamination, 1 < Cf < 3 indicates moderate contamination, 3 < Cf < 6 indicates considerable contamination, and Cf > 6 indicates very high contamination.

The pollution load index (PLI) provides an easy way to prove the deterioration of the soil conditions because of the accumulation of heavy metals (Varol 2011), which was calculated as a geometric average of CF based on the following formula:

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \dots \dots CF_n}$$

Where n is the number of metals and CF is the contamination factor value. The pollution load index value of zero indicates perfection; a value of one indicates the presence of only baseline levels of pollutants, and values above one would indicate progressive deterioration of the site quality (Varol 2011).

Statistical analysis

All obtained data were subjected to statistical analysis using analysis of variance (ANOVA) to evaluate the effect of different irrigation treatments on soil and plant parameters. ANOVA was chosen because it allows comparison of mean values across multiple treatments while accounting for experimental variability. When significant differences were detected ($p \leq 0.05$), means were compared using the Least Significant Difference (L.S.D.) test at the 5% significance level, following Snedecor and Cochran (1989).

Table 2 Soil quality assessment

Indicator	Unit	Description	Threshold	Reference
EC	dSm ⁻¹	Non-saline Very slightly saline Slightly saline Moderately saline Strongly saline	< 2 2–4 4–8 8–16 > 16	(Yao et al. 2013)
pH	-	Neutral Slightly alkaline Moderately alkaline Strongly alkaline Very strongly alkaline	6.6–7.3 7.3–7.8 7.8–8.4 8.4–9.0 > 9	(Soil Science Division Staff 2017)
ESP	%	non-sodic sodic	< 15 > 15	(Richard 1954)
Organic matter (OM)	%	Very high High Moderate Low Very low Extremely low	> 5 5–3 3–1.7 1.7–1 1–0.7 < 0.7	(Hazelton and Murphy 2016)
Available N	mg kg ⁻¹	High Moderate Low	> 217,108–217 < 108	(Verma et al. 2005)
Available P	mg kg ⁻¹	High MediumLow	> 2510–25 < 0	(Singh 2024)
Available K	mg kg ⁻¹	High Moderate Low	> 12,452–124 < 52	
Soil fertility evaluation by using ASLE	Fertility Class	Description	Fertility Index (%)	(Ismail and Morsi 2001)
	C1	Excellent	> 80	
	C2	Good	< 80–> 60	
	C3	Fair	< 60–> 40	
	C4	Poor	< 40–> 20	
	C5	Very poor	< 20–> 10	
	C6	Non agriculture	< 10	
Trace elements and heavy metals	Cu	mg kg ⁻¹	Very high High Moderate Low Very low	(Jones 2001)
			> 2.5 2.5–1.3 1.3–0.9 0.9–0.3 < 0.3	
	Zn	mg kg ⁻¹	Very high High Moderate Low Very low	
			> 6 6–3.1 3.1–1.1 1.1–0.5 < 0.5	
	Cd	mg kg ⁻¹	Normal range Optimal	(Adriano 1986)
			2–0.01 0.35	
	Ni	mg kg ⁻¹	Normal range Optimal	
			500–5 40	
	Pb	mg kg ⁻¹	Normal range Optimal	
			200–2 20	

Results

Effect of water chemical properties on soil chemical properties

The data presented in Table 3 show some chemical characteristics of water and soil samples collected from

the study area under different irrigation sources, sewage wastewater (SWW), sewage and industrial wastewater (SIWW), and Nile water (NW). The measured parameters of water were the hydrogen ion concentration (pH), electric conductivity (EC), sodium adsorption ratio (SAR), and Total dissolved salts (TDS), while the measured parameters of soil were pH, EC, and CaCO₃.

Table 3 Chemical properties of water and soil samples in the study area

Source of irrigation water	Water				Soil		
	pH	EC (dSm ⁻¹)	SAR	TDS (mg L ⁻¹)	pH	EC (dSm ⁻¹)	CaCO ₃ (%)
NW	7.54a	0.49c	1.44c	313.60c	8.52a	1.17b	2.08b
SWW	7.27b	2.06a	6.56a	1318.40a	8.32a	1.77a	3.59a
SIWW	7.56a	1.60b	4.85b	1024b	8.41a	1.74a	3.35a
LSD at 0.05	0.17	0.23	0.85	146.12	0.33	0.13	0.46

NW Nile water, SWW sewage wastewater, SIWW sewage and industrial wastewater

Water

Irrigation water pH was slightly alkaline, ranging from 7.27 (SWW) to 7.56 (SIWW), with no significant difference among sources (Table 3). The values of EC, SAR, and TDS were significantly higher in both wastewater sources than their corresponding values in Nile water. It could be observed that the values of EC, SAR, and TDS were significantly higher in SWW (2.06 dSm⁻¹, 6.56 and 1318.40 mg L⁻¹, respectively) than SIWW (1.60 dSm⁻¹, 4.85 and 1024 mg L⁻¹, respectively) (Table 3), the increase in salinity of SWW and SIWW compared to NW was 320.4% and 226.5%, respectively.

Soil

The pH values of the studied soil samples ranged from 8.32 in soil samples under SWW irrigation to 8.52 in soil samples under Nile water irrigation (slightly alkaline), with no significant difference among them. Comparing the pH results of irrigation water and soil reveals that the relative decrease in wastewater led to a decrease in soil pH compared to soil irrigated with Nile water, which recorded the

highest pH value in the study area, as shown in Fig. 2. On the other hand, EC values were higher in soil samples under wastewater irrigation (both wastewater sources SWW and SIWW) than soil samples under NW irrigation (by 51.28% and 48.72%, respectively), with a significant difference between them. The soil samples under SWW irrigation recorded the highest value of EC (1.77 dSm⁻¹). As shown in Fig. 2, the relationship between soil salinity and irrigation water salinity is clear. There was no significant change in soil pH due to irrigation with wastewater, but the EC of soils under wastewater irrigation was nearly twice that under Nile water irrigation. The data presented in Table 3 indicate that the values of CaCO₃ increased significantly in the soil samples collected from sites under wastewater (SWW and SIWW) irrigation (3.59% and 3.35%, respectively) as compared with their corresponding values in soil samples collected from sites under NW irrigation, the corresponding increases were 72.59% and 61.06%, respectively.

As shown in Fig. 3, the lowest ESP values were recorded in soils irrigated with NW, while the highest values were recorded in soils irrigated with SWW. The ESP values in the studied soils were less than 15%, which indicates that the studied soils were non-sodic.

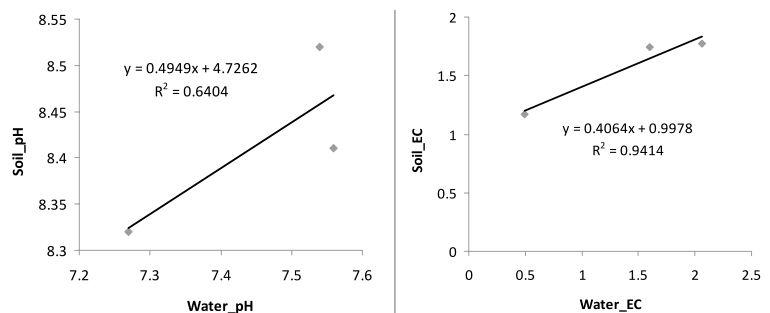
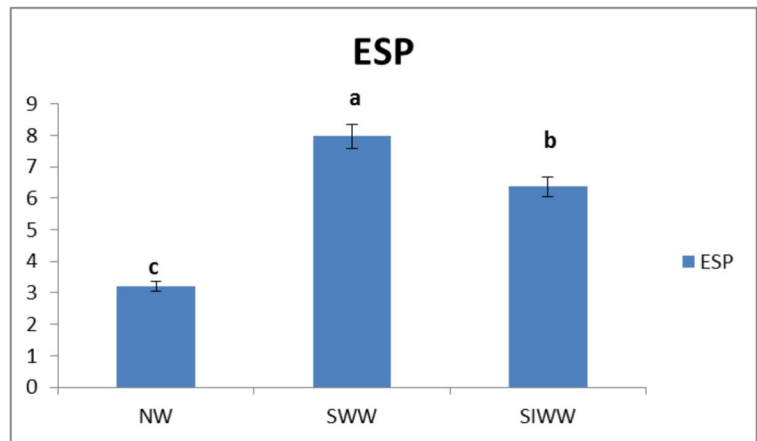
Fig. 2 Linear relationships between pH and EC of water and soil in the studied areas

Fig. 3 Comparison between ESP in the soils of the studied areas

Effect of irrigation sources on nutrient content of soil and plant

Water

Table 4 shows Nutrient content in water and soil samples collected from sites under SWW, SIWW, and NW irrigation. The measured parameters were nitrate (NO_3^-), ammonium (NH_4^+), phosphorus (P), chemical oxygen demand (COD), biochemical oxygen demand (BOD) in water irrigation, available NPK, organic matter (OM) in the soils of the studied area, and NPK content of rice plant grains. Integrate this into the soil properties section: "All soils were classified as clay. Notably, the clay fraction was significantly higher in wastewater-irrigated soils (Fig. 4), suggesting a potential long-term physical impact.

The water samples collected from SWW recorded the highest values of nitrate (NO_3^-), ammonium (NH_4^+), and phosphorus (P) (33.65, 5.45, and 2.46 mg L^{-1} , respectively), followed by water samples collected from SIWW. On the other hand, the

Nile water samples recorded the lowest values for the three parameters, with a significant difference among the three water sources. According to FAO (1985), ammonia and phosphorus values of SWW were above permissible limits, while NO_3 values of SWW and SIWW ranged from slight to moderate. On the other hand, phosphorus and ammonia levels in the SIWW were within acceptable limits.

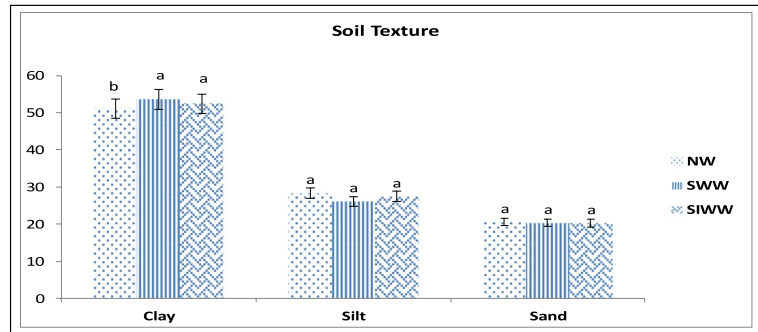
As for the chemical oxygen demand (COD) and biochemical oxygen demand (BOD), the data revealed that the values of both parameters increased significantly in wastewater samples (SWW and SIWW) as compared with their corresponding values in NW. The SWW recorded the highest values for both parameters (301.21 and 170.81 mg L^{-1} for COD and BOD, respectively) with a significant difference as compared with other water sources (Table 4). According to the United States Environmental Protection Agency (USEPA) (2012), the values of COD and BOD of wastewater sources were higher than the permissible level (Table 1.) by more than 5 and 3 times for SWW and SIWW, respectively.

Table 4 Nutrient content in water, soil, and plant samples in the study area

Source of irrigation water	Water					Soil				Plant		
	NO_3^-	NH_4^+	P	COD	BOD	N	P	K	OM	N	P	K
	(mg L^{-1})					(mg kg^{-1})			%	%		
NW	4.89c	1.43c	0.36c	20.57c	11.3c	101.41b	9.42b	341.0b	1.25c	8.61a	0.22b	2.19b
SWW	33.65a	5.45a	2.46a	301.2a	170.81a	133.27b	42.61a	1404.0a	1.93a	9.55a	0.32a	2.88a
SIWW	29.0b	2.58b	1.85b	186.9b	111.84b	244.10a	38.27a	1302.1ab	1.61b	8.77a	0.25b	2.60a
LSD at 0.05	1.55	1.14	0.46	59.30	17.86	53.42	11.00	1057.29	0.27	1.32	0.05	0.38

NW Nile water, SWW sewage wastewater, SIWW sewage and industrial wastewater

Fig. 4 Comparison between clay, silt, and sand in the soils of the studied areas



Soil

Available soil nitrogen was significantly higher under SIWW irrigation (244.1 mg kg^{-1}) than under SWW (133.3 mg kg^{-1}) or NW irrigation (101.4 mg kg^{-1}) (Table 4). While available P and K contents were the highest in soil under SWW irrigation (42.61 and $1404.01 \text{ mg kg}^{-1}$ for P and K, respectively). In general, the soils under wastewater irrigation contained available NPK higher than the soils under Nile water irrigation.

The data presented in Table 4 indicate that the values of OM increased significantly in the soil samples collected from sites under wastewater (SWW and SIWW) irrigation as compared with their corresponding values in soil samples collected from sites under Nile water irrigation. Considering that the soils under SWW and SIWW irrigation recorded the highest values of OM (1.93 and 1.61%, respectively). The corresponding increases were 54.4% and 28.8% compared with NW, respectively.

As shown in Fig. 4 regarding soil texture, the data showed that all soil texture classes of all studied sites were clay with a significant difference in percentage of clay particles between soils under Nile water irrigation and soils under wastewater irrigation, which recorded the highest percentage of clay particles.

Plant

Rice grain N content was highest from SWW-irrigated fields (9.55%), intermediate from SIWW fields (8.77%), and lowest from NW fields (8.61%), though these differences were not statistically

significant (Table 4). The P and K content in rice plant grains followed the same trend as N content, but with significant differences among plants under different irrigation sources. The percentages of P content were 0.32, 0.25, and 0.22% for grains of rice plants grown in soils under SWW, SIWW, and NW irrigation, respectively. Meanwhile, the percentages of K content were 2.88%, 2.60%, and 2.19% for rice plant grains grown in soils under SWW, SIWW, and NW irrigation, respectively.

As illustrated in Fig. 5, the summary of this section shows that soil and plant parameters (N, P, and OM) were directly affected by the content of irrigation water (N, P, and BOD), and that different irrigation water sources had a direct and proportionally increasing impact.

Effect of irrigation sources on heavy metals of soil and plant

Water

The results of heavy metals (Cu, Zn, Cd, Ni, and Pb) content of water samples collected from different water sources are presented in Table 5. The highest values of the five heavy metals were recorded in water samples of SWW and decreased significantly until they reached the minimum values in water samples of Nile water. According to FAO (1985), the Zn and Pb content of all the studied water samples were lower than the permissible level (2 and 5 mg L^{-1} for Zn and Pb, respectively), the concentration of Cu in SWW and SIWW was higher than the permissible level (0.2 mg L^{-1}) by 285% and 630%, respectively,

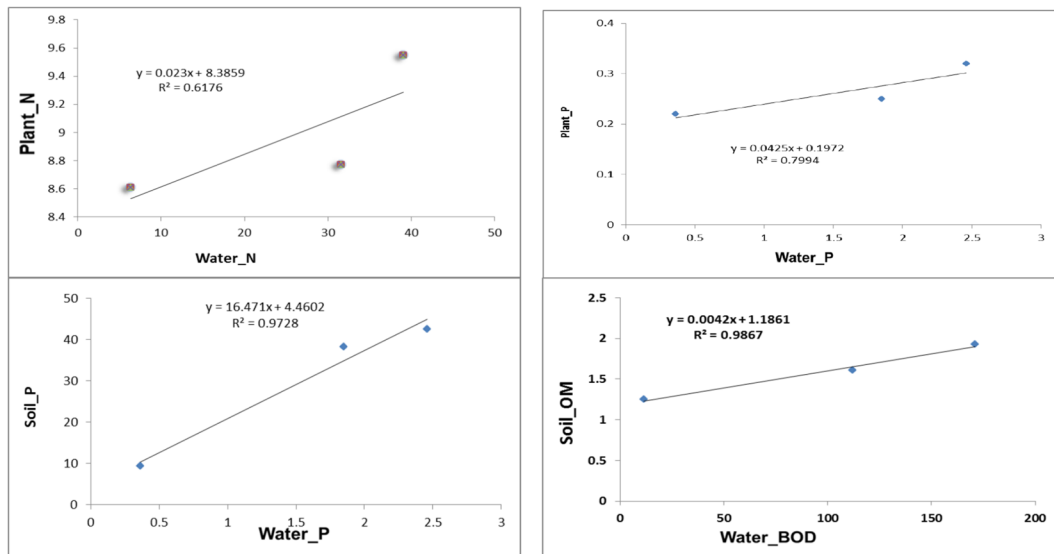


Fig. 5 Linear relationships between the water content and nutrient level in the soil and the plant in the studied area

The concentration of Cd in SIWW equal to the permissible level (0.01 mg L^{-1}), but in SWW it exceeded by 200%. As for Ni concentration, it was greater than the permissible level (0.2 mg L^{-1}) by 290% and 155% for SWW and SIWW, respectively. The limits of most elements were within acceptable limits.

Soil

As shown in Table 5, the results of heavy metals (Cu, Zn, Cd, Ni, and Pb) content in soil samples collected from different sites. Similarly, as with different water sources, the highest values of the five heavy metals were recorded in soil under irrigation with SWW irrigation (6.41, 7.23, 0.28, 1.62, and 2.11 mg kg^{-1} for Cu, Zn, Cd, Ni, and Pb, respectively) and decreased significantly until they reached the minimum values in soils under NW irrigation. However, the content of all studied heavy metals in all soil samples was lower than the permissible levels according to the Food and Agriculture Organization (FAO)/World Health Organization (WHO) (2011). Figure 6 illustrates the effect of different irrigation water sources and their heavy metal content on the soil content of these elements.

Plant

The data presented in Table 5 show some chemical characteristics of rice grains that were collected from sites under different irrigation sources (SIWW, SWW, and NW). The measured parameters were the content of Cu, Zn, Cd, Ni, and Pb in rice plant grains.

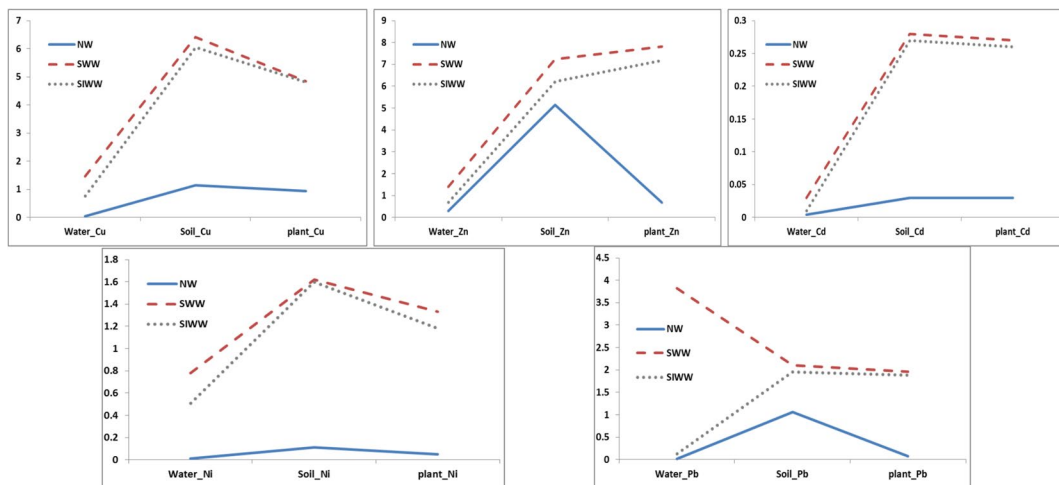
The highest values of the five heavy metals were recorded in rice plant grains grown in soils under SWW irrigation (4.84, 7.81, 0.27, 1.33, and 1.96 mg kg^{-1} for Cu, Zn, Cd, Ni, and Pb, respectively) and decreased significantly until they reached the minimum values in rice plant grains grown in soils under NW irrigation.

The Cu, Zn, and Pb contents of all studied rice samples were lower than the permissible level (40, 60, and 5 mg L^{-1} for Cu, Zn, and Pb, respectively). The concentration of Cd in rice grains grown under SIWW and SWW irrigation was higher than the permissible level (0.2 mg L^{-1}) by 30 and 35%, respectively. As for Ni concentration in all studied plants, it was greater than the permissible level (not detectable) according to WHO/FAO (2007). Heavy metal concentrations in rice grains showed a strong positive correlation with their respective concentrations in both irrigation water and soil (Fig. 6), confirming a direct transfer along the water-soil-plant continuum.

Table 5 Heavy metals in water, soil, and plant samples in the study area

Source of irrigation water	Water (mg L ⁻¹)					Soil (mg kg ⁻¹)				
	Cu	Zn	Cd	Ni	Pb	Cu	Zn	Cd	Ni	Pb
NW	0.05c	0.29b	0.004b	0.01c	0.02b	1.14b	5.14b	0.03b	0.11b	1.06b
SWW	1.46a	1.40a	0.030a	0.78a	3.82a	6.41a	7.23a	0.28a	1.62a	2.11a
SIWW	0.77b	0.68b	0.010b	0.51b	0.13b	6.05a	6.21ab	0.27a	1.60a	1.96a
LSD at 0.05	0.43	0.42	0.006	0.10	0.93	0.64	1.86	0.05	0.08	0.82
The permissible level of heavy metals (FAO 1985)	0.2	2	0.01	0.2	5	100	100	3	50	100
Source of irrigation water					Plant (mg kg ⁻¹)					
						Cu	Zn	Cd	Ni	Pb
NW						0.94 b	0.69 b	0.03 b	0.05 b	0.08 b
SWW						4.84 a	7.81 a	0.27 a	1.33 a	1.96 a
SIWW						4.81 a	7.18 a	0.26 a	1.18 a	1.88 a
LSD at 0.05						0.59	0.73	0.05	0.22	0.16
The permissible level of heavy metals (WHO/FAO 2007)						40	60	0.2	-	5

NW Nile water, SWW sewage wastewater, SIWW sewage and industrial wastewater

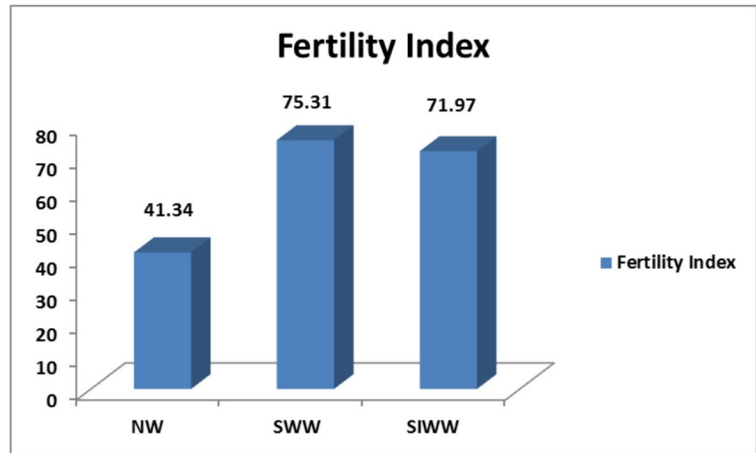
**Fig. 6** Effect of heavy metal concentration in irrigation water on their accumulation in soil and plant

Evaluation of soil fertility

The data presented in Fig. 7 show the ranges of the fertility index and fertility class of the studied area. The results of soil fertility index under NW, SWW, and SIWW irrigation were 41.34, 75.31, and 71.97, respectively, which are Fair-C3, Good-C2, and

Good-C2, respectively. The data revealed that it increased in soil samples collected from sites under SWW and SIWW irrigation as compared with their corresponding values in soils under NW irrigation. The increase in soil fertility index of SWW and SIWW compared to NW was 82.17% and 74.09%, respectively.

Fig. 7 Ranges of Soil fertility and index under different irrigation water sources in the studied area



Pollution quantification

The soil contamination factor (CF) and pollution load index (PLI) at the sites under SWW and SIWW irrigation are shown in Table 6. The CF values for Cu, Zn, Cd, Ni, and Pb were 5.62, 1.41, 9.33, 14.73, and 1.99, respectively, in soils under SWW. Meanwhile, the CF values for Cu, Zn, Cd, Ni, and Pb were 5.31, 1.21, 9.00, 14.55, and 1.85, respectively, in soils under SIWW. From the CF mean values of the five heavy metals, they could be arranged descendingly in the order of: Ni > Cd > Cu > Pb > Zn. According to Hakanson (1980) classification, Ni and Cd can cause very high contamination; Cu can cause considerable contamination; Pb and Zn can cause moderate contamination.

The PLI of soil samples was 4.65 and 4.35 at soils under SWW and SIWW, respectively. According to Varol (2011), all studied soils under wastewater irrigation suffer from progressive deterioration of the soil quality ($PLI > 1$). It could be noticed that the soil samples under SWW irrigation recorded the highest values of PLI and CF for all studied heavy metals.

Discussion

Effect of water chemical properties on soil chemical properties

Water

The slight but non-significant reduction in soil pH under wastewater irrigation could be attributed to the nitrification of ammonium and the mineralization of organic matter, both processes releasing H^+ ions (Gorfie et al. 2022; Ofori et al. 2024). This highlights that even within an acceptable pH range, wastewater can influence soil chemical processes. The pH of SIWW (7.56) and SWW (7.27) were well within the acceptable range of 6.5–8.4 (FAO 1985; FAO 2003). However, it turns out that (SWW) and (SIWW) have a slight effect on reducing soil pH compared to irrigation with Nile water. These results agree with those reported by Alnaimy et al. (2021) and Farrag et al. (2017).

The results indicated that wastewater sources exhibited higher EC, SAR, and TDS values compared to Nile water. In this regard, Khafagi et al. (2018) reported that

Table 6 The contamination factor and pollution load index of soil samples collected from sites under different irrigation water sources

Source of irrigation water	The contamination factor for the studied heavy metals					PLI
	Cu	Zn	Cd	Ni	Pb	
SWW	5.62	1.41	9.33	14.73	1.99	4.65
SIWW	5.31	1.21	9.00	14.55	1.85	4.35
Mean	5.47	1.31	9.17	14.64	1.92	4.50

SWW sewage wastewater, SIWW sewage and industrial wastewater, PLI Pollution load index

EC values of wastewater samples collected from the Bahr El Baqar drain at The Old Haggagia village, Fakous, El Sharkia Governorate, increased by 61% compared to Nile water samples. They added that this increase in EC values may be due to the dumping of many wastes in the wastewater canal (drain) from different anthropogenic activities. According to the FAO and the literature, EC, SAR, and TDS values indicate medium salinity dangers because the EC, SAR, and TDS of the collected water samples (SWW and SIWW) ranged from slight to medium (FAO 1985; Hussein et al. 2022; Pescod 1992).

Soil

Based on the available results, soil salinity values and water SAR levels were below the critical limit, indicating no evidence of soil degradation (Farrag et al. 2017). The results indicated that wastewater irrigation influenced soil EC, SAR, CaCO_3 , and ESP values more than Nile water, while soil pH remained relatively stable. The increase in EC values due to the disposal of industrial and domestic effluents in irrigation water (Elliethy et al. 2022). According to Yao et al. (2013), the soils in the study area are not considered saline despite the increase in EC. The higher soluble salt added to the soil from wastewater explains why the EC of soils under wastewater irrigation was nearly twice that under Nile water irrigation (Elliethy et al. 2022). The significant increases in CaCO_3 values under SWW and SIWW irrigation agree with Elliethy et al. (2022). Conversely, these results contradict Alnaimy et al. (2021) and Farrag et al. (2017), who found that over time, prolonged irrigation with wastewater can significantly reduce the amount of calcium carbonate (CaCO_3) in the top-soil layer, this decrease may be due to an increase in soil pH as a result of the production of organic acids resulting from the anaerobic decomposition of organic matter, which leads to the dissolution of CaCO_3 . The ESP values and their correlation with water SAR suggest that long-term irrigation with wastewater does not create sodicity hazards, as values remained below 15%, consistent with Hussein et al. (2022). This supports the predictive relationship between Na^+ in water (SAR) and soil ESP to evaluate sodicity risk (Minhas and Qadir 2024; Van de Graaff and Patterson 2001).

Effect of irrigation sources on nutrient content of soil and plant

Water

The results indicated that wastewater irrigation contained higher nutrient and organic load levels than the Nile water. The main sources of phosphorus in wastewater are human excreta, phosphorus-containing household detergents, and some industrial and trade effluents (Son 2024). Nitrogen in water can be found in mineral (ammonium, nitrate) or organic form. Its organic presence results in a consumption of oxygen in the natural environment, increases BOD, and alters the living conditions. In sanitation, the nitrogen cycle follows the different stages of biogeochemical evolution of the component. It leads to the formation of nitrogen gas (N_2), starting with organic nitrogen and passing through ammonium, nitrite, and nitrate (Ganji et al. 2024). The amount of COD and BOD present in wastewater depends on the availability of organic matter in water, which includes human wastes present in municipal wastewater and organic wastes from some manufacturers in industrial wastewater, all of which contribute to increased oxygen demand (Raychaudhuri et al. 2014).

Soil

The results indicated that wastewater irrigation enhanced soil nutrient availability compared to Nile water irrigation. Our results corroborate previous work in the region demonstrating the fertilizer value of wastewater (Farrag et al. 2017; Hashem and Qi 2021; Khafagi et al. 2018). The marked increase in soil OM and available NPK (Table 4) translates to a quantifiable fertility improvement, as reflected in the elevated ASLE index (Fig. 7), offering farmers a significant economic incentive. They attributed this improvement to the presence of organic and inorganic compounds in wastewater containing nutrients such as nitrogen, phosphorus, and potassium. This is also in agreement with Abd-Elwahed (2018), who demonstrated that irrigation with industrial wastewater or sewage improves soil fertility levels due to the high nutrient load in sewage. In this concern, Hashem and Qi (2021); Raychaudhuri et al. (2014) demonstrated that nutrient enrichment and increased soil fertility may be related to enhanced

microbial activity, which depends on increased organic matter content in both water and soil.

The observed increase in soil organic matter under wastewater irrigation is consistent with previous studies (Abd-Elwahed 2018; Elliethy et al. 2022; Farrag et al. 2017; Hussain et al. 2017; Khafagi et al. 2018), which attributed this increase to the presence of organic compounds in wastewater. Regarding soil texture, similar results were reported by Elliethy et al. (2022), who suggested that the higher clay content in soils irrigated with wastewater might be due to the accumulation of clay particles carried by wastewater during irrigation.

Plant

The results indicated that wastewater irrigation enhanced nutrient accumulation in rice grains compared to Nile water irrigation. The plants irrigated with wastewater (domestic or industrial wastewater) contained greater N, P, and K concentrations than plants irrigated with fresh water (Nile water). This may be attributed to the increased availability of nutrients and organic matter in soils because of their higher concentrations in wastewater used for irrigation, which consequently enhanced soil fertility (Elliethy et al. 2022; Hashem and Qi 2021; Odone et al. 2024).

Effect of irrigation sources on heavy metals of soil and plant

Water

The results indicated that wastewater, particularly SWW, contained higher concentrations of heavy metals compared to Nile water. These results agree with those reported by El-Agrodi et al. (2018), Alnaimy et al. (2021), and Hussein et al. (2022). In this concern, Odumbe et al. (2023) reported that industrial effluents originate from processes such as metal smelting, electroplating, leather tanning, textile industries, mineral extraction, and nuclear power generation, whereas municipal effluents arise from residential and municipal discharges. Municipal and industrial effluents contain organic matter, water contaminants, and heavy metal ions. Heavy metals mainly emanate from various industries and are

non-biodegradable, requiring removal from wastewater effluents before disposal, as their presence in water deteriorates water quality.

Soil

The results indicate that the higher concentrations of heavy metals in soils under SWW and SIWW irrigation were influenced by the quality of irrigation water. This agrees with Alnaimy et al. (2021), Hashem and Qi (2021), Khafagi et al. (2018), and Odumbe et al. (2023), who reported that the available heavy metal concentration in soil is affected by irrigation practices, and that the application of municipal, industrial, or agricultural wastewater can result in a marked increase in soil metal content.

Plant

The results indicate that the higher concentrations of heavy metals in rice grains under SWW and SIWW irrigation are influenced by the metal content of the irrigation water and the soil. This agrees with Elliethy et al. (2022), who reported that cereal crops such as rice, wheat, and corn can safely be grown under wastewater irrigation as they absorb only small amounts of heavy metals in their edible parts, unlike leafy vegetables, which accumulate higher concentrations. However, according to Egyptian Code of Practice 501/2015 (ECP 501/2015), certain crops such as dry cereal crops, cooked and processed vegetables, fruit crops, and medicinal plants should be irrigated with Nile freshwater, while timber trees, bio-charcoal crops, bio-diesel fuel crops, and cellulose production crops can be irrigated with agricultural drainage water or mixed wastewater (Abbas et al. 2020). These findings highlight the importance of crop type and irrigation water quality in managing the transfer of heavy metals to edible plant parts.

Evaluation of soil fertility

The higher soil fertility observed under SWW and SIWW irrigation is likely due to the increased organic matter content, higher soil concentrations of nitrogen, phosphorus, and potassium, and enhanced microbial

activity. These findings are consistent with previous studies by Abd-Elwahed (2018), Ali et al. (2020), Farrag et al. (2017), Fouda et al. (2019), Hashem and Qi (2021), Khafagi et al. (2018), Raychaudhuri et al. (2014), Van de Graaff and Patterson (2001), which reported that wastewater irrigation can improve soil fertility by supplying essential nutrients and stimulating microbial processes.

Pollution quantification

The high CF and PLI values observed in soils under SWW and SIWW irrigation indicate that wastewater irrigation contributes to the accumulation of heavy metals in the soil. Ni and Cd were identified as causing very high contamination, while Cu caused considerable contamination, and Pb and Zn caused moderate contamination, reflecting the composition of the wastewater and its interaction with soil properties. The varying response of soils to wastewater irrigation could be attributed to differences in the quantity of sewage received through flooding irrigation and the interaction between sewage and the soils in the affected lands, which may also be due to the type and content of heavy metals in the wastewater used in irrigation (Ahmed et al. 2010; Elnasr et al. 2017; Hamed et al. 2022; Kabel et al. 2017; Rezapour et al. 2024; Shahin et al. 2019). Therefore, the management of wastewater irrigation must move beyond generic guidelines. Our study identifies Cd and salinity as the priority constraints in this system. Mitigation should focus on i) targeted source control of Cd in sewage, and ii) agronomic practices (e.g., selective irrigation scheduling, soil amendments) to reduce Cd bioavailability and salt stress, ensuring the long-term viability of this necessary but risky practice (Hilles and Abushbak 2011; Kholikulov et al. 2025; Mohamed et al. 2023).

Conclusion

The results of the current study showed that wastewater samples recorded the highest values of most measured parameters as compared with Nile water samples, but the parameters were higher in SWW than in SIWW. Although the concentration of some heavy metals in wastewater was higher than the permissible

level, the concentration of other studied heavy metals was still under the safe limits. The results of water reflected on the soil, where the soils under SWW irrigation recorded the highest values of OM, clay percentage, available NPK, EC, and studied heavy metals, followed by soils under SIWW, as compared with soils under Nile water irrigation. The concentration of all studied heavy metals in soils under wastewater irrigation was lower than the permissible levels, which means that using wastewater in irrigation improves soil fertility in the study area safely. As for the number of rice plants, it followed the same trend where plants grown in soil under SWW irrigation recorded the highest values of N, P, K, and the studied heavy metals, with the notation that the content of most heavy metals in rice was lower than the permissible level. Consequently, the authors suggested close and periodic monitoring and checking for soluble salts and heavy metals content of both wastewater and soils under wastewater irrigation in the study area to avoid any future damage from the soluble salts and heavy metals to the soil and cultivated plants under wastewater irrigation.

In general, continuous examination of water, soil, and plant quality is required to ensure the successful use of wastewater. More studies are needed to study the limitations and benefits of reusing wastewater in crop irrigation.

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Data availability Data from the present article are available in the paper.

Declarations

Ethical approval This study has no experiments on persons or animals.

Informed consent Not applicable.

Conflict of interest The authors declare no competing interests.

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