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Environmental assessment of toxic heavy metals and natural radionuclides in irrigation water from Rustenburg, South Africa

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A B S T R A C T

Water is a transparent, tasteless and odourless inorganic compound, essential for life and sustainable development. It is important for food and energy production, socio-economic growth, healthy ecosystems and human existence. Global attention is given to water quality monitoring due to the role it plays in human exposure to different kinds of contaminants, including radioactive and toxic contaminants from industrial, agrochemicals, mining and other anthropogenic activities. This work presents the results of measured natural radionuclides and toxic heavy metals in Rustenburg, and their associated non-carcinogenic and carcinogenic risk. The average concentrations of Cd, Cu, Co, Fe, Ni, Mn, Pb and Zn are 0.00007 mg/l, 0.0087 mg/l, 0.0033 mg/l, 0.0636 mg/l, 0.0052 mg/l, 0.0217 mg/l, 0.0003 mg/l and 0.0047 mg/l respectively and are below the safe limit of toxic heavy metals in water. The activity concentration of ^{40}K and ^{238}U ranges from 7.07 Bq/l to 13.2 Bq/l and 1.24×10^{-04} Bq/l to 1.09×10^{-02} Bq/l, with a mean activity concentration of 11.6 Bq/l and 2.78×10^{-03} Bq/l respectively. ^{232}Th was not found in all measured water samples. The estimated average committed effective dose from ingestion of natural radionuclides was observed to be below 170 μSv/yr for ^{40}K, 120 μSv/yr for ^{232}Th and ^{238}U, and a total of 290 μSv/yr reported by the United Nations Scientific Committee on the Effects of Atomic Radiation. The assessment of human health risks resulting from exposure to toxic heavy metals shows negligible carcinogenic and non-carcinogenic health risks to the exposed population, making the water sources from which the sample was collected, safe for agricultural and domestic use. The obtained results will also serve as reference data for future environmental studies.

1. Introduction

Several deaths and diseases associated with water pollution highlight the significance of water to life (Babuji et al., 2023; Chaudhry and Malik, 2017). Mining and agricultural practices are major contributors to water pollution in both developing and developed countries (Zahoor and Mushtaq, 2023). This is due to waste products from mining activities, and the increased use of agrochemicals capable of runoff and leaching from agricultural sites into surrounding rivers, lakes and dams, thereby polluting domestic water sources. Agricultural, mining and industrialization, though essential in the development of national economy and ensuring food security for the increasing world population, have led to increased levels of radionuclides and toxic heavy metals in the environment (Olagbaju et al., 2021b).

Radionuclides are radiation-emitting isotopes of unstable nuclides. Emitted radiation from unstable nuclides are known to be harmful to living organisms and the environment, although they are used for several medical, industrial and military applications (Aladjadjiyan, 2022; Mbuende, 2022). Aside from natural sources, anthropogenic activities such as mining, nuclear testing and accidents, also contribute to their level in the environment. Similarly, heavy metals are metallic elements with relatively high density compared to water, and are widely used in modern technology and play essential role in the development of biological systems. However, they can toxic to the human body when their concentration above permissible limit (Sharma et al., 2022). The concentration of natural radionuclides (^{238}U, ^{40}K and ^{232}Th) and toxic heavy metals (Mn, Fe, Co, Ni, Cu, Zn, Pb and Cd) depends on the mineral, anthropogenic and geological variation of an area, making their concentration to vary from one region of the world to another (Olagbaju et al., 2021a; Ahmad and Pandey, 2020).Radionuclides andheavy metals are ubiquitous in the environment and play essential roles in human medicines and metabolism. Though they have several medical, industrial, energy, education and research applications, their incorporation into the human body can result in significant health risks. At higher concentrations, they are associated with various health effects such as neurocognitive effects, cardiovascular disease and cancer. These have resulted in regular evaluation, monitoring and review by various international and national regulatory agencies such as the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), United States Environmental Protection Agency (USEPA), World Health Organization (WHO), International Atomic Energy Agency (IAEA) and International Commission on Radiological Protection (ICRP) (Järup,

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Table 1
Sampling description and coordinates of sampling points.

S/N	Sample Code	Description	Longitude (S)	Latitude (E)
1	IWT1	Canal	25°42′37.7"	27°50′44.7"
2	IWT2	Canal	25°42′35.5"	27°50′43.4"
3	IWT3	Pond	25°40′09.1"	27°48′26.9"
4	IWT4	Canal	25°42′35.2"	27°50′42.7"
5	IWT5	Pond	25°42′11.0"	27°49′10.9"
6	IWT6	Canal	25°41′44.2"	27°49′08.7"
7	IWT7	Canal	25°41′44.1"	27°49′08.6"
8	IWT8	Pond	25°42′10.3"	27°49′10.1"
9	IWT9	Pond	25°40′16.3"	27°48′55.2"
10	IWT10	Pond	25°40′17.5"	27°48′55.2"
11	IWT11	Canal	25°40′18.4"	27°48′43.3"
12	IWT12	Pond	25°40′17.6"	27°48′50.0"
13	IWT13	Pond	25°40′15.8"	27°48′48.6"
14	IWT14	Borehole	25°40′07.5"	27°48′52.3"
15	IWT15	Borehole	25°40′09.1"	27°48′52.2"
16	IWT16	Pond	25°42′11.7"	27°49′11.2"
17	IWT17	Borehole	25°40′01.7"	27°49′09.9"

2003; UNSCEAR, 2000).

Natural radionuclides and toxic heavy metals constitute a class of major global contaminants in our environment (Linnik et al., 2020; Masok et al., 2016). This is due to their long half-life, non-biodegradable, ionizing and toxic properties. Radioactive and toxic element pollution is a global challenge due to numerous industrial, mining and domestic waste discharges into terrestrial and aquatic systems, and the various health risks they pose to humans (Dellantonio et al., 2010; Olagbaju et al., 2023). Measurement and monitoring of these contaminants in water are essential in assessing its quality. It also helps in estimating the associated health risks, and establishing and bench-marking contamination levels in water bodies in order to ascertain any changes that might arise in the future.

According to Adesiyan et al. (2018), radioactive and toxic contaminants in ground and surface water can result in contamination of irrigation and drinking water quality, thus posing both non-carcinogenic and carcinogenic health risks to humans via various exposure pathways (Mathuthu et al., 2021; Olagbaju et al., 2021b). Health effects associated with exposure to radioactive and toxic substances are predominant in regions with agricultural, mining and industrial waste (Sharma et al., 2015; Saleh et al., 2019). Thus, associated health risks with exposure to these contaminants have prompted the UNSCEAR and WHO among other regulatory bodies to set global average values, commonly referred to as the safe limits (Gad et al., 2019; Olowoyo et al., 2010).

Elevated levels of radionuclides and toxic heavy metals have been observed in soil and water in agricultural sites as a result of agrochemical usage, and proximity to industrial and mining areas (Adesiyan et al., 2018; Kamunda et al., 2016b; Saleh et al., 2019). The discharge and seep of natural radionuclides and toxic heavy metals into surface and groundwater bodies have led to their absorption into the human food chain and contamination of domestic and drinking water (Naja and Volesky, 2017). This has made necessary the study of irrigation water and farmlands through which they are incorporated into the human food chain, especially in contaminated areas (Karamanis et al., 2007; Lion and Olowoyo, 2013). Thus, this study aims to measure naturally occurring radionuclides and toxic heavy metals levels in irrigation water in the farming area of Rustenburg, South Africa. It will also assess the associated human health risks resulting from exposure via dermal and ingestion pathway. The study is an extension of a work carried out on radiological assessment of irrigation water used in Rustenburg, South Africa (Olagbaju et al., 2023).

2. Methodology

2.1. Study area and sampling

For the investigation carried out in this study, seventeen water sources consisting of eight ponds, three boreholes and six canals used for irrigation in Rustenburg were selected. To ensure traceability and future referencing, the location of each water source was recorded using a global positioning system (Table 1), and presented in Fig. 1. About one litre of water was collected from each source into a washed polyethylene bottle, and was well labelled for identification purposes. After collection, 10 ml hydrochloric acid was added to each water sample for acidification, to avoid radionuclide absorption on the container walls, upsurge of organic materials and ionic changes (Guidebook, 1989; Ugbede et al., 2020).

Rustenburg, the study area is situated at the edge of the Bushveld Igneous complex, one of the world's most mineralized and diversified regions for producing minerals, according to Ololade et al. (2008). It is also known as the economic center of North-West province, South

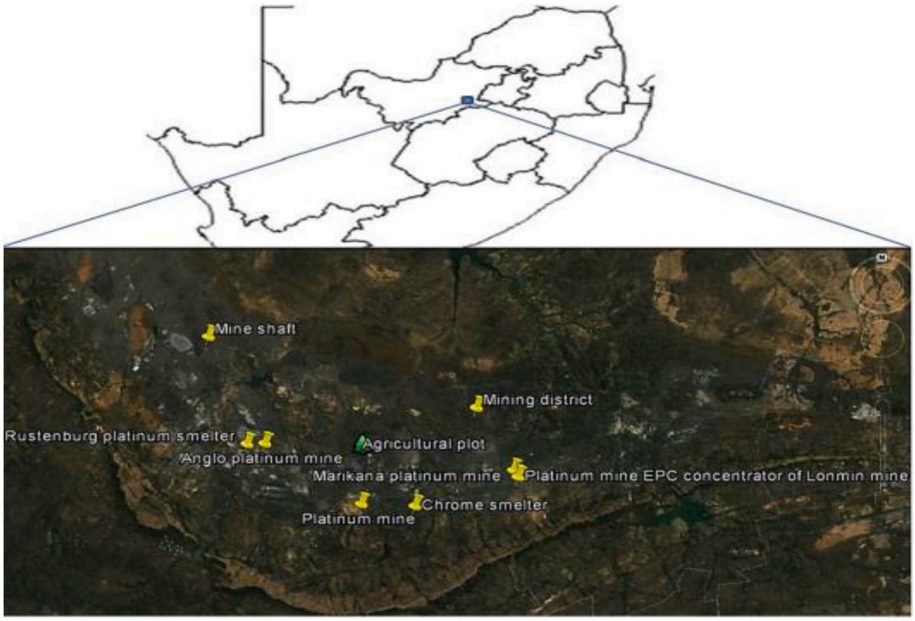

Fig. 1. Map showing the farming area in Rustenburg, North-West Province of South Africa (Mosai et al., 2017).

Africa, having the presence of several mining and industrial activities.

2.2. Measurement method

Toxic heavy metals in water were determined using a well calibrated inductively coupled plasma mass spectrometry. Inductively coupled plasma mass spectrometry (ICP-MS) was adopted because of its precision and accuracy, along with simultaneous multi-element measurement, wide detection range and high sensitivity (Kamunda et al., 2016a; Nde et al., 2021).

For quality control and to avoid cross-contamination of samples and to ensure there is no drift during measurement, the ICP-MS machine was set to run blank solution and a certified standard after every sample measured (Olawoyin et al., 2012). The concentration of toxic heavy metal (mg/l) was calculated using (Kaur et al., 2018; Kamunda et al., 2016a):

$$Concentration\left(\frac{\mu g}{g}\right) = C \times \frac{V_f}{w \times s} \times \frac{DF}{1000} \quad (1)$$

where, w = initial aliquot amount (g), Vf = final digestion volume (ml), C = toxic heavy metal concentration (μg/l) and s = % solids/100. The elemental concentration of uranium, thorium and potassium were converted to the activity concentration (Bq/kg) of ^{238}U, ^{232}Th and ^{40}K, using "ppm to Bq/kg" conversion factors of (313 Bq/kg = 1%), (12.35 Bq/kg = 1 ppm) and (4.06 Bq/kg = 1 ppm) for ^{40}K, ^{238}U and ^{232}Th respectively, according to the International Atomic Energy Agency (Adagunodo et al., 2019; Joel et al., 2018; Maxwell et al., 2013).

3. Human health risk assessment

In environmental monitoring and protection, human health risk assessment is essential because the elemental concentration and activity concentration of toxic heavy metals and natural radionuclides alone are not sufficient to ascertain associated health risk in humans. In this study, both carcinogenic and non-carcinogenic risk of exposure to toxic heavy metals and natural radionuclides is estimated to establish the health risks associated with exposure.

The ingestion dose E_{ing} (mSv/yr) from the consumption of ^{232}Th, ^{40}K, and ^{238}U in water samples was estimated using (UNSCEAR, 2002).

$$E_{ing}(\mathrm{mSv}/Yr) = C_\tau I_{ing} \sum_{j=1}^{3} DCF_{ing}, \quad (2)$$

where, DCF_{ing} = effective dose coefficient (Sv/Bq), for ingestion of naturally occurring radionuclides, C_τ = activity concentration of the radionuclides in water samples and I_{ing} = consumption rate per year.

For ^{232}Th, ^{238}U and ^{40}K, effective dose coefficient of 2.30×10^{-7} Sv/Bq, 4.50×10^{-8} Sv/Bq and 6.20×10^{-9} Sv/Bq respectively were used (ICRP , 2012). The average consumption rate of 600 l/yr was used for the estimation of effective doses for water ingestion (DEA, 2010).

Lifetime cancer risk (L_R) was also estimated using:

$$L_R = E_{ing} \times LE \times RF, \quad (3)$$

where E_{ing} (mSv/Yr) = annual effective dose (Sv/yr) from ingestion of ^{40}K, ^{232}Th and ^{238}U in water, LE = life expectancy (70 years), and RF = risk factor (Sv^{-1}). For risk assessment, the nominal probability coefficient = 7.3×10^{-2} Sv^{-1} (ICRP, 1990).

Human health risks resulting from exposure to toxic heavy metals is estimated using the average daily intake (ADI) (mg/l-day) for dermal and ingestion pathways, and is estimated using equations (4)–(8) as prescribed by EPA (1989):

$$ADI_{ing} = \frac{C_s \times IR_{ing} \times EF \times ED}{BW \times AT \times 10^6} \quad (4)$$

Table 2
Exposure parameters for assessing human health risk via different exposure pathways.

Symbols	Parameters	Adult	Children	References
C_s	Concentration of toxic heavy (mg/l)			
CF	Unit conversion factor (l/cm^{-3})	0.001	0.001	USEPA (2004)
BW	Body weight of the exposed individual (kg)	70	15	DEA (2010)
AT	Average dose time (Days)	365 × 30	365 × 6	EPA (2011)
IR_{water}	Ingestion rate (l/yr)	600	400	DEA (2010)
SA	Exposed skin area (cm^2)	5800	2100	DEA (2010)
PC	Dermal permeability coefficient (cm/h)	0.001	0.001	USEPA (2004)
EF	Exposure frequency (days/year)	350	350	DEA (2010)
ET	Exposure time during bathing and shower (hr/day)	0.3	0.3	USEPA (2004)
ED	Exposure duration (years)	30	6	USEPA (2004)

Table 3
Toxic heavy metals cancer slope factor and reference dose.

Toxic heavy metals	Reference Dose		Cancer Slope factor		
	Ingestion	Dermal	Ingestion	Dermal	
Pb	3.60×10^{-03}	5.25×10^{-04}	8.50×10^{-03}		DEA (2010)
Cu	3.70×10^{-02}	2.40×10^{-02}			(DEA, 2010; EPA, 2011)
Zn	3.00×10^{-01}	7.50×10^{-02}			(DEA, 2010; EPA, 2011)
Ni	2.00×10^{-02}	5.60×10^{-03}			DEA (2010)
Cd	5.00×10^{-04}	5.00×10^{-04}			(DEA, 2010; EPA, 2011)
Co	2.00×10^{-02}	5.70×10^{-06}			EPA (2011)
Fe	8.4	0.07			EPA (2011)
Mn	0.14	0.0035			EPA (2011)

$$ADI_{dems} = \frac{C_s \times SA \times PC \times ET \times EF \times ED \times \mathrm{CF}}{BW \times AT} \quad (5)$$

Hazards risk (HQ) is expressed as the ratio of exposure the reference dose (RfD) of specific toxic heavy metal (EPA, 1989; Liu et al., 2013).

$$HQ = \frac{ADI}{RFD} \quad (6)$$

Hazard index (Hi) is used to express the sum of hazard quotients for all investigated toxic heavy metals, and is given by:

$$Hi = \sum_{k=1}^{n} \frac{ADI_k}{RFD_k} \quad (7)$$

where ADI_k is the average daily intake of toxic heavy metal (k) and RFD_k is the chronic reference dose for toxic heavy metal k.

Carcinogenic risk of toxic heavy metals is defined as the probability of an individual lifetime health risk from carcinogens and is the product of average daily intake to cancer slope factor (ADI × CSF). Total cancer risk is estimated as

$$TCR = \sum_{k=1}^{n} ADI_k \times CSF_k \quad (8)$$

HI values > 1 indicate the probability of non-carcinogenic risk in exposed humans and TCR values of 1×10^{-6} to 1×10^{-4} are considered acceptable by the United State Environmental Protection Agency for regulatory purposes of cancer risk. Tables 2 and 3 show exposure

Table 4
Concentration of toxic heavy metal in irrigation water in Rustenburg.

Sample Id	Toxic heavy metal (mg/l)							
	Mn	Cu	Co	Fe	Ni	Pb	Zn	Cd
IWT 01	0.027	0.0078	0.0001	0.0560	0.0002	0.0002	0.0124	0.00004
IWT 02	0.027	0.0078	0.0006	0.0515	ND	0.0001	0.0068	0.00005
IWT 03	ND	0.0001	0.0275	ND	0.0547	0.0002	ND	0.00007
IWT 04	0.028	0.0157	0.0022	0.0564	ND	0.0002	0.0052	0.00005
IWT 05	0.0048	0.0184	0.0031	0.0842	0.0003	0.0003	0.0084	0.00005
IWT 06	0.0035	0.0070	0.0010	0.0711	ND	0.0002	0.0019	0.00005
IWT 07	0.0285	0.0139	0.0029	0.0669	0.0002	0.0003	0.0065	0.00007
IWT 08	0.0036	0.0032	0.0006	0.0680	0.0001	0.0001	0.0015	0.00004
IWT 09	0.0255	0.0070	0.0012	0.0467	ND	0.0002	0.0030	0.00010
IWT 10	0.0056	0.0101	0.0022	0.0762	0.0002	0.0003	0.0034	0.00006
IWT 11	0.0150	0.0108	0.0030	0.1120	0.0005	0.0003	0.0049	0.00010
IWT 12	0.0435	0.0119	0.0022	0.0785	0.0005	0.0004	0.0044	0.00012
IWT 13	0.0433	0.0099	0.0019	0.0646	0.0002	0.0003	0.0035	0.00007
IWT 14	0.0452	0.0111	0.0027	0.0737	0.0002	0.0003	0.0043	0.00010
IWT 15	0.0439	0.0087	0.0029	0.0676	0.0003	0.0003	0.0030	0.00008
IWT 16	0.0010	0.0012	0.0009	0.0205	ND	ND	ND	ND
IWT 17	0.0024	0.0031	0.0018	0.0233	ND	ND	0.0014	0.00001
Maximum	0.0452	0.0184	0.0275	0.1120	0.0547	0.0004	0.0124	0.00012
Minimum	ND	0.0001	0.0001	ND	ND	ND	ND	ND
Average	0.0217	0.0087	0.0033	0.0636	0.0052	0.0003	0.0047	0.00007

ND = Not Detectable.

Table 5
Permissible limits of toxic heavy metal in drinking water.

Countries	Permissible limits for toxic heavy metals in drinking water (mg/l)								
	Ni	Co	Fe	Mn	Cu	Zn	Pb	Cd	References
South Africa	NA	NA	NA	NA	1.0	NA	0.01	0.003	Hodgson and Manus (2006)
WHO	0.07	NA	NA	NA	2.0	NA	0.01	0.003	WHO (2008)
USEPA	NA	0.1	NA	NA	1.3	0.5	0.015	0.005	USEPA (2012)
Present study	0.0052	0.0033	0.0636	0.0217	0.0087	0.0047	0.0003	0.000007	

NA = Not Available.

Table 6
Pearson correlation matrix between-naturally occurring radionuclides and toxic heavy metals in irrigation water.

	^{238}U	^{40}K	Mn	Fe	Co	Ni	Cu	Zn	Pb	Cd
^{238}U	1.00									
^{40}K	0.40	1.00								
Mn	0.04	0.53	1.00							
Fe	0.10	0.22	0.33	1.00						
Co	−0.20	0.16	−0.27	−0.51	1.00					
Ni	−0.16	0.14	−0.30	−0.58	0.99	1.00				
Cu	0.32	0.52	0.44	0.70	−0.35	−0.44	1.00			
Zn	0.62	0.49	0.34	0.42	−0.34	−0.34	0.62	1.00		
Pb	−0.06	0.71	0.61	0.60	0.08	0.00	0.70	0.40	1.00	
Cd	−0.20	0.48	0.62	0.50	0.13	0.07	0.40	0.11	0.82	1.00

parameters, cancer slope factor and reference doses used for the non-carcinogenic and carcinogenic assessment of toxic heavy metals in water.

4. Results and discussion

The concentrations of toxic heavy metals and natural radionuclides of irrigation water collected from a canals, ponds, boreholes in farming area of Rustenburg, were measured using ICP-MS and the preliminary results are available in (Olagbaju and Wojuola, 2023) and (Olagbaju et al., 2023), as presented in Tables 4 and 7 respectively. Arsenic, chromium and mercury were not found in all measured irrigation water. This was linked to spectral interference, from the measurement method adopted (Amaral et al., 2015; Thomas, 2013).

The mean concentrations of Cd, Co, Cu, Fe, Mn, Ni, Pb and Zn are 0.00007 mg/l, 0.0033 mg/l, 0.0087 mg/l, 0.0636 mg/l, 0.0217 mg/l, 0.0052 mg/l, 0.0003 mg/l and 0.0047 mg/l respectively, and are observed to be below the WHO, USEPA and South Africa safe level for heavy metals in drinking water as shown in Table 5. The average concentration of measured toxic heavy metal in water increases in the order of Cd < Pb < Zn < Cu < Co < Ni < Mn < Fe (see Fig. 1).

Fig. 2 reveal the estimated non-carcinogenic health risk resulting from exposure to toxic heavy metals via dermal contact and ingestion of water by adults and children. Exposure via dermal contact is observed to contribute more compared to the ingestion pathway, in both adults and children, ascribed to the frequent hand-to-mouth habit. Also, from the result obtained for the hazard quotient calculated from the average daily intake, Pb shows the most threat to human health with children more susceptible to non-cancer risk. The estimated hazard quotient and hazard index are found to be less than one, indicating insignificant non-carcinogenic risk of exposure (EPA, 1989; DEA, 2010). Also, the estimated carcinogenic risk resulting from exposure to toxic heavy metals in

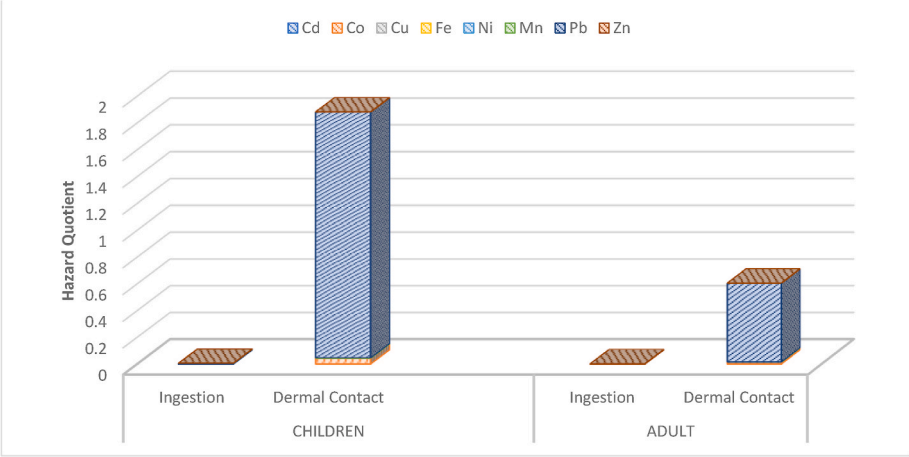

Fig. 2. Calculated hazard quotient for irrigation water sources in Rustenburg.

Table 7
Activity concentration and ingestion dose of natural radionuclides in for irrigation water sources in Rustenburg.

Sample ID	Bq/l		Eing (mSv/yr)		Total	LCR
	^{238}U	^{40}K	^{238}U	^{40}K		
IWT 01	5.80×10^{-03}	$1.29 \times 10^{+01}$	1.57×10^{-07}	4.79×10^{-05}	4.81×10^{-05}	1.68×10^{-04}
IWT 02	1.09×10^{-02}	$1.24 \times 10^{+01}$	2.93×10^{-07}	4.60×10^{-05}	4.63×10^{-05}	1.62×10^{-04}
IWT 03	9.88×10^{-04}	$1.26 \times 10^{+01}$	2.67×10^{-08}	4.70×10^{-05}	4.70×10^{-05}	1.64×10^{-04}
IWT 04	5.93×10^{-03}	$1.25 \times 10^{+01}$	1.60×10^{-07}	4.64×10^{-05}	4.66×10^{-05}	1.63×10^{-04}
IWT 05	5.06×10^{-03}	$1.32 \times 10^{+01}$	1.37×10^{-07}	4.93×10^{-05}	4.94×10^{-05}	1.73×10^{-04}
IWT 06	3.83×10^{-03}	$1.13 \times 10^{+01}$	1.03×10^{-07}	4.21×10^{-05}	4.22×10^{-05}	1.48×10^{-04}
IWT 07	4.69×10^{-03}	$1.32 \times 10^{+01}$	1.27×10^{-07}	4.89×10^{-05}	4.91×10^{-05}	1.72×10^{-04}
IWT 08	3.21×10^{-03}	$1.14 \times 10^{+01}$	8.67×10^{-08}	4.24×10^{-05}	4.25×10^{-05}	1.49×10^{-04}
IWT 09	1.11×10^{-03}	$1.14 \times 10^{+01}$	3.00×10^{-08}	4.26×10^{-05}	4.26×10^{-05}	1.49×10^{-04}
IWT 10	9.88×10^{-04}	$1.16 \times 10^{+01}$	2.67×10^{-08}	4.33×10^{-05}	4.33×10^{-05}	1.52×10^{-04}
IWT 11	1.11×10^{-03}	$8.51 \times 10^{+00}$	3.00×10^{-08}	3.17×10^{-05}	3.17×10^{-05}	1.11×10^{-04}
IWT 12	8.65×10^{-04}	$1.32 \times 10^{+01}$	2.33×10^{-08}	4.93×10^{-05}	4.93×10^{-05}	1.73×10^{-04}
IWT 13	7.41×10^{-04}	$1.27 \times 10^{+01}$	2.00×10^{-08}	4.71×10^{-05}	4.72×10^{-05}	1.65×10^{-04}
IWT 14	8.65×10^{-04}	$1.30 \times 10^{+01}$	2.33×10^{-08}	4.84×10^{-05}	4.84×10^{-05}	1.69×10^{-04}
IWT 15	8.65×10^{-04}	$1.23 \times 10^{+01}$	2.33×10^{-08}	4.59×10^{-05}	4.59×10^{-05}	1.61×10^{-04}
IWT 16	1.24×10^{-04}	$7.07 \times 10^{+00}$	3.33×10^{-09}	2.63×10^{-05}	2.63×10^{-05}	9.21×10^{-05}
IWT 17	2.47×10^{-04}	$8.04 \times 10^{+00}$	6.67×10^{-09}	2.99×10^{-05}	2.99×10^{-05}	1.05×10^{-04}
Maximum	1.09×10^{-02}	$1.32 \times 10^{+01}$	2.93×10^{-07}	4.93×10^{-05}	4.94×10^{-05}	1.73×10^{-04}
Minimum	1.24×10^{-04}	$7.07 \times 10^{+00}$	3.33×10^{-09}	2.63×10^{-05}	2.63×10^{-05}	9.21×10^{-05}
Average	2.77×10^{-03}	$1.16 \times 10^{+01}$	7.51×10^{-08}	4.32×10^{-05}	4.33×10^{-05}	1.51×10^{-04}

water is found to be below the safe limit of 10^{-6}, signifying negligible carcinogenic health risk.

Similarly, the activity concentration of measured natural radionuclides in investigated water is presented in Table 7. The elemental concentration of thorium was observed to be below detection level in all investigated irrigation water. This is similar to the observation made by Ugbede and Osahon (2021). The elemental concentration of uranium and thorium ranges from 1.00×10^{-05} to 8.83×10^{-04} mg/l and 2.26×10^{-02} to 4.22×10^{-02} mg/l and mean values of 2.24×10^{-04} mg/l and 3.71×10^{-05} mg/l respectively. This corresponds to the activity concentration of ^{238}U and ^{40}K which ranges from 1.24×10^{-04} Bq/l to 0.01 Bq/l, and 7.07 Bq/l to 13.2 Bq/l, with mean values of 0.01 Bq/l and 11.60 Bq/l respectively. The elemental concentration of uranium and thorium are observed to be well below the United States Environmental Protection Agency and World Health Organization's guidelines of 30 and 15 μg/l respectively, showing the investigated water sources are significantly safe for domestic, recreational and agricultural purposes.

Table 7 presents the committed effective dose and excessive lifetime cancer risk resulting from the intake of irrigation water. The mean committed effective dose resulting from the ingestion of ^{238}U and ^{40}K in irrigation water is 4.32×10^{-05} mSv/yr and 7.51×10^{-08} respectively. The mean committed effective dose is less than the reported global average value of 2.4 mSv/yr, suggesting insignificant health risk (UNSCEAR, 2000; ICRP, 2008). Similarly, the excess life cancer risk is also below the reported global average of 2.5×10^{-3} by the United Nations Scientific Committee on the Effects of Atomic Radiation, with values ranging from 9.21×10^{-05} to 1.73×10^{-04}. The result indicates negligible radiological risk, thus making the investigated irrigation water safe for use.

The elemental concentration of thorium was observed to be below the detection level, this makes it impossible to estimate the activity concentration of ^{232}Th in investigated irrigation water as earlier stated. The concentration of ^{238}U and ^{40}K was correlated with the concentration of toxic heavy metals (Fe, Pb, Cd, Zn, Co, Mn, and Cu) in irrigation water, and the results are presented in Table 6. Forty-three positive and twelve correlation pairs were observed in Table 6, while values of correlation coefficient above ±0.5 are taken to be significant (Ugbede et al., 2020). The activity concentration of ^{40}K was observed to be positively correlated with all measured toxic heavy metals in irrigation water. The activity concentration of ^{238}U shows a negative correlation with the concentration Co, Ni, Pb and Cd, and a positive linear relationship with Mn, Fe, Cu, and Zn in sampled irrigation water. The weak correlation of toxic heavy metals observed in irrigation water from Tables 6 and is due to various debris and wastes, which are sources of different toxic heavy metals, eroded or deposited in water bodies. Also, the positive correlation observed between Pb and Cd, Mn and Pb, Cu and Pb, Mn and Cd, Cu and Zn, Fe and Cd, Fe and Cu, Co and Ni, and Fe and Pb suggests similar contaminants sources for each pair.

5. Conclusion

Water is one of the natural resources abundant on earth and essential for life. They are vital for sustaining human life and supporting food production. For human consumption and agricultural uses, there are quality guidelines by national and international agencies it must meet, for the general well-being of man. In this study, the concentrations of toxic heavy metals and natural radionuclides in irrigation water collected in the farming area of Rustenburg, North-West Province of South Africa were measured using inductively coupled plasma spectrometry. Human health risks resulting from exposure to both toxic heavy metals and natural radionuclides were also assessed and compared with various national and international recommendations. In all measured water samples, elemental concentrations of thorium, arsenic, mercury and chromium were not detected. The average committed effective dose and cancer risk resulting from exposure to natural radionuclides, via ingestion of ^{238}U and ^{40}K was found to be less than the global average value reported by the United Nations Scientific Committee on the Effects of Atomic Radiation and the International Commission on Radiological Protection. Estimated non-carcinogenic and carcinogenic risk due to exposure to toxic heavy metals in investigated water was also observed to be below the safe limit for toxic heavy metals in drinking water reported by WHO, USEPA and South Africa permissible limit. The results obtained for investigated water show there is no potential health risk to exposed populations, thus making them safe for domestic and agricultural purposes. This study will also serve as baseline data for ascertaining future contamination resulting from natural and anthropogenic activities around the area.

CRediT authorship contribution statement

Peter Oluwadamilare Olagbaju: Writing – original draft, Methodology, Investigation, Conceptualization. **Olanrewaju Bola Wojuola:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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