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Assessment of Heavy Metal Pollution in Tap Water: Implications for Human Health in Egypt

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ABSTRACT

Egypt is undergoing rapid development, accompanied by a continuous increase in per capita tap water consumption. Consequently, the presence of various contaminants in drinking water has raised significant public health concerns. Among these contaminants, heavy metals are particularly alarming due to their toxicity and potential for long-term health effects. This study aimed to assess the concentrations of heavy metals in tap water sources and evaluate the associated health risks. A total of 27 tap water samples were collected from six different districts. The concentrations of 24 heavy metals and trace elements, including mercury (Hg), arsenic (As), lead (Pb), cadmium (Cd), and chromium (Cr), were quantitatively determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The results revealed that certain heavy metals exceeded the permissible limits established by the World Health Organization (WHO). To evaluate potential health risks, both carcinogenic and non-carcinogenic assessments were conducted using the United States Environmental Protection Agency (USEPA) guidelines, including the Chronic Daily Intake (CDI), Incremental Lifetime Cancer Risk (ILCR), Hazard Quotient (HQ), and Hazard Index (HI).

The findings indicated notable carcinogenic and non-carcinogenic risks associated with exposure to some heavy metals present in the tap water samples, highlighting the urgent need for continuous monitoring and effective water quality management strategies.

Keywords: Carcinogenic risk, Non-cancer risk, Heavy metals, Tap water.

1. INTRODUCTION

The occurrence of heavy metals in drinking tap water and their concentration have provided threats to human health [1, 2]. Long-term exposure may result in heavy metal accumulation in the human body, resulting in chronic diseases or effects, such as atherosclerosis, kidney damage, liver damage, impaired intellectual function, and cognitive function [3, 4, 5]. The risk from heavy metal exposure depends on the metal's inherent toxicity and the length of the exposure, the dose, the route of exposure, and the individual's characteristics (such as age, genetics, lifestyle, and nutritional status) [6, 7]. Waters contaminated with heavy metals from industrial effluents or natural sources pose a serious threat, not only to humans and other life forms but also for the ecosystem. In particular, heavy metal pollution is responsible for the most common water quality problems. The identified essential heavy metals are available for human beings through drinking water in suitable concentrations. However, the intake of heavy metals from water in industrial processes, leaching from landfills and waste deposits, and other human-induced activities is high. Continuous intake results in metal ions accumulating in the human body. This metal ions' concentration increases and leads to producing many severe and even life-threatening diseases, primarily when heavy metal concentrations exceed acceptable standard levels [8, 9, 10]. Heavy metal pollutants will remain and accumulate in drinking water sources for a long time [11]. Heavy metals are a common pollutant that contaminates the environment. Heavy metals in water are also very toxic and harmful to human health [12, 13]. The sources of heavy metals include manured soil, sewage effluents, industrial facilities such as chemical, electrical, and galvanization industries, and the discharge of waste from industries [14, 15, 16].

The global issue of environmental contamination affects several aspects of ecosystems. Pollutants from industrial or human waste are constantly recirculate into the ecosystem, agricultural land, livestock, and eventually into human health via the food chain [17]. Humankind is seriously concerned about heavy metal (HM) contamination of water, specifically in developing countries [1]. In every part of the world, water contamination is a serious problem. The river appears to be a huge waste container due to the intricacy of human activities along the watershed. The primary cause of the river's deterioration hazard is anthropogenic heavy metal pollution. Because heavy metals accumulate in water bodies and biota, they are toxic, carcinogenic, and harmful if they contaminate watersheds. [18]. However, industrial activities, inadequate disposal of waste, and the frequent use of household and distribution networks can all lead to the contamination of drinking waters with harmful trace elements [19, 20]. The corrosion of home plumbing systems is an additional origin for the trace elements detected in tap waters. Pipe corrosion can be effectively controlled by various factors, including the type of pipe used and its internal protective coating. Usually, corrosion develops gradually and discharges certain elements into the water when water comes into contact with the metal covering [21]. The health of individuals is at risk from heavy metals in drinking water. Though few heavy metals can bio accumulate in the human body (for example, in lipids and the gastrointestinal tract) and cause cancer and other hazards, populations are mainly exposed to heavy metals through water consumption [22]. Water quality is determined by its biological and physicochemical characteristics. Water can become unfit for human consumption due to changes in characteristics, including pH, temperature, and essential and non-essential trace metal concentrations. Heavy metal ions can contaminate water and cause a number of health problems in humans, including kidney and gastric damage, skin and gastric cancer, negative effects on the reproductive system, and mental disorders [23]. The most harmful toxic waste found in water is heavy metals. They have harmful, cancer-causing properties, and they cause bio magnification and bio accumulative effects in animals. In addition, compared to other heavy metals, mercury, lead, and cadmium are the most toxic and difficult to naturally degrade [24]. Although Cd is linked to cancer and kidney disability, it is also linked to skin damage and cancer risk. There have also been reports of additional consequences, including kidney and liver damage from Hg, gastrointestinal disorders from Cu, and anemia from Pb [25, 26]. Human health can be affected by acute or toxic consequences when certain pollutants, heavy metals, and nitrogen compounds are consumed through water or come into contact with the skin [27]. Aluminum is reported to be an extremely potent neurotoxic ant. It has also been reported that Al may be the cause of AD or

Alzheimer's disease. Inadequate coagulation with aluminum coagulants may be the source of the abnormally high aluminum content in tap water. Given that high concentrations of aluminum may be harmful to human health and cause changes in the brain that are indicative of Alzheimer's disease, it is crucial to make sure that the quantity of aluminum remaining in water appropriate for human consumption is as low as possible [28]. Numerous anthropogenic and natural processes, such as landfill leaching, can release these metals into the aquatic environment, home and industrial sewage, shipping, storm runoff, atmospheric release, and harbor operations [29, 30]. Excessive levels of heavy metals are harmful because they cause ecosystems to become unstable due to bioaccumulation in organisms, have toxic effects on the biota, and can even cause the death of the majority of organisms [31]. The prevalent heavy metal contaminants are present everywhere in trace amounts. Numerous sources, including atmospheric sources household effluents, electronic debris, industrial waste, and other metal-based industries, can contaminate aquatic habitats with heavy metals [32]. The present study aims to evaluate the quality of drinking tap water in selected districts of Egypt and to assess the potential non-carcinogenic and carcinogenic health risks associated with exposure to heavy metals.

2. STUDY AREA

Site Description: The current study was carried out to assess the quality of potable water distributed through household tap water systems in five distinct locations within the study region. The selected areas were chosen to represent a range of environmental and anthropogenic influences, including industrial activities, and urban residential zones (Fig. 1).

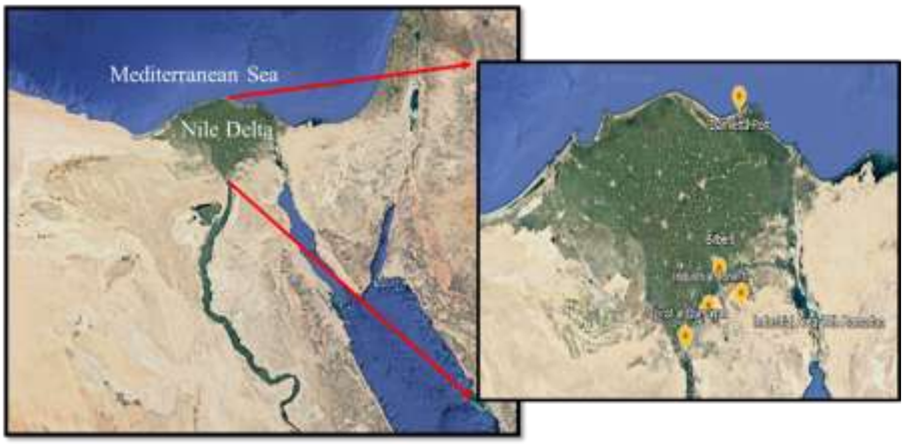

Fig (1): Location map of sampling sites for the present study

3. MATERIALS AND METHODS

3.1 Samples collection and analysis: As shown in Table 1, a total of 27 drinking tap water samples were collected in triplicate from nine sampling sites distributed across six main districts in Egypt. These sites were selected to reflect variations in spatial distribution and potential differences in local water distribution systems within each district. Following the standard protocol recommended by [33], 1000 milliliters of tap water were collected for each sample between April and November 2023, covering a range of conditions potentially influenced by seasonal variation. Water samples were collected using polyethylene containers that had been acid-washed. The water samples for heavy metal analysis were acidified with 0.5% nitric acid (HNO3) to a pH below 2.0, Water samples were acidified to minimize the precipitation and adsorption of metals on the walls of the container [34]. Samples were transported to the lab at a low temperature for further analysis. According to the Standard Method [33], each water sample was evaluated for a number of physicochemical characteristics, such as pH, electrical conductivity (EC), salinity, total dissolved solids (TDS), and heavy metals. The samples' pH was determined using a pH meter (Lutron pH-206 model). A digital portable TDS/conductivity meter (Lutron YK-22CT model) was used to measure the samples' salinity, electrical conductivity (EC), and total dissolved solids (TDS). The concentration of heavy metals was measured using Thermo Fisher Scientific iCAP 7400 Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES). The analysis was conducted using a Thermo Scientific™ iCAP™ 7400 ICP-OES spectrometer (Serial No. IC74DU0222, Germany) following acid digestion with HNO_3 (69%) and H_2O_2 (30%) in a Milestone MLS 1200 Mega microwave digestion system, based on the method of [103]. Calibration was performed using certified calibration standards, and full QA/QC protocols were applied through Qtegra™ ISDS software, including the use of blanks and certified reference materials (CRMs). Instrument detection limits (IDLs) were statistically determined using replicate measurements (n = 10) of blank and standard solutions (at 50× expected IDL), and calculated using standard deviation and signal differences between the blank and standard. Representative detection limits achieved in Axial view include 1.06 µg/L for Pb, 0.07 µg/L for Cd, 1.43 µg/L for As, 0.14 µg/L for Hg, and 0.21 µg/L for Cr. Recovery rates were verified by analyzing CRMs within the analytical sequence, confirming the accuracy and reliability of the method, while blank samples were used to ensure system cleanliness and validate detection limits.

Table 1: Location of sampling sites

Location	Site
Jazirat Al-Qursayah, Al-Giza	Site 1
Industrial Zone , Obour City, Qalyubia	Site2 Site 3 Site 4
Belbeis, Al-Sharkeya	Site5
10th of Ramadan, Industerial City, Al-Sharkeya	Site6
Damietta Port, Damietta	Site7
Industrial Zone , Obour City, Qalyubia	Site8 Site9

3.2 Human health risk evaluation

3.2.1 Exposure assessment: The chronic daily intake (CDI) of heavy metals (HMs) was used to evaluate the risks of cancer and non-cancer risk in both children and adults [35, 36]. Equation 1 was used to determine the HMs' CDI when ingested orally.

$$CDI = (C \times IR \times EF \times ED)/ (BW \times AT) \quad (1)$$

Where: C is the concentration of the contaminant in water sample (mg/L); body weight "BW" is (70 kg for adults and15 kg for children); AT is the average exposure time (for non-carcinogens, AT = ED x 365 = 2190, and 10950 days for children and adults, respectively; for carcinogens, AT is calculated as 70 × 365 = 2550 days for both children and adults); IR is the ingestion rate per unit time (a child consumes 1 L/day and an adult consumes 2.2 L/day); and CDI is the chronic daily intake (mg/kg/day) [35].

3.2.2 Non-Cancer risks: The non-cancer hazards arising from the non-carcinogenic effects of heavy metals (HMs) in drinking water were determined by applying Eq. 2, non-cancer hazard quotient.

$$HQ = CDI/RfD \quad (2)$$

Where, according to [37], Table 2 shows the chronic oral reference dose (RfD), the non-cancer hazard quotient (HQ), and the chronic daily intake (mg metal/kg/day) as well as the daily oral exposure level of the overall population plus a sensitive subpopulation that is likely to be free from a significant lifetime risk of adverse effects. The potential risk to human health provided by exposure to many heavy metals was measured using the chronic hazard index (HI), which is the sum of all HQ calculated for each heavy metal [38]. If HQ or HI is less than 1, there are no substantial non-cancer hazards; if HQ or HI is greater than 1, there are considerable non-cancer risks, which increase as HQ or HI increases [39].

$$HI = \Sigma HQ_{HM1}\ HQ_{HM\ 2} \ldots HQ_{HMn}$$

3.2.3 Cancer risk: The risk of developing cancer is the result of a lifetime average exposure to a pollutant at a dose of 1 mg/kg body weight/day. The probability of developing cancer over a 70-year lifetime as a result of a 24-hour exposure to a possible carcinogen is known as incremental lifetime cancer risk, or ILCR [40]. This is the method by which cancer risk was expressed. The calculation of cancer risk involved multiplying the cancer slope factor (CSF), expressed in mg/kg/day, by the CDI $(mg/kg/day)^{-1}$ (Equation 3) [40]:

$$ILCR = CDI \times CSF \quad (3)$$

Where ILCR refers to incremental life cancer risk, CDI for chronic intake (mg/kg/BW/day), and CSF for cancer slope factor, Table 2. It was assumed that the total cancer risk resulting from drinking a specific type of water and being exposed to various contaminants was equal to the sum of each metal incremental risk (∑ILCR). According to [38], the United States Environmental Protection Agency (USEPA) determines the permissible or minimum cancer risk for regulation reasons to be between 1×10^{-6} and 1×10^{-4}.

3.3 Statistical analysis

The findings are presented as the three replicates' mean ± standard deviation (SD). Using SPSS (ver. 26), a one-way ANOVA was performed on the data. Duncan's multiple ranges were used to perform mean separation at $P<0.05$. To determine whether there was a linear relationship between the water quality parameters, the Pearson's r coefficient was computed.

4. RESULTS AND DISCUSSION

4.1 Physical and chemical parameters

Physical and chemical parameters for the assessed tap water samples are shown in Fig.2. The pH of water is one of the most critical operational quality parameters [41]. Though it doesn't directly affect human health, the pH parameter can have an indirect impact because of its effects on water quality parameters like pathogen survival and element solubility. Samples of drinking water were found to have an average pH of 7.27, with minimum and maximum levels of 6.84 and 7.69 at Site 1 and Site 5, respectively. As seen in Figure 2, the pH of drinking water samples was within the permissible limits (6.5-8.5) set by WHO, in 2017 for drinking water. According to [42], pH values of drinking tap water ranged from 6.3 to 7.0 and this nearly matches the obtained results. According to [41]; pH values of Tap water ranged from 7.01 to 7.43 from different industrial cities of Egypt and from 7.25 to 7.64 as reported by [43] for different tap water samples and this agreed with the obtained results.

Samples of drinking water were found to have an average EC of 0.384 ms/cm with a minimum value of 0.19 ms/cm and a maximum value of 0.429 ms/cm. The EC evaluates the concentration of ions and dissolved solids in water that facilitate the flow of current. Higher EC indicates a higher concentration of dissolved solids and salts [44]. Since EC indicates the amount of salt in water, drinking water with a high EC can cause a variety of diseases, including hepatitis, cancer, diarrhea, and gastroenteritis, which can harm the kidneys, stomach, and heart [45].

With minimum and maximum TDS values of 94.33 and 293.67 mg/L at Sites 6 and 8, respectively, drinking water samples showed an average TDS value of 253.05 mg/L. The TDS value is significantly lower than 1,000 mg/l, which is the highest allowable limit established by the WHO, therefore there aren't any health problems. Higher TDS levels in drinking water result in the scaling of water distribution pipelines and give the water an unpleasant taste [46]. The salinity values of drinking water samples were between 0.01 and 0.02 with an average of 0.019.

Table 3 displays the overall concentrations of the metals studied in the water samples as well as the WHO-established maximum permissible limits [47, 48]. The maximum Al content in drinking water samples was 904.17 recorded at Sites 8. Al concentrations were higher than the WHO-recommended limit of 0.1 mg/L for all sites, except it was not detected at site 5. Because it occurs naturally and as a result of human activity, aluminum is a metal that is widely distributed in nature and can be found in water [49]. Toxicological research has demonstrated the neurotoxicity of aluminum [50].

The Se level at site 4, showed the maximum value of 20.1 mg/L. All the measured values were higher than the permissible limit of 0.04 mg/L except for 6, which was not found. Due to its limited daily intake range and importance as a nutrient for humans, selenium is receiving attention; yet, excessive doses can be toxic [51, 52].

The V level was not detected in Sites 1, 8 and 9. It showed the highest value of 2.7 mg/L in site 5. The contaminant vanadium has been recognized as possibly hazardous [53, 54]. According to [55], vanadium compounds are extremely hazardous to both people and animals.

Hg in site 3 displayed maximum value of 5.179 mg/L, above the allowed limit of 0.006 for all sites except for sites 4, 5 and 6 as it was not detected. Mercury is extremely mobile and highly toxic. Compared to other hazardous and nonradioactive heavy metals, it is thought to be more harmful. Additionally, it is highly likely to bio accumulate and biomagnify throughout the environment [56]. At sites 9 and 8, silver wasn't detected, while the maximum value detected was 2.4 mg/L.

Maximum of 11.8 mg/L were recorded for B, which was not found in Site 5. All measured values exceeded the permissible limit of 2.4 mg/L.

Ba was not found at Sites 5, 8 and 9. Maximum values of 1.34 mg/L was recorded in Site 4 which is at the maximum limit of 1.3 mg/L. Ba can accumulate in the muscle and bone systems like the quantity of Ca [57].

While cadmium was not detected in site 5, 8, and 9, it was found at a maximum level in site 3 of 0.228 mg/L. The measured values for all sites were higher than the allowed limit of 0.003 mg/L. Cadmium (Cd), a known carcinogen, has a preferred distribution in these organs and can have detrimental effects on the kidney and bone [58].

Co is not found in sites 1, 3, 4, 5, 8 and 9, maximum value of 0.18 mg/L was found in in site 7. According to [59], chronic exposure to cobalt may cause cancer, oxidative stress, pneumonia, fibrosis, and damage to DNA.

Cr was not detected at site 6, 9 at maximum concentration of 6.5 mg/L. all measured values were above the allowed limit of 0.05 mg/L. When consuming water contaminated with Cr (a highly toxic heavy metal), problems with the Gastric, intestines, and liver emerge [59].

Cu was found in sites 6, with a maximum value of 2.4 mg/L exceeding the maximum limit of 2.0. In all sites, the measured values were higher than the permissible limit except at site 5, where Cu was not found. Although copper doesn't bio accumulate in human bodies, excessive consumption of it can make it extremely toxic, resulting in vomiting, kidney and liver damage, diarrhea, coma, eye and nose irritation, and even death [96].

Fe levels varied from 0.2 in site 5 to 42.8 mg/L in site 7. All concentrations of Fe were higher than the permissible limit except in site 5. Mn was found with a maximum value of 0.6 mg/L at site 4 and a low value of 0.074 mg/L at site 8, and in sites 2, 4 and 7, it was higher than the allowed limit. The WHO recommends that the concentrations of Fe and Mn in drinking water not exceed 0.3 mg/L and 0.4 mg/L, respectively. Fe can have a harmful effect on human health at high doses, influencing the respiratory, neurological, or cardiovascular systems as well as causing Parkinson's and Alzheimer's disease. Low amounts of iron are necessary for proteins, enzymes, and hemoglobin [59]. Excessive Mn intake through water can have harmful effects on the nervous system, affecting motor and cognitive functions [60].

Ni levels varied from 0.12 to 3.3 mg/L, with site 8 having the lowest value and site 2 having the highest, above the allowed limit (0.07 mg/L) for all sites. The U.S. EPA states that as nickel contributes significantly to water pollution, it must be monitored and a related health risk assessment must be implemented [61].

Except for site 7, where In showed the highest value of 3.12 mg/L, it wasn't detected in any of the other sites.

Li exhibited a maximum concentration of 3.07 mg/L in site 5 and in sites 2, 3, 4, 6, 8 and 9 Li was not detected. In Denmark [62] and Argentina [63], Li has been found in drinking water in varying quantities. Human health is affected if it exceeds the MAC, leading to problems with the kidneys, vomiting, and disorders of the circulatory system [64].

Mg levels ranged from 9.2 to 1360.1 mg/L; site 9 had the highest levels while site 5 had the lowest. A high concentration of magnesium can have detrimental consequences on the human body, including laxative effects, nausea, and even paralysis [65, 64]. Nevertheless, magnesium is another element with significant benefits, as it ensures the well-functioning of cells in enzyme activation.

The highest value for Pb was 1.64 mg/L in site 5. This value exceeded the maximum limit of 0.01 mg/L for all sites except for sites 4, 6, 8, and 9 as Pb was not detected. According to [66], lead is a highly toxic substance that carries long-term health hazards, such as headache, kidney problems, lung cancer, hypertension, and mental retardation.

Site 5 had the lowest value for Sr of 0.28, while site 9 had the highest value at 8.5 mg/L. Because Sr can substitute calcium in bones, it can affect bone growth and strength. As a result, Sr in water becomes harmful when concentrations beyond the permissible limit [52].

Zn exceeded the permitted limit of 3 mg/L for all sites except for sites 8, and 9 as it was below the limit, a maximum value of 12.17 at site 4, and a minimum of 1.93 at site 8. Zinc is a necessary mineral for good health, but excessive use can lead to anemia, cramping or vomiting, renal and hepatic lesions of chronic diseases, and diabetes [59].

For As, it wasn’t detected in sites 8 and 9, and the highest value being 1.4 mg/L at site 5, exceeding the maximum limit of 0.01 mg/L for all sites. The health of humans and the environment is greatly threatened by the toxic heavy element arsenic [67, 68]. Due to its high toxicity, arsenic causes negative health effects when consumed in large quantities over an extended period of time. Several diseases, including skin lesions, cancer (including kidney and skin cancer), neurological conditions, and cardiovascular illnesses, have been linked to prolonged exposure to high levels of arsenic in drinking water [69].

Na levels ranged from 10.2 at site 5 to 10143 at site 9. Sodium is the most prevalent cation in water and a necessary nutrient for both domestic and agricultural water use. Alkali feldspar, which is a representation of the geological structure, or weathering processes are sources of sodium. However, if it exceeds the thresholds, it causes a risk for individuals with circulatory, renal, or cardiac diseases, as well as vomiting and hypertension [65, 64].

K exhibited a maximum of 412.4 mg/L in site 9, and a minimum of 6.5 mg/L in site 1. People with kidney disease, heart disease, coronary artery disease, hypertension, diabetes, and those using medications that interfere with the body's normal processing of potassium may experience major health impacts from increased exposure to potassium [70].

With a high level of 604.66 mg/L in site 8 and a minimum value of 95.7 mg/L in site 5. Calcium is necessary for many biological processes, such as the formation of bones and the permeability of cell walls [71]. Cardiovascular disorders are caused by significantly excessive calcium levels [44]. Bi was not found in sites 5, 6, 7 and 8, while in site 3, the highest value was 2.3.

The elevated concentrations of certain heavy metals observed in the tap water samples analyzed in this study may be linked to multiple anthropogenic and infrastructural factors. In particular, the presence of high levels of lead (Pb), copper (Cu), and iron (Fe) in several sites may be attributed to the corrosion of aging water distribution networks, old galvanized pipes, or plumbing systems containing lead solder.

Previous studies have reported elevated concentrations of lead (Pb) and cadmium (Cd) in the River Nile, with Pb levels exceeding the permissible limits in several cases [100]. In a separate investigation conducted from July 2019 to June 2020, Pb contamination was notably high at certain locations within the Greater Cairo region, whereas Cd concentrations remained within acceptable regulatory thresholds across all monitored sites [101]. Recent findings by [102] revealed notable levels of heavy metal contamination in both water and sediment samples from a coastal landscape in the Nile Delta. In water samples, the highest concentrations were recorded for iron (Fe: mean = 1.16 mg/L), zinc (Zn: 1.13 mg/L), and aluminum (Al: 1.05 mg/L), with lead (Pb) reaching up to 1.20 mg/L in some sites, well above the WHO permissible limits for drinking water. Manganese (Mn), copper (Cu), and nickel (Ni) were also detected at moderate levels. These elevated concentrations indicate significant anthropogenic inputs, likely from industrial discharge, agricultural runoff, and wastewater.

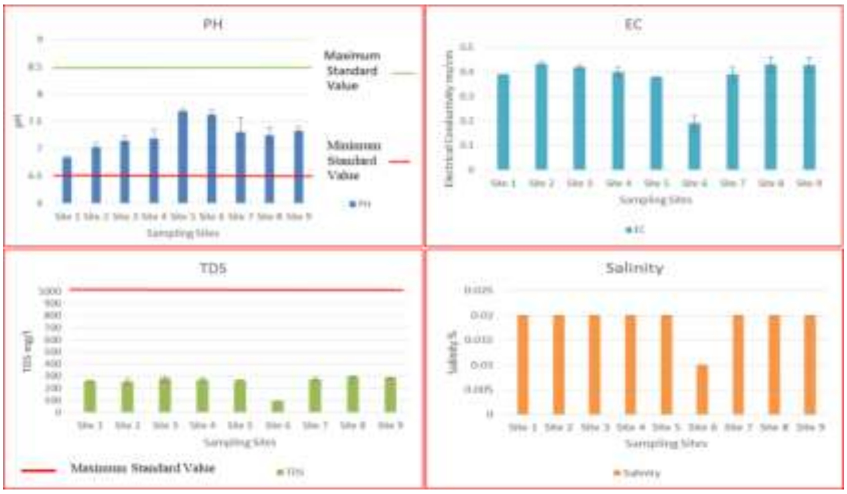

Fig (2): Physicochemical parameters of drinking water samples with the WHO permissible limits

Table 2: Standard permissible limits used in this study, oral reference dose (RFD) of metal elements from the US EPA IRIS, and cancer slope factor (CSF) [99; 98; 48]; and The maximum permissible limits for the standards and specifications that must be available in drinking water and domestic use, issued by a decision of the Minister of Health and Population No. 458 of 2007.

	WHO (mg/L)	USEPA(mg/L)	Egyptian standards (mg/L)	Rfd (mg kg^{-1} day^{-1})	CSF (mg kg^{-1} day^{-1})
Al	0.1	0.2	0.2	1	-
Se	0.04	0.05	0.01	0.005	-
Hg	0.006	0.002	0.001	0.0003	-
B	2.4	-	2.4	0.2	-
Ba	1.3	2	0.7	0.07	-
Cd	0.003	0.005	0.003	0.0005	0.38
Cr	0.05	0.1	0.05	0.003	0.5
Cu	2.0	1.3	2.0	0.04	-
Fe	0.3	-	0.3	0.7	-
Mn	0.4	-	0.4	0.14	-
Ni	0.07	-	0.02	0.02	1.7
Pb	0.01	0.015	0.01	0.0035	0.0085
Zn	3	-	3.0	0.3	-
As	0.01	0.01	0.01	0.0003	1.5

Table 3: Heavy metals concentrations (mg/L) in drinking water. The means that are followed by the same letter do not differ significantly at $p < 0.05$. Each result is the mean of three replicates ± SD.

Site	Heavy Metals									
	Ag	**Al**	**As**	**Cd**	**Cr**	**Cu**	**Hg**	**Pb**	**Bi**	**Ba**
1	1.02 ± 0.03^{bc}	**169.96 ± 150.6 ^{b}**	**0.42 ± 0.3^{bc}**	**0.1 ± 0.02^{c}**	**0.531 ± 0.6^{ab}**	1.9 ± 0.2^{cd}	**3.5 ± 5.7^{bc}**	**0.052 ± 0.004^{a}**	0.44 ± 0.038^{a}	0.77± 0.14cd
2	0.254 ± 0.05^{ab}	**43.63 ± 7.6 ^{a}**	**0.336 ± 0.13^{b}**	**0.185 ± 0.01^{d}**	**3.75 ± 0.29^{cde}**	2.08 ± 0.4^{cd}	**1.17 ± 0.36^{ab}**	**0.3 ± 0.1^{b}**	1.3 ± 0.5^{bc}	0.59 ± 0.41^{bcd}
3	1.3 ± 1.3 ^{cd}	**40.569 ± 1.6 ^{a}**	**0.237 ±0.05^{ab}**	**0.228 ± 0.02^{e}**	**3.6 ± 1.7^{cde}**	1.46 ± 0.8^{bc}	**5.179 ± 0.3^{c}**	**0.56 ± 0.07^{c}**	2.3 ± 0.68^{d}	0.555 ± 0.4^{bcd}
4	0.7 ± 0.32 ^{abc}	**30.4 ± 22.6 ^{a}**	**0.41 ± 0.2^{bc}**	**0.2 ± 0.04^{e}**	**3.359 ± 2.9^{bcd}**	2.1 ± 0.1^{d}	ND^{a}	ND^{a}	1.77 ± 0.1^{c}	1.34 ± 0.3^{d}
5	0.3 ± 0.007 ^{ab}	ND ^{a}	**1.4 ± 0.11 ^{d}**	ND ^{a}	**0.9 ± 0.1^{abc}**	ND^{a}	ND^{a}	**1.64 ± 0.17^{e}**	ND^{a}	ND ^{a}
6	2.4 ± 0.56 ^{d}	**246.65 ± 3.3 ^{b}**	**0.439 ± 0.05^{bc}**	**0.03 ± 0.004^{b}**	ND^{a}	**2.4** ± 0.31^{d}	ND^{a}	ND^{a}	ND^{a}	0.33 ± 0.04^{ab}
7	0.033 ± 0.005 ^{a}	**75 ± 48.83 ^{a}**	**0.602 ± 0.04^{c}**	**0.05** ± **0.01^{b}**	**4.9 ± 3.6^{de}**	0.95 ± 0.45^{b}	**2.4 ± 1.4^{abc}**	**1.2 ± 0.18^{d}**	ND^{a}	0.5 ±0.09^{bc}
8	ND ^{a}	**904.17 ± 27.9^{c}**	ND ^{a}	ND ^{a}	**1.09 ± 0.041^{abc}**	1.86 ± 0.149^{cd}	**1.963 ± 0.35^{abc}**	ND^{a}	ND^{a}	ND ^{a}
9	ND ^{a}	**16.8 ± 5.7 ^{a}**	ND ^{a}	ND ^{a}	**6.5 ± 0.3^{e}**	1.6 ± 0.1^{cd}	**3.2 ± 0.41^{abc}**	ND^{a}	1.233 ± 0.09^{b}	ND ^{a}
WHO	**--**	**0.1**	**0.01**	**0.003**	**0.05**	**2.0**	**0.006**	**0.01**	**-**	**1.3**
	Fe	**Li**	**Mn**	**Ni**	**Se**	**V**	**Zn**	**Ga**	**In**	**B**
1	**7.7 ± 1.57^{ab}**	0.008 ± 0.003^{a}	0.198 ± 0.04^{bc}	**0.143 ± 0.09^{a}**	**8.4 ± 0.9^{b}**	ND ^{a}	**7.284 ± 0.7^{abc}**	ND ^{a}	ND ^{a}	**3.05 ± 4.3^{a}**
2	**15.7 ± 9.4^{bc}**	ND ^{a}	0.437 ± 0.32^{bcd}	**3.313 ± 0.6^{d}**	**19.4 ± 7.3^{c}**	0.6 ± 0.3^{bc}	**10.12 ± 8.5^{bc}**	7.815 ± 1.2^{c}	ND ^{a}	**10.9 ± 2.28^{cd}**
3	**16.74 ± 9.5^{bc}**	ND ^{a}	0.29 ± 0.38^{bcd}	**1.9 ± 1.65^{bcd}**	**17.1 ± 1.3^{c}**	0.78 ± 0.4^{bc}	**7.62 ± 6.96^{abc}**	7.98 ± 0.9^{c}	ND ^{a}	**11.8 ± 3.2^{d}**
4	**21.4 ± 14.7^{cd}**	ND ^{a}	**0.6 ± 0.35^{c}**	**2.8 ± 2.3^{cd}**	**20.1 ± 0.9^{c}**	0.87 ± 0.11^{c}	**12.17 ± 9.01^{c}**	ND ^{a}	ND ^{a}	**11.1 ± 2.1^{cd}**
5	0.2 ± 0.01^{a}	3.07 ± 0.58^{c}	0.19 ± 0.009^{bc}	**0.3 ± 0.14^{ab}**	**1.7 ± 0.2^{ab}**	2.7 ± 0.2^{d}	2.9 ± 0.12^{ab}	ND ^{a}	ND ^{a}	ND ^{a}
6	**10.6 ± 0.73^{abc}**	ND ^{a}	0.122 ± 0.0095^{a}	**1.27 ± 0.06^{abc}**	ND ^{a}	0.56 ± 0.2^{bc}	**4.4 ± 0.32^{abc}**	2.9 ± 0.24^{b}	ND ^{a}	**3.2 ± 0.7^{ab}**
7	**42.8 ± 6.9^{e}**	0.93 ± 0.13^{b}	**0.5 ± 0.18^{bc}**	**1.45 ± 0.6^{abc}**	**1.6 ± 0.18^{ab}**	0.5 ± 0.2^{b}	**3.767 ± 1.45^{abc}**	2.564 ±0.5^{b}	3.12 ± 0.18^{b}	**9.513 ± 2.4^{cd}**
8	**5.075 ± 0.18^{ab}**	ND ^{a}	0.074 ± 0.02^{a}	**0.12 ± 0.019^{a}**	**6.88 ± 0.3^{ab}**	ND ^{a}	1.939 ± 0.09^{a}	ND ^{a}	ND ^{a}	**7.236 ± 0.41^{bc}**
9	**33.7 ± 3.04^{de}**	ND ^{a}	0.27 ± 0.04^{bcd}	**0.96 ± 0.05^{ab}**	**7.3 ± 10.4^{ab}**	ND ^{a}	2.36 ± 0.17^{ab}	0.2 ± 0.06^{a}	ND ^{a}	**9.7 ± 1.87^{cd}**
WHO	**0.3**	-	**0.4**	**0.07**	**0.04**	-	**3.0**	-	-	**2.4**

Site	**Co**	Ca	K	Mg	Na	Sr
1	ND ^{a}	337.95 ± 77.6^{abc}	6.503 ± 0.15^{a}	42.5 ± 6.04^{a}	85.2 ± 6.6^{a}	0.849 ± 0.08^{a}
2	0.026 ± 0.02^{b}	358.339 ± 277.9^{abcd}	50.4 ± 12.4^{ab}	41.6 ± 24.6^{a}	97.24 ± 27.7^{a}	0.86 ± 0.3^{a}
3	ND ^{a}	410.3 ± 243.9^{bcd}	52.6 ± 13.6^{ab}	50.05 ± 21^{a}	104.3 ± 23.56^{a}	0.9 ± 0.19^{a}
4	ND ^{a}	533.8 ± 274.7^{cd}	69.6 ± 5.16^{ab}	59.56 ± 22.95^{a}	112.4 ± 36.9^{a}	1.17 ± 0.48^{a}
5	ND ^{a}	95.7 ± 4.27^{a}	ND ^{a}	9.2 ± 0.27^{a}	10. ± 21.7^{a}	0.28 ± 0.04^{a}
6	0.06 ± 0.013^{c}	222.1 ± 32.05^{ab}	134.5 ± 15.29^{bc}	25.7 ± 0.3^{a}	59.97 ± 4.4^{a}	0.67 ± 0.067^{a}
7	0.18 ± 0.026^{d}	470.2 ± 184.98^{bcd}	215.5 ± 191.5^{c}	662.7 ± 670.2^{b}	4653.3 ± 4959.5^{b}	4.4 ± 3.76^{b}
8	ND ^{a}	604.662 ± 13.8^{d}	401.105 ± 8.1^{d}	1328.4 ± 25.17^{c}	9836.7 ± 93.08^{c}	8.067 ± 0.5^{c}
9	ND ^{a}	601.8 ± 18.3^{d}	412.4 ± 10.9^{d}	1360.1 ± 24.4^{c}	10142.8 ± 343.5^{c}	8.5 ± 1.4^{c}
WHO	-	**-**	**-**	**-**	**-**	**-**

Table 4: Statistical Analysis of Variance (ANOVA) of Elemental Concentrations across Sampling Sites

Element and source of variation	df	Mean Square	F	*P* Value	Element and Source of variation	df	Mean Square	F	*P* Value	Element and source of variation	df	Mean Square	F	P Value
Ag					**Fe**					**Bi**				
Site	8	**1.837**	**7.425**	**0.000**	Site	**8**	**483.660**	**9.039**	**0.000**	Site	**8**	**2.298**	**24.790**	**0.000**
Error	17	**0.247**		**0.86**	Error	**17**	**53.506**		**12.602**	Error	**17**	**0.093**		**0.52**
Al					**Li**					**In**				
Site	8	**245919.66**	**77.525**	**0.000**	Site	**8**	**3.187**	**79.120**	**0.000**	Site	**8**	**2.256**	**605.358**	**0.000**
Error	17	**3172**		**97.03**	Error	**17**	**0.040**		**0.3457**	Error	**17**	**0.004**		**0.1052**
As					**Mn**					**Ba**				
Site	8	**0.509**	**26.958**	**0.000**	Site	**8**	**0.104**	**2.196**	**0.082**	Site	**8**	**0.583**	**10.767**	**0.000**
Error	17	**0.019**		**0.237**	Error	**17**	**0.047**		**0.38**	Error	**17**	**0.054**		**0.401**
Cd					**Ni**					**B**				
Site	8	**0.027**	**105.680**	**0.000**	Site	**8**	**3.934**	**3.861**	**0.009**	Site	**8**	**54.194**	**9.491**	**0.000**
Error	17	**0.000**		**0.0276**	Error	**17**	**1.019**		**1.739**	Error	**17**	**5.710**		**4.117**
Cr					**Se**					**Ca**				
Site	8	**14.213**	**4.959**	**0.003**	Site	**8**	**177.421**	**9.111**	**0.000**	Site	**8**	**87677.500**	**2.934**	**0.030**
Error	17	**2.866**		**2.92**	Error	**17**	**19.472**		**7.60**	Error	**17**	**29881**		**297.807**
Cu					**V**					**Co**				
Site	8	**1.523**	**11.767**	**0.000**	Site	**8**	**2.104**	**50.014**	**0.000**	Site	**8**	**0.009**	**149.768**	**0.000**
Error	17	**0.129**		**0.6197**	Error	**17**	**0.042**		**0.353**	Error	**17**	**0.00006**		**0.013**
Hg					**Zn**					**K**				
Site	8	**9.952**	**2.468**	**0.056**	Site	**8**	**39.067**	**1.623**	**0.191**	Site	**8**	**76443.632**	**17.332**	**0.000**
Error	17	**4.033**		**3.460**	Error	**17**	**24.067**		**8.45**	Error	**17**	**4410.656**		**114.42**
Pb					**Ga**					**Mg**				
Site	8	**1.047**	**116.644**	**0.000**	Site	**8**	**33.143**	**106.063**	**0.000**	Site	**8**	**985933.177**	**18.667**	**0.000**
Error	17	**0.009**		**0.163**	Error	**17**	**0.312**		**0.963**	Error	**17**	**52817**		**395.93**
Na					**Sr**					**PH**				
Site	8	**56634969.389**	**19.726**	**0.000**	Site	**8**	**32.479**	**16.308**	**0.000**	Site		**0.213**	**3.368**	**0.017**
Error	17	**2871105**		**2919.18**	Error	**17**	**1.992**		**2.431**	Error		**.063**		**0.43**
EC					**TDS**					**Salinity**				
Site	8	**0.018**	**11.646**	**0.000**	Site	**8**	**10994.806**	**28.606**	**0.000**	Site	**8**	**0.00003**		
Error	17	**.002**		**0.07**	Error	**17**	**384.355**		**33.78**	Error	**17**	**0.000**		**0**

4.2 Human Health Risk Assessment

4.2.1 Non-cancer risk

The process of determining the nature and magnitude of harmful health consequences that humans who may be exposed to toxic substances in a contaminated environment are exposed to is known as human health risk assessment. Based on the USEPA guidelines, risk assessments was evaluated in the present work. Drinking water is one of the main ways that humans are exposed to heavy metals [72]. Daily ingestion of heavy metals has a direct correlation with their level of toxicity to human health. In this study, chronic daily intake was evaluated, computing the values for CDI is the first step in the non-carcinogenic analysis. Table 5 displays the results for the ingestion pathway's chronic daily intake (CDI) for both adults and children at the sampling sites. The results indicated that children have higher CDI values than adults. Al showed the highest CDI in all sites. Table 6 shows the hazard quotient (HQ) and hazard index (HI) values of metals in drinking tap water. This study established a higher hazard quotient (HQ) of metals in drinking tap water, which is greater than 1, which indicates a high non-carcinogenic/ carcinogenic risk to individuals. The highest HI value of 1573.07 was recorded for site 3 followed by site 1 of 1030.36 as Hg is a main contributor to non-cancer risks for children. For adults, the highest HI of 741.59 was recorded in site 3 followed by site 1 with an HI value of 485.7 as Hg is a main contributor to non-cancer risks for adults. The highest mean HQ was recorded in site3 and its mean for children was higher than adults as Hg is a main contributor. The highest coefficient of variation (CV) was recorded for site1. The extremely high Hazard Index (HI) values for children, such as the alarming value of 1573.07 at

Site 3, indicate a severe health risk due to chronic exposure to heavy metals, particularly mercury (Hg) and lead (Pb). These levels are especially concerning for vulnerable populations like children, whose developing nervous systems are more susceptible to toxic insults. Mercury exposure is associated with serious neurodevelopmental effects, including cognitive impairments, learning disabilities, and behavioral problems, while lead exposure has been linked to reduced IQ, attention deficits, memory loss, and long-term neurological damage. These findings highlight the urgent need for mitigation strategies to reduce exposure, improve water quality, and implement public health interventions to protect at-risk groups.

Fish and shellfish consumption is the main way that people in general consume mercury. The majority of mercury emitted into the atmosphere by human activity originates from the burning of fossil fuels, solid waste combustion, smelting, and mining. All mercury that is emitted into the environment eventually ends up in surface water bodies or soil, where it potentially finds its way into sources of drinking water. When mercury is ingested through drinking water, it can lead to immunodeficiency and impaired neurological development, among other detrimental consequences [73]. The term "heavy metals" describes a broad range of potentially hazardous substances that are primarily found in trace concentrations in the environment. A number of these heavy metals are necessary for good health but can be dangerous in excess of recommended quantities. The effects of heavy metals on health are frequently dependent upon the type of metal, its valence state, and the solubility of the compound that is absorbed through the skin, breathed, or consumed [74, 32, 5]. Drinking water contains a number of heavy metals that, if consumed, could adversely affect health of individuals. Usually, heavy metals bind to proteins and/or enzymes to change their structure, impede their activity, or even replace vital parts of the enzymes with other materials. This is how heavy metals cause toxicity. Generally speaking, these metals react at low amounts and pass through the digestive system gradually. Damage to the skin, lungs, and other body systems involved in the absorption are additional harmful effects [12, 75, 76]. Heavy metal compounds can release metal ions in an aqueous environment and dissolve easily in water. The sulfur and selenium atoms found in the active parts of numerous enzymes and proteins can form reversible bonds with these metal ions. By changing the structure of proteins, reducing the activity of enzymes, and substituting vital enzyme components at various sites, the ionization process has a harmful effect. Metals can become metal ions, which can inhibit and degrade metalloenzymatic activity, when they attach to vital carrier biomolecules and enter the body. Thus, heavy metal toxicity in biological systems results from a decrease in the functionality of enzymes or an inhibition of their catalytic activity [77, 78, 79, 80].

Table 5: Chronic daily intake (CDI) dose in different sites (mg/kg/day)

	Site 1		Site 2		Site 3		Site 4		Site 5		Site 6		Site 7		Site 8		Site 9	
	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children
Aluminum (Al)	5.34	11.33	1.371	2.91	1.3	2.7	0.96	2.02	0	0	7.8	16.4	2.36	5	28.42	60.278	0.5	1.1
Selenium (Se)	0.27	0.56	0.61	1.29	0.5	1.14	0.63	1.34	0.05	0.116	0	0	0.05	0.1	0.22	0.46	0.23	0.49
Mercury (Hg)	0.11	0.23	0.04	0.08	0.16	0.35	0.00	0.00	0	0	0	0	0.08	0.16	0.062	0.131	0.1	0.216
Boron (B)	0.096	0.2	0.34	0.72	0.37	0.79	0.34	0.74	0	0	0.1	0.22	0.3	0.6	0.23	0.48	0.3	0.646
Barium (Ba)	0.02	0.05	0.02	0.04	0.017	0.037	0.04	0.09	0	0	0.01	0.022	0.02	0.03	0	0	0	0
Cadmium (Cd)	0.003	0.007	0.006	0.012	0.007	0.015	0.007	0.01	0	0	0.001	0.002	0.002	0.003	0	0	0	0
Chromium (Cr)	0.017	0.035	0.12	0.25	0.11	0.24	0.12	0.22	0.029	0.06	0	0	0.16	0.33	0.03	0.07	0.21	0.436
Copper (Cu)	0.06	0.13	0.07	0.14	0.046	0.097	0.066	0.139	0	0	0.07	0.16	0.03	0.06	0.06	0.124	0.05	0.11
Iron (Fe)	0.24	0.516	0.49	1.05	0.53	1.116	0.67	1.4	0.006	0.014	0.33	0.706	1.35	2.85	0.16	0.34	1.1	2.3
Manganese (Mn)	0.006	0.013	0.013	0.03	0.009	0.019	0.02	0.0422	0.006	0.013	0.004	0.008	0.016	0.03	0.002	0.005	0.009	0.0182
Nickel (Ni)	0.004	0.01	0.1	0.22	0.06	0.13	0.09	0.19	0.01	0.02	0.04	0.08	0.05	0.097	0.004	0.008	0.03	0.064
Lead (Pb)	0.002	0.003	0.01	0.02	0.018	0.037	0	0	0.05	0.11	0	0	0.04	0.08	0	0	0	0
Zinc (Zn)	0.23	0.49	0.32	0.67	0.24	0.508	0.38	0.8	0.09	0.19	0.14	0.293	0.12	0.25	0.06	0.13	0.07	0.157
Arsenic (As)	0.013	0.03	0.011	0.023	0.007	0.0158	0.013	0.028	0.04	0.09	0.014	0.029	0.02	0.04	0	0	0	0

Table 6: HQ and HI in different drinking water sites

	Site 1		Site 2		Site 3		Site 4		Site 5		Site 6		Site 7		Site 8		Site 9		Adult			Children		
	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Mean	SD	CV	Mean	SD	CV
Al	5.34	11.33	1.37	2.91	1.28	2.70	0.96	2.02	0	0	7.8	16.4	2.36	5	28.4	60.3	0.5	1.1	5.33	9.02	169.06	11.31	19.13	169.06
Se	55.03	112.5	121.8	258.3	107.4	227.8	126.2	268.3	10.98	23.2	0	0	9.85	20.8	43.2	91.76	46.1	97.8	57.85	49.33	85.28	122.20	104.85	85.58
Hg	366.67	777.8	122.85	260.39	542.58	1150.8	0	0	0	0	0	0	251	532.2	205.6	436.2	339	719.2	203.88	191.38	94.23	430.78	405.82	94.23
B	0.48	1.017	1.7	3.61	1.88	3.87	1.7	3.68	0	0	0.5	1.08	1.49	3.17	1.14	2.41	1.5	3.23	1.16	0.67	57.80	2.48	1.42	57.80
Ba	0.343	0.73	0.288	0.58	0.248	0.53	0.6	1.3	0	0	0.13	0.31	0.23	0.48	0	0	0	0	0.20	0.20	98.79	0.43	0.42	98.79
Cd	6.9	14.6	11.4	24.7	14.33	30.4	13.6	28.3	0	0	2.12	4.49	3.12	6.6	0	0	0	0	5.74	6.02	104.87	12.17	12.77	104.87
Cr	5.58	11.8	38.3	83.4	38.23	81.1	35.2	74.9	9.6	20.4	0	0	53.76	108.87	11.4	24.19	68.5	145.4	28.83	23.42	81.17	61.23	49.68	81.17
Cu	1.5	3.18	1.8	3.5	1.15	2.42	1.8	3.4	0	0	1.87	3.96	0.75	1.58	1.46	3.1	1.28	2.71	1.25	0.57	45.63	2.66	1.21	45.63
Fe	0.35	0.74	0.71	1.5	0.75	1.59	0.96	2.0	0.01	0.02	0.49	1.01	1.9	4.078	0.23	0.48	1.5	3.2	0.77	0.62	80.47	1.65	1.31	80.47
Mn	0.04	0.08	0.088	0.21	0.063	0.14	0.14	0.3	0.04	0.09	0.03	0.06	0.1	0.24	0.02	0.031	0.06	0.13	0.07	0.04	61.32	0.14	0.08	61.32
Ni	0.22	0.48	5.21	11.04	3.06	6.5	4.4	9.5	0.16	1.07	2	4.2	2.28	4.85	0.18	0.38	1.5	3.2	2.13	1.88	83.98	4.58	3.82	83.98
Pb	1.46	0.89	2.38	4.14	5.03	10.7	0	0	14.7	31.2	0	0	10.99	25.1	0	0	0	0	3.78	5.33	143.22	8.04	11.97	143.22
Zn	0.76	1.62	1.06	2.25	0.8	1.69	1.3	2.7	0.33	0.8	0.46	0.98	0.39	0.84	0.2	0.43	0.23	0.52	0.61	0.28	62.29	1.30	0.81	62.29
As	44	93.3	20.2	74.7	24.3	32.7	42.2	91.6	143.5	308.8	45.96	97.2	63.1	133.3	0	0	0	0	44.87	43.27	96.87	94.75	91.76	96.87
Mean	34.73	73.80	24.89	52.38	52.97	112.38	16.45	34.38	12.88	27.32	4.33	9.20	28.32	60.11	20.81	44.24	32.88	69.71	333.33	188.39	33.89	710.72	421.26	33.89
SD	97.08	205.87	40.28	91.88	140.84	303.11	34.37	73.33	38.47	81.86	12.13	25.77	67.88	142.35	34.78	116.21	90.37	192.13	22.38	14.39	33.89	33.84	30.89	33.88
CV	279.5	279.73	175.2	175.24	271.34	271.34	210.20	210.20	298.47	298.47	277.28	277.28	235.18	235.18	282.69	282.69	275.46	275.46	84.84	40.11	82.12	137.12	85.18	82.12
HI	485.7	1030.38	343.7	733.38	741.39	1573.67	230.2	488.4	181.7	385.5	61.3	130.1	389.5	847.89	282	619.5	422.1	460.5	233.78	59.26	13.47	233.78	39.28	13.47

4.2.2 Cancer-risk assessment

Cancer risk is displayed in Table 7, results for both the adult and child populations resulting from exposure to heavy metals (HMs) in drinking water sources according to USEPA guidelines. The ILCR values of Cr, Ni, As and Cd were found to be the highest. According to USEPA guidelines, the carcinogenic risk range for Cd ranged from 0.00 – 1.2 $x10^{-3}$ for adults and 0.00 – $1.1x10^{-2}$ for children. The range of carcinogenic risk for Cr is 0.00 - $4.4x10^{-2}$ for adults and 0.00 – 1.9 $x10^{-2}$ for children. For children as well as adults, the range of carcinogenic risk for nickel is $2.7x10^{-3}$ - 7.6 $x10^{-2}$ and 1.1 $x10^{-3}$ – $3.2x10^{-2}$, respectively. The carcinogenic risk range for lead (Pb) is 0.00 - $1.0x10^{-4}$ for adults and 0.00 – $5.9x10^{-5}$ for children. The carcinogenic risk range for As is 0.00 - $2.8x10^{-2}$ for adults and 0.00 – $5.2x10^{-3}$ for children. It is important to note that individual ILCR values were calculated for each metal separately, thereby providing metal-specific risk estimates. However, cumulative ILCR values were also determined by summing the individual ILCRs for all carcinogenic metals at each site, for both children and adults. This approach helps assess the overall cancer risk from simultaneous exposure to multiple heavy metals. Several sites showed total ILCR values exceeding the acceptable risk range set by the USEPA (1×10^{-6} to 1×10^{-4}), particularly for children, highlighting the need for urgent mitigation strategies and public health protection in these vulnerable populations.

Due to As significant environmental mobility, it can originate from both anthropogenic and natural sources [81]. In addition to various health risks associated with its dietary intake that are related to damage to neurons, skeletons, and kidneys, including cardiovascular disorders, the International Agency for Research on Cancer (IARC) classified lead as carcinogenic [73]. In connection with this risk range, the study's findings showed that lifetime consumption of water causes significant cancer risks to adults and children similarly. Furthermore, the risk assessments' constant variables suggest that the concentrations of HMs in the water samples directly correspond to the carcinogenic and non-carcinogenic risks. To prevent cancer in the future, efforts should be performed to minimize both early and inconspicuous intake of pollutants in order to avoid cancer in the future [82]. The essential components of natural ecosystems are heavy metals. These elements are frequently introduced to soils, surface waters, groundwater, and the atmosphere by human activity. Heavy metals in drinking water have a detrimental effect on human health. The heavy metals chromium VI and lead can have a variety of negative impacts on the human body, including increased risk of breast cancer, increased mortality from digestive organ cancer, accumulative lesions of the cardiovascular and nervous systems, and altered blood trace element concentrations. The risk increases with the duration of the effects. Risk assessments for heavy metal exposure typically identify a substance that poses a risk or is dangerous, as well as its human intake, exposure dose, toxicity, and other features like the quantitative relationship. From there, they evaluate the substance's potential effect on human health [83, 84, 10, 85]. It is well recognized that heavy metals cause cancer of the liver, lungs, and other organs [86, 87]. It is well recognized that prolonged exposure to Ag, Ba, Cd, Ni, Sr, and V can result in a variety of cancer [88, 89]. Certain cancer cell types include metal carcinogenic pathways that include oxidation, regulation of inflammation, reduction of cell growth, regulation of invasion, inhibition of chemo resistance, and inhibition of damage repair [90, 91, 84, 85]. There have been reports of significant correlations between drinking water contamination with aluminum (Al), nickel (Ni), strontium (Sr), and vanadium (V) and liver cancer [92, 93, 94, 95].

Table 7: ILCR in different drinking water sites

	Cd		**Cr**		**Ni**		**Pb**		**As**		**Total**	
	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children
Site 1	5.6 x10^{-04}	2.4 x 10^{-04}	3.6 x 10^{-03}	1.5 x10^{-03}	3.3x10^{-03}	1.4 x10^{-03}	6.0x10^{-06}	2.5 x10^{-06}	8.5 x10^{-03}	3.6 x10^{-03}	1.6 x10^{-02}	6.8 x10^{-03}
Site 2	9.5 x 10^{-04}	8.8 x10^{-03}	2.5 x 10^{-02}	1.1 x10^{-02}	7.6 x10^{-02}	3.2 x10^{-02}	3.7 x10^{-05}	1.6 x10^{-05}	6.8 x10^{-03}	2.9 x10^{-03}	1.1 x10^{-01}	5.5 x10^{-02}
Site 3	1.2 x 10^{-03}	1.1 x 10^{-02}	2.5 x 10^{-02}	1.0 x10^{-02}	4.5 x10^{-02}	1.9 x10^{-02}	6.4 x10^{-05}	2.7 x10^{-05}	4.8 x10^{-03}	2.0 x10^{-03}	7.5x10^{-02}	4.2 x10^{-02}
Site 4	1.1 x 10^{-03}	8.9 x 10^{-03}	2.3 x 10^{-02}	7.4 x10^{-03}	6.4 x10^{-02}	2.1 x10^{-02}	0	0	8.4 x10^{-03}	3.5 x10^{-03}	9.6 x10^{-02}	4.1 x10^{-02}
Site 5	0	1.0 x 10^{-02}	6.2 x 10^{-03}	9.6 x10^{-03}	7.4 x10^{-03}	2.7 x10^{-02}	1.9 x10^{-04}	0	2.8 x10^{-02}	3.5 x10^{-03}	4.2 x10^{-02}	5.0 x10^{-02}
Site 6	1.7 x 10^{-04}	1.6 x 10^{-03}	0	0	2.9 x10^{-02}	1.2 x10^{-02}	0	0	8.9 x10^{-03}	3.8 x10^{-03}	3.8 x10^{-02}	1.8 x10^{-02}
Site 7	2.5 x 10^{-04}	2.4 x 10^{-03}	3.3 x 10^{-02}	1.4 x10^{-02}	3.3 x10^{-02}	1.4 x10^{-02}	1.4 x10^{-04}	5.9 x10^{-05}	1.2 x10^{-02}	5.2 x10^{-03}	7.9 x10^{-02}	3.6 x10^{-02}
Site 8	0	0	7.3 x 10^{-03}	3.1 x10^{-03}	2.7 x10^{-03}	1.1 x10^{-03}	0	0	0	0	1.0 x10^{-02}	4.2 x10^{-03}
Site 9	0	0	4.4 x 10^{-02}	1.9 x10^{-02}	2.2 x10^{-02}	9.3 x10^{-03}	0	0	0	0	6.6 x10^{-02}	2.8 x10^{-02}

This study is subject to several limitations. First, only tap water samples were analyzed, and no groundwater samples were included, which may limit the generalizability of the findings to other local water sources. Second, the sampling campaign was conducted during a specific period (April to November 2023), and seasonal or temporal variations in heavy metal concentrations were not assessed. Third, the health risk assessment focused exclusively on oral ingestion through drinking water and did not account for other potential exposure pathways such as dermal absorption or inhalation. These factors may lead to an underestimation of the total exposure burden, especially in industrial or agricultural communities. Future studies should include multi-seasonal sampling, groundwater analysis, and comprehensive exposure modeling to enable a more robust and accurate health risk assessment.

4.3. Pearson correlation matrix

Pearson's correlation coefficient was used to perform correlation analysis. Table 8 shows the correlation matrix of the water quality parameters. The results indicate the following correlations:

There was very highly significant positive correlation ($P< 0.001$) between:

EC, TDS, and Salinity; TDS, and Salinity; Ca, Cr, Fe, Mg, K, and Sr; Se, and Bi; V, Li, Pb, and As; B, and Bi; Ba, Cd, Mn, and Zn; Ca, Cr, Fe, Mg, K, and Sr; Cd, Ni, Zn, Na, Co, and In; Cr, and Fe; Fe, and In; Li, Pb, and As; K, Sr, Na, and Mg; Mn, Ni, and Zn; Ni, and Zn; Pb, and As; K, Sr, and Na; Sr, and Na.

Also, there was a highly significant positive correlation ($P<0.01$) between:

Al, Mg, K, and Na; Se, Ni, and Zn; B, Ca, Cd, Cr, Fe, Mn, and Ni; Ba, and Ni; Ca, and Mn; Cd, and Ga; Co, and Fe; Cr, and Ni; Fe, and Ni; Ga, and Ni; In, and Pb; Li, and pH

The positive correlation was just significant ($P<0.05$) between:

Se, and Mn; Ec, and Salinity; V, and pH; Hg, and B; B and Zn; Ba, and Bi; Co, and Pb; Cr, Mg, Mn, K, Sr, Na, Bi, EC, TDS, Salinity; Fe, K, and Sr; Ga, and Bi; Mg, and TDS; Sr, TDS, and EC; Zn, and Bi; Na, and TDS

On the other hand, there was very highly significant negative correlation ($P<0.001$) between:

Ca, and As; Cu, Li, Pb, and As

Also, there was a highly significant negative correlation ($P<0.01$) between:

V, Ca, K, and Sr; Ag, Cr, Mg, Sr, Na; B, Li, and As; Cd, Mg, K, Sr, and Na; Mg, and As; K, and As; Sr, and As

The negative correlation was just significant ($P<0.05$) between:

Se, Co, and pH; Al, and Mn, V and Na; Hg, and pH; Ag, and Ca; Ca, and Li, Cd, and Ph; Li, and Bi, Mg, and Zn; Zn, Bi, and Na

Table 8: Correlation matrix between parameters in the studied water samples

	Al)	As)	(V)	(Hg)	(Ag)	(B)	(Ba)	(Co)	(Cd)	Cu)	(Cr)	(Cu)	(Fe)	(Ga)	In)	Li)	(Mg)	Mn)	(Ni)	(Pb)	(K)	Sr)	(Zn)	(As)	(Na)	(Bi)	PH	EC	TDS
Se)																													
(V)	-0.338*																												
(Hg)																													
(Ag)																													
(B)		0.604**		0.417*																									
(Ba)		0.563**																											
(Co)			0.547**		0.455*	0.511*																							
(Cd)		0.801**				0.647**	0.582**																						
Cu)		0.381*																											
(Cr)					0.493**	0.812**		0.646**																					
(Cu)		0.384*	0.615**																										
(Fe)						0.547**		0.628**		0.564**	0.827**																		
(Ga)		0.397*				0.422*			0.553**																				
In)										0.928**			0.632**																
(Li)		0.421*	.837**			0.536**		-0.387*				0.833**																	
(Mg)	.601**		0.457*		-0.500**		-0.481*	.634**	-0.537**		0.486*																		
(Mn)	0.397*	0.403*				0.495**	0.735**	.500**	0.456*		0.485*																		
(Ni)		0681**				0.594**	0.598**		0.649**		0.532**		0.465**	0.517**				0.711**											
(Pb)			.722**							0.388*		-0.838**			0.482**	0.858**													
(K)	.618**		0.618**				-0.440*	.608**	-0.527**		0.442*		0.361*				0.972**												
Sr)	.485*		0.908**		-0.498**		-0.420*	.844**	-0.503**		0.489*		0.383*				0.989**				0.962**								
(Zn)		0.888**				0.381*	.831**	0.418*	0.697**								0.409*	0.818**	0.727**										
(As)			.839**			-0.530**		-0.663**				0.691**				0.853**	0.938**			0.784**	0.560**	-0.532*							
(Na)	.602**		0.479*		-0.484*		-0.482*	0.596**	-0.581**		0.462*						0.999**				0.971**	0.991**	-0.428*	-0.397*					
(Bi)	0.415*	0.787**				0.658**	0.396*		0.778**		0.397*			0.461*		0.409*			0.471*				0.390*						
PH		0.384*	.424*	0.390*					-0.391*							0.462**													
EC		0.434*			-0.819**						0.425*											0.384*							
TDS					-0.871**						0.418*						0.411*					0.483*			0.407*			0.901**	
Salinity		0.396*			0.704**						0.389*																	0.886**	0.943**

5. CONCLUSION

This study highlights significant contamination of drinking water in the selected regions of Egypt, with heavy metal concentrations exceeding the World Health Organization (WHO) permissible limits at most sites. The human health risk assessment revealed considerable potential health hazards for both adults and children, particularly in industrial zones, emphasizing the urgent need for effective interventions to mitigate pollution sources and ensure the provision of safe drinking water. These findings directly support Sustainable Development Goal 6 (SDG 6), which aims to ensure the availability and sustainable management of clean water and sanitation for all. Moreover, the results align with Egypt’s Vision 2030 and the national water quality strategy, which emphasize improving drinking water safety, upgrading distribution infrastructure, and enhancing regular monitoring to protect public health and achieve long-term environmental sustainability.

RECOMMENDATIONS

Given the elevated levels of high-risk metals such as mercury (Hg), arsenic (As), cadmium (Cd), and lead (Pb) in several drinking water samples, especially in areas like Site 3 and Site 5, immediate actions are required to protect public health. Recommended interventions include the replacement of aging and corroded water distribution pipes, especially those containing lead or other reactive metals, and the implementation of point-of-use filtration systems (e.g., reverse osmosis or activated carbon filters) in affected households. Furthermore, periodic monitoring of water quality at the household and municipal levels should be institutionalized to detect early contamination. Public awareness campaigns should also be introduced to educate communities on proper water storage and the risks associated with heavy metal exposure.

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