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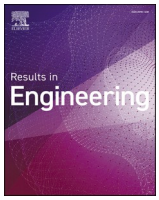

Review article

Understanding uranium distribution: A systematic review and meta-analysis in the context of drinking water resources

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ABSTRACT

Anthropogenic activities such as uranium mining, coal ash disposal, and phosphate fertilizers utilization can further enhance uranium mobilization in the environment. This systematic review investigated the uranium (U) concentration in world water sources with a meta-analysis assessment. A search strategy was done in PubMed, Science Direct, Web of Science, Google Scholar databases, and gray literature, and 46 records were included. Heterogeneity among the studies was assessed using the I^2 statistic and Cochran's chi-square test. Funnel curve asymmetry was evaluated by Egger's regression asymmetry test. Sensitivity analysis was conducted to specify the robustness of the findings. The uranium mean concentration in water sources was 0.15 μg/L (0.13–0.16), and mean of uranium in groundwater and surface water was 0.17 (0.13, 0.21), 0.19 (0.13, 0.25), 0.14 (0.12, 0.16), 0.16 (0.12, 0.20), 0.14 (0.12, 0.16), 0.13 (0.09, 0.17), 0.15 (0.13, 0.16), and I^2 = 8 %, 0.09 (0.03, 0.15), 0.29 (0.11, 0.47), 0.17 (0.02, 0.36), and I^2 = 77.5 % respectively. The concentration of uranium in water sources varies significantly across different countries, with the maximum concentration detected in surface water from South Africa (0.29 μg/L) and the minimum in groundwater from the USA (0.01 μg/L). The meta-regression test also indicated that the number of samples, the sampling area, and the publication year did not affect the heterogeneity between the studies. The results of subgrouping based on the water source showed that the surface water affected the heterogeneity value.

1. Introduction

Uranium is a naturally occurring radioactive and toxic heavy metal in the earth's crust, and it is present in varying concentrations in soil, air, and water. Uranium consists of isotopes, with U-238 being the most common (99.27 %), followed by U-235 (0.72 %) and U-234 (0.01 %). It is classified as a lithophilic element and is usually found in large masses of minerals. Uranium is a heavy metal that can cause serious health risks in drinking water. Exposure to uranium through drinking water is associated with carcinogenic and non-carcinogenic risks [1].

Studies have shown that exposure to uranium in drinking water can increase the risk of cancers, especially lung, bladder, and kidney cancer. In addition to carcinogenic effects, acute exposure to uranium can cause gastrointestinal effects such as diarrhea, vomiting, and abdominal pain. Chronic exposure to uranium has been related to kidney tubular dysfunction and can lead to weakened bones and severe joint and back pain. In summary, uranium content in drinking water causes significant health risks in cancer development and other adverse health effects. Therefore, it is essential to monitor and reduce high levels of uranium concentration to protect human health [2–5].

In addition to natural sources of uranium in air, water, and soil, human activities such as mining, smelting, phosphate fertilizers, electronic industry wastes, and ammunition factories are anthropogenic sources. It emits alpha and gamma radiations and is present in varying concentrations globally. Uranium emits α and γ radiation and presents in varying concentrations globally and can enter aquatic systems through river flow and surface run-off, and radioactivity enrichment in groundwater has become a global concern [6–9].

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The presence of uranium in water treatment can also be influenced by factors such as the region geology, the proximity to uranium sources, and the effectiveness of water treatment processes in removing uranium [3,10]. Uranium can accumulate in the body with drinking water over time, which can cause harmful effects on health. It has a relatively short half-life in bone, estimated at 70–200 days, and 80–90 % excreted after 1.5 years [11–13]. This systematic review embarks on a critical mission to measure the extent of uranium contamination in drinking water source, and to rank the urgency and toxicity of various contaminants. Therefore, this systematic review aims to quantify the uranium contamination of drinking water sources and prioritize quantity and type. Based on our best knowledge, it is the first comprehensive and systematic study of uranium concentration in drinking water sources. Moreover, the present paper may assist in reformulating a global policy based on substantial statistical findings about uranium toxicity in the environment.

2. Materials & methods

PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) is a widely used guideline for reporting systematic reviews and meta-analyses [31]. The protocol of this systematic review was recorded in the PROSPERO database (Registration Number: CRD42022361847).

2.1. Eligibility criteria

The original papers, preprints, peer-reviewed journals, and reports were considered in this study. Based on the research question, the studies must have involved uranium in drinking water sources. Overall, translation bias can be a significant source of error in research, and to minimize its impact on the validity and reliability of the findings, studies in English were selected. No time and place restrictions were considered.

2.2. Search strategy

A comprehensive literature search in the field of uranium in drinking water supply sources was conducted. In this regard, related studies were regained from international databases of PubMed, Science Direct, and Scopus through a proper strategy by considering keywords such as uranium, “radioactive contaminants”, groundwater, “surface water”, and the MeSH system. Boolean operators are symbols for connecting search terms and help refine or broaden search results in a research project.

In addition, Google Scholar, gray literature, citation databases that index theses and news databases such as DOE Information Bridge, Environmental Sciences and Pollution Management (ESPM), GeoRef, The International Atomic Energy Agency (IAEA), and CDC. gov were also searched with suitable keywords.

2.3. Screening process and data extraction

This systematic review extracted all estimates of uranium concentrations in different drinking water sources separately for surface and groundwater sources from studies that met inclusion criteria, and then the results were transformed in the EndNoteX9 software while restricting the inclusion of duplicate citations. The expert team screened the citations using titles and abstracts, with blinding to obtain relevant studies, and the full-text screening was done. This process is presented in the **Flowchart 1**.

2.4. Data analysis

Data from the included records were summarized in an Excel spreadsheet, recording information including title, first author, year, country, study type, sample size, the sampling area, and the type of water source, the concentration of uranium, and the standard error value. Studies were included in the research based on the amount, type, causes, and control methods of uranium radioactive contamination in

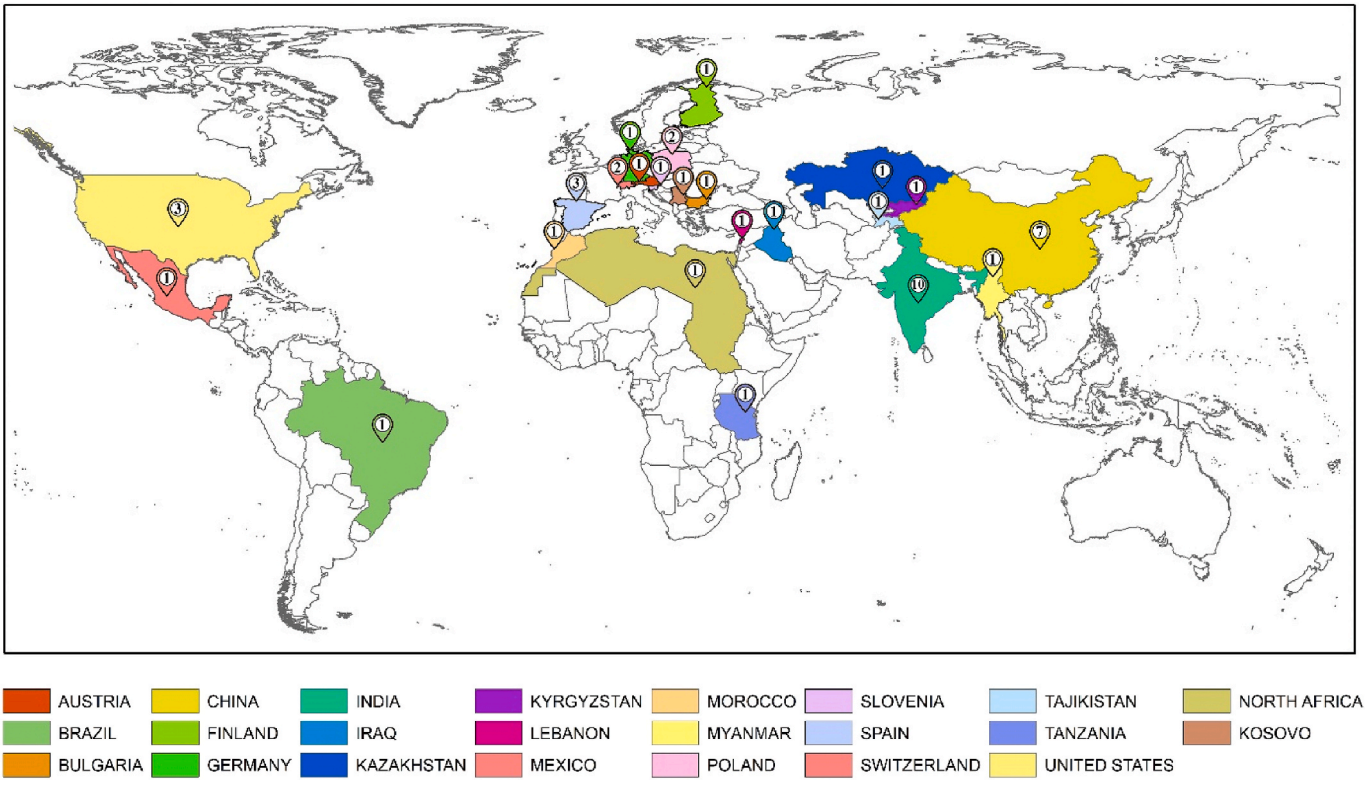


Fig. 1. Spatial distribution of records in the world.

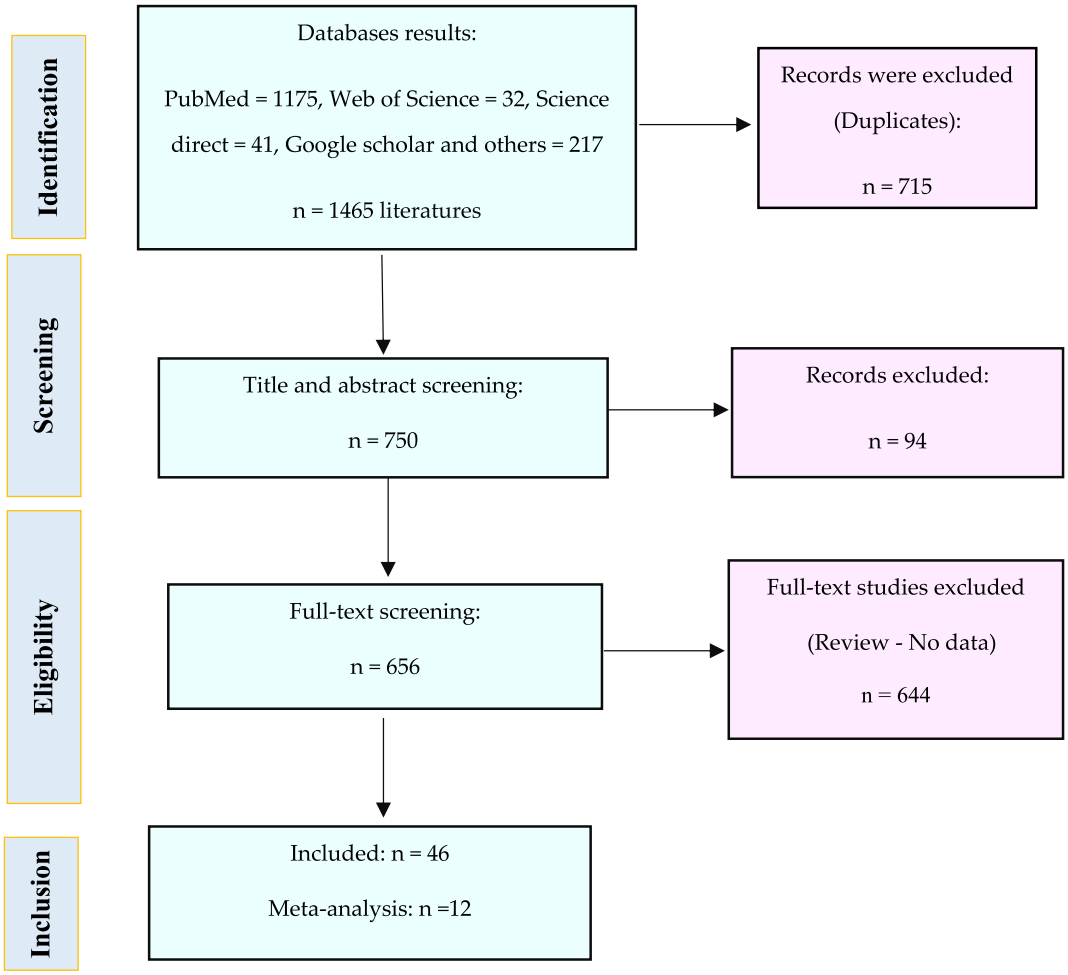


Chart 1. The subgrouping based on the type of source of water.

surface, underground, or both water sources (Table 1). Review articles, letters to the editor, commentary, replicated or unrelated studies, and pieces of literature with insufficient data were excluded from the research. The data was transferred to STATA software (StataCorp version 11.2.) for meta-analysis with the random effects model.

2.5. Measurement and standardization

The quality of the studies was evaluated using the Newcastle Ottawa scale checklist [47]. This checklist considers scores between 0 and 10 for the studies. Therefore, any article that has presented the required data of the checklist better gets a higher score. Finally, the studies were categorized into weak and strong.

2.6. Data synthesis

The random effects model was used to perform a comprehensive analysis, and to visualize the results, a forest plot was employed. Additionally, the I^2 citations and Cochran's chi-square statistical test (Q) were conducted to assess the heterogeneity among the studies. Egger's regression asymmetry test was performed to evaluate the funnel curve asymmetry. The impact of specific decisions regarding the inclusion of certain studies on the findings was assessed with sensitivity analysis. All statistical tests were conducted in two domains, and the significance level for all tests, except those related to evaluating publication bias, was set at 0.95 (CI = 0.95) and declared significant at 0.05 ($p < 0.05$).

3. Results and discussion

3.1. Included records

In this study, the records that were published until September 2022 were retrieved. In addition, to increase the sensitivity of the search and improve the number of studies, additional records were identified by hand searching and checking the reference lists of the retrieved articles. In the beginning, 1465 articles were retrieved from international databases. Of these, 1175 studies were regained from Google Scholar and gray literature review, 217 from PubMed, 41 from Science Direct, and 32 from the Web of Science. By limiting the uranium concentration in water sources, 46 articles remained for detailed review in this study. The overview content about the included record distribution is shown in Table 2. The distribution of records also varied globally. Most records belonged to the continents of Asia, Europe, Africa, and America, respectively. In terms of time, the records were from 2001 to 2022. Also, India, China, Spain, and America countries had a higher record, and the spatial representation of countries' involvement is shown in Fig. 1.

3.2. Certainty of evidences

In this study, the concentration of uranium in different sources of drinking water was investigated, and the results of the present meta-analysis (CI = 0.95) determined that the free concentration of the findings was 0.15 μg/L with a range of 0.13–0.16 μg/L. Considering that the statistical test of heterogeneity is not significant (p-value = 0.74), it can be concluded that the findings of the studies have a common point

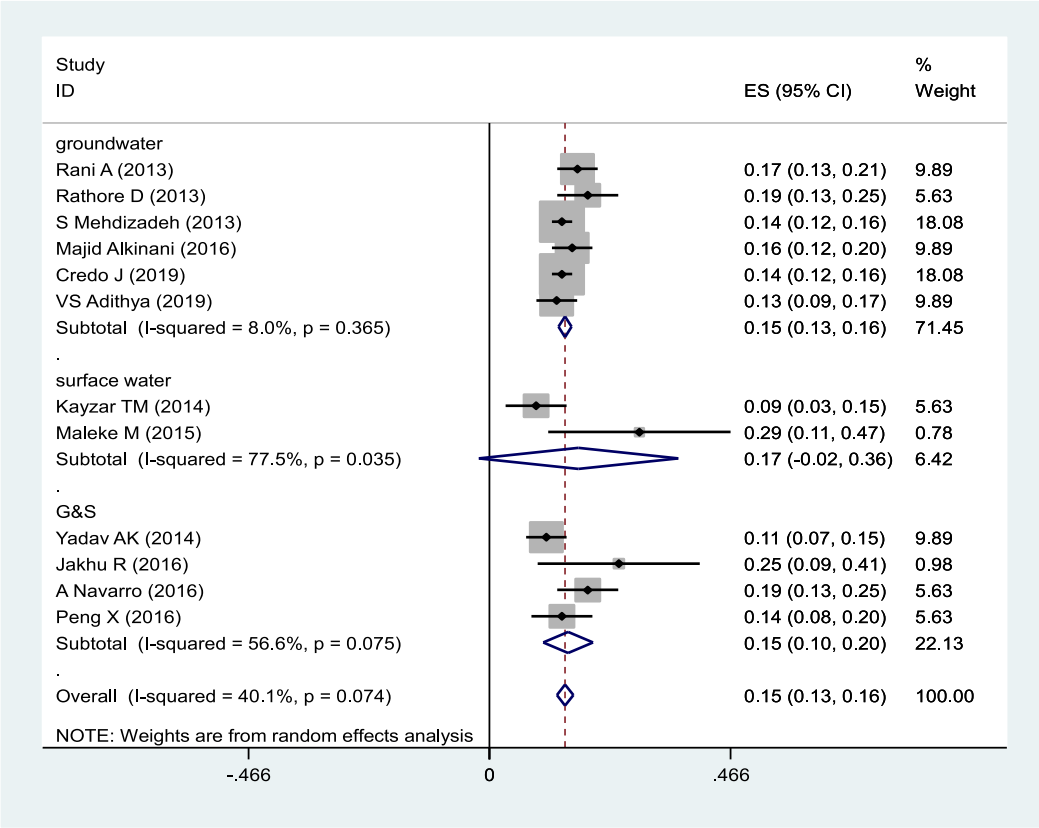


Chart 2. Funnel plot showing the publication bias in studies.

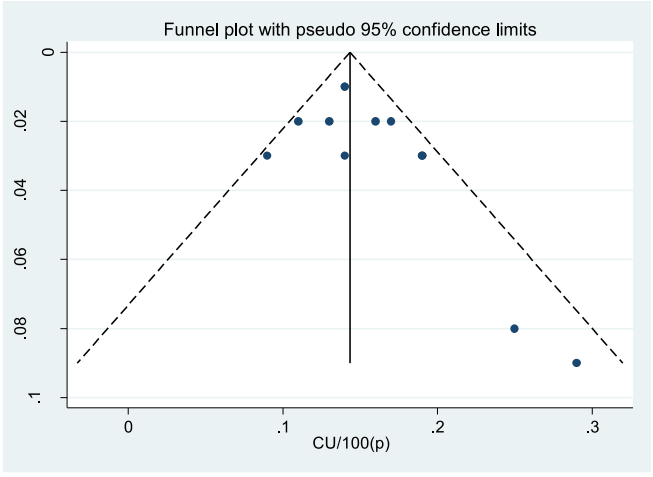


Chart 3. Forest diagram about uranium concentration meta-analysis in drinking water sources.

that the concentration of uranium in water sources is lower than the EPA maximum contaminant level (MCL) as 30 μg/L in drinking water.

3.3. Heterogeneity

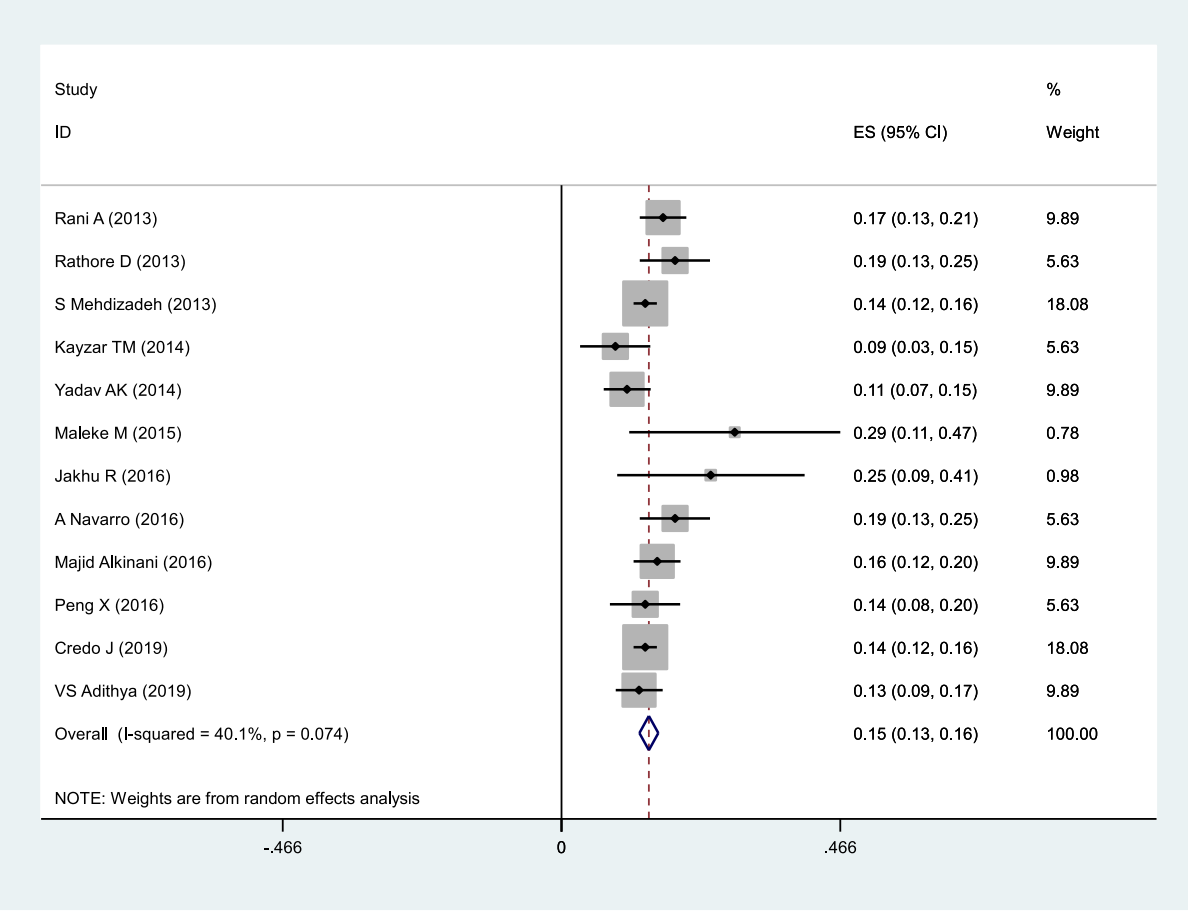
A meta-regression test was performed for the variables of the year of study, sampling location, sample size, and water source to determine the source of heterogeneity between studies. Based on the results, the type of water source was the most influential factor in heterogeneity in studies among the investigated factors. As indicated in forest plot (Chart 1), by conducting a subgroup based on the type of water source, it was found that the mean of uranium in groundwater and surface water was 0.17 (0.13, 0.21), 0.19 (0.13, 0.25), 0.14 (0.12, 0.16), 0.16 (0.12, 0.20), 0.14 (0.12, 0.16), 0.13 (0.09, 0.17), 0.15 (0.13, 0.16), and I^2 = 8 %, 0.09 (0.03, 0.15), 0.29 (0.11, 0.47), 0.17 (0.02, 0.36), and I^2 = 77.5 % respectively. Also, the results of the Subgroup based on the studied region showed that the highest concentration was related to the South African region at 0.29 μg/L, and the lowest was in the Northern California region at 0.09 μg/L. In addition, China has 0.14, Uttar Pradesh with a concentration of 0.11, and Spain has 0.19 μg/L. In the examination of the average concentration among the continents, the results showed that the highest concentration was associated with the continent of Africa (0.29 μg/L), followed by the continent of Europe, whose average concentration was estimated at 0.19 μg/L. The average concentration in the Asian continent was 0.15 μg/L.

By selecting eligible records and extracting data, the meta-analysis results shown in Chart 2 interpreted most of the results were close to the confidence interval and were located around the overall effect axis.

As can be seen in Chart 3, the mean uranium concentration was 0.15 μg/L within a range of 0.13–0.16 μg/L. It was also found that the test of heterogeneity between studies was not statistically significant and its *p*-value was 0.74. The I^2 index was estimated at 40.1 % as well. Also, the *p*-value of 0.05 indicates that the study heterogeneity test is not significant.

3.4. Uranium stress in water supplies

Uranium can enter the food chain through water and soil, potentially harming the health of the community. Uranium mining and processing can contaminate aquatic ecosystems for hundreds of years, threatening downstream communities and wildlife. Even small amounts of some pollutants can poison fish, accumulate in the food chain, and cause



Flowchart 1. The literature review screening flow diagram.

Table 1
Studies and specifications of each of them that entered the meta-analysis.

Country	Year	Source type	Sample	U concentration	SE	Reference
India	2017	groundwater	45	0.17	0.02	[14]
India	2014	groundwater	22	0.19	0.03	[15]
USA	2019	groundwater	296	0.14	0.01	[16]
Northern California	2014	surface water	9	0.09	0.03	[17]
India	2016	both	5	0.25	0.08	[18]
India and Uttar Pradesh	2014	both	38	0.11	0.02	[19]
India	2019	groundwater	54	0.13	0.02	[20]
Spain	2016	both	27	0.19	0.03	[21]
Iran	2013	groundwater	99	0.14	0.01	[22]
South Iraq	2016	groundwater	43	0.16	0.02	[23]
china	2016	both	19	0.14	0.03	[24]
South Africa	2015	surface water	5	0.29	0.09	[25]

deformities and reproductive problems for aquatic species [69,70]. Uranium mining has widespread effects, contaminating the environment with radioactive dust, radon gas, water-borne toxins, and increased background radiation. Uranium has no known normal metabolic function or essential human elemental requirement. It has been shown to cause chemical toxicity, and because it emits predominantly alpha particles, uranium is a suspected human carcinogen [68]. The highest uranium activity concentrations were measured in the thermal groundwater from Mszczonow and Cieplice, while the lowest were observed in thermal ground water from Uniejow and Poddebice [43]. A survey conducted on uranium and 226-Ra concentrations in drinking water supplied by Finnish waterworks found that the concentrations of these radionuclides were generally below the detection limit, the annual effective doses to the public were minimal, and the EU Drinking Water Directive's limit for radionuclide concentrations in drinking water was not exceeded in any of the water distribution networks. The highest uranium concentration in a single sample was 25 μg/L in the Riihimäki waterworks [27]. Kaishwa et al. [28] assessed the levels of uranium in soil, rock, and water sources in Singida Urban District, Tanzania. The levels of uranium in this context were relatively high, which subsequently led to higher levels of uranium in surface and underground water sources, and drinking water in Singida Urban District may have elevated levels of uranium. Also, the concentrations of uranium in the groundwater tested in Myingyan Township, Myanmar exceeded health-based reference values in most wells [26].

The laser fluorimetry (LF) and fission track analysis (FTA) techniques were compared for estimating uranium concentration in drinking water samples from Punjab. The results obtained by LF and FTA techniques

Table 2
Overview of included records.

Code	First author	Country	Study design	Main result
R008	Bacquart et al. [26]	Myanmar	Myanmar ground and surface waters analyzing for multiple inorganic contaminants	The water in Myanmar has many harmful substances that are not natural, like uranium.
R010	Turtiainen et al. [27]	Finland	The research looked at how much uranium and 226Ra is in the water given out by water plants in Finland.	The average amount of uranium in water provided by Finnish waterworks was 0.58 μg L^{-1}, or in terms of 238U, it was 7.2 mBq L^{-1}.
R014	Kaishwa et al. [28]	Tanzania	This talks about the connection between uranium in soil and rock and the amount of uranium found in surface and underground water.	The soil and rock have higher levels of uranium. This, in turn, leads to high levels of uranium in drinking water sources.
R017	Benedik et al. [29]	Slovenia	Samples were collected from tap water from people's homes for 238U, 234U, 226Ra, 228Ra, 210 Pb, and 210Po evaluation.	The range of 238U and 234U in samples were (0.17–372) and (0.22–362)mBq L^{-1}.
R018	Prabhu et al. [30]	India	Drinking water samples were taken for uranium assessment.	The amount of uranium in the samples ranged from 3.2–605 ppb and was similar to laser fluorimetry results.
R023	Sahoo et al. [31]	India	Uranium intake values in samples and different age groups	The concentration of uranium was bellow guideline values.
R029	Min et al. [32]	China	Surface and groundwater sources in the Shihong Tan mining area were analyzed to evaluate the origin of uranium.	The water comes from a combination of different sources.
R036	Stalder et al. [33]	Switzerland	The study was done to see how much uranium is in the drinking water in Switzerland.	High levels of uranium found in Swiss drinking water are caused by the type of rock formations underground. It needs to take action in these areas.
R047	Nazir et al. [34]	India	Testing the radioactivity in the groundwater of Srinagar City by using uranium and radon as indicators.	The amount of uranium found was lower than what is considered safe worldwide.
R048	Mourad et al. [35]	Lebanon	The amount of natural radioactivity in the drinking water in southern Lebanon was measured.	The annual effective dose from just one sampling exceeded the single dose standard.
R049	Ali et al. [36]	Iraq	Evaluation of radioactivity of 238U, 232Th and their daughter products in water samples.	The values of 238U and 232Th vary between 0.20 and 3.50 ppm and from 0.03 to 1.83 ppm
R058	Han et al. [37]	China	Examine hydraulic connection and U distribution are related by analyzing water chemistry and isotopes (234U/238U, δ11B)	Hydrochemistry and several isotopic (B, U) values indicated that hydraulic connections are complex in the Gas Hure salt lake.
R060	Ratia et al. [38]	Spain	The study tested 196 samples of drinking water to find out how much α and ß activity there was.	23 % of the samples tested had a higher value of the crude alpha parameter, which was set at 0.1 Bq/L
R067	Pregler et al. [39]	Switzerland	Water samples were taken from different places like springs, creeks, and pipes where water drains.	Scientists discovered that the uranium amount in some groundwater and surface waters in the Swiss Plateau had increased.
R072	Csondor et al. [40]	Hungary	A hydrogeological approach for evaluation the radioactivity.	River water level fluctuations are correlated with uranium content in wells, highlighting the transient nature of river bank filtered system.
R073	Christensen et al. [41]	USA	Application of strontium isotopes to assess spatial variations in groundwater recharge.	The findings showed differences in the amounts and types of Sr isotopes in the groundwater and surface water samples. The research also showed how the shape of the land affects where water seeps into the ground and how it adds to the underground water supply.
R074	Baumann et al. [42]	Germany	This document talks about a study that used a specific type of laser to look at how uranium in water seeps out of the ground and in the water that is found in small spaces in soil that has a lot of heavy metals.	This study showed that TRLFS is a suitable and helpful technique for studying how uranium is distributed in water samples that occur naturally. These water samples have a pH range of 3.2 to 40.
R075	Grabowski et al. [43]	Poland	Scientists measured the amount of 234U and 238U in different water samples such as thermal groundwater, deep well water, and river water.	The amount of 234U and 238U is different in different water sources. The concentration is higher in thermal groundwater. The ratio of activities of 234U and 238U gave us information about how water moves

(*continued on next page*)

Table 2 (*continued*)

Code	First author	Country	Study design	Main result
				and flows in large water storages.
R079	Krachler et al. [44]	Austria	The goal is to study how much uranium is in the water and sediment at Lake Neusiedl in Austria.	The amount of uranium found was surprisingly high, especially in places with lots of salt. The levels of uranium isotopes were the same in all samples, which suggests that they all came from the same place.
R80	Shalumon et al. [45]	India	A total of 830 water samples from different sources were collected during pre and post-monsoon seasons. These samples were analyzed for uranium concentration and 11 other water quality parameters.	The amount of uranium in the water changed from less than 0.5–1254 μg/L pre-monsoon, and from less than 0.5–593 μg/L after the monsoon.
R85	Alvarado et al. [46]	Kyrgyzstan	Water samples were collected from the drinking water distribution system (DWDS), rivers, shallow aquifers, and drainage water from the mine tailings.	Radionuclides and trace metal contents in the DWDS water were generally low, but iron, aluminum, and manganese levels were extremely high, correlated with high turbidity levels.
R090	Navarro et al. [21]	Spain	Elevation the concentrations of U and Hg in drinking water from public supply and agricultural wells.	In granitic areas with long residence times and significant salinity, U levels are highest, while Hg concentrations are associated with the migration of Hg from granitic materials and the use of mercury-based fungicides in golf courses and residential areas.
R091	Singhal et al. [47]	India	Determination of the ultra-trace levels of uranium in groundwater with adsorptive stripping voltammetry.	The adsorptive stripping voltammetry was a sensitive method for determining ultra-trace levels of uranium in ground water.
R092	Sekudewicz et al. [48]	Poland	Uranium and polonium isotopes were measured in tap water and groundwater within the Warsaw region.	The mean values of 210Po, 234U, and 238U in surface intakes were 0.12, 3.91, and 2.75 mBq dm^{-3}, respectively, while for deep water intakes, they were 0.25, 0.24, and 0.20 mBq dm^{-3}.
R102	Peng et al. [24]	China	Uranium concentration and the exercises of	The 234U/238U activity ratio generally

Table 2 (*continued*)

Code	First author	Country	Study design	Main result
			238U, 234U, and 230Th were decided for groundwater, spring waters, and lake water.	increased with decreasing U concentrations in the groundwater.
R112	Sahoo1 et al. [49]	India	Assessment of the uranium substance in drinking water sources.	Uranium was detected in 83.6 % of the collected water samples.
R114	Silva et al. [50]	Brazil	Assessment the levels of gross alpha and beta natural radio activities in surface, underground and drinking water	The preliminary results showed varying levels of natural radiation, with gross alpha activity ranging from 0.02 ± 0.001 Bq/L to 0.80 ± 0.04 Bq/L, and gross beta activity ranging from 0.010 ± 0.006 Bq/L to 3.0 ± 0.2 Bq/L.
R117	Villalobos et al. [51]	Mexico	The most objective of this consider is to decide whether the uranium stores within the San Marcos outcrops in Chihuahua City, Mexico, can be considered as a source of U-isotopes within the encompassing environment.	Uranium may filter into ground and surface water, leading to exchange with biota. U-isotopes in biota may contribute to neighbouring population's doses.
R125	Bonotto et al. [52]	Brazil	Evaluation the contents of mineral waters from conspicuous springs, surface waters, and water.	Based on results fluoride, barium, and 210 Po levels surpassed the WHO limits for drinking water in a few tests, potential wellbeing risks and confinements on the utilize of water as a drinking water asset.
R132	Kraemer et al. [53]	California	Determination of 234U/238U activity ratios (UAR) in natural waters using commonly available ICP/MS instrumentation	It has been effectively utilized to analyze UARs in new to decently saline waters with U concentrations extending from less than 1 μg/L to about 100 μg/L.
R149	Jakhu et al. [54]	India	The uranium concentration within the drinking water for the inhabitants of the Jaipur and Ajmer locale of the Rajasthan has been measured.	The day by day admissions of uranium from the drinking water for the inhabitants of the think about region was found to differ from 0.4 to 123.9 μg day-1.
R153	Chen et al. [55]	China	investigation the hydro-geochemical characteristics of water samples from the sandstone-hosted uranium mineralization in the northern Ordos Basin	Different hydro-geochemical forms are included within the formation of uranium stores within the locale.

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Table 2 (*continued*)

Code	First author	Country	Study design	Main result
R154	Cunha et al. [56]	USA	This findings highlighted the contamination of groundwater with uranium and its decay products from past uranium mining activities.	The total uranium concentration in 19 % of the water samples exceeded the maximum concentration level for drinking water.
R156	Martinez et al. [57]	Spain	Physicochemical parameters and natural tracers (uranium, radium, and radon) were analyzed in surface water and groundwater samples from the River Andarax.	The concentration of uranium in the river water was found to vary, with higher concentrations in the headwaters (2 mg/L) and lower concentrations in the lower reaches (6 mg/L).
R163	Hakam et al. [58]	Morocco	Assurance of the radioisotopes particular exercises of uranium (234-U, 238-U) in a few drinking water tests from diverse sources (tap water, mineral water and wells water).	The uranium particular exercises are generally tall within the well waters and those of radium are moderately tall within the warm spring waters.
R169	Ma et al. [59]	China	A total of 110 samples, including 96 solid and 14 water samples, were collected to assess the occurrence and distribution of U in the soil-water system.	The results showed that half of the soil sampling sites were moderately polluted. In groundwater samples, U concentrations ranged from 0.55 ± 0.04 mg/L to 3.36 ± 0.02 mg/L, with a mean value of 2.36 ± 0.36 mg/L.
R172	Berisha et al. [60]	Kosovo	The study analyzed 951 water samples using inductively coupled plasma mass spectrometry (ICPMS).	2.6 % of analyzed water samples exceeded WHO drinking water guidelines of 30 μg/L 44 % of the water samples exceed the recommended concentration for babies (2 μg/L).
R184	Kailley et al. [61]	India	Estimation of U and overwhelming metal substance.	According to the Central Groundwater Board report, 80 % of Punjab's area is affected by uranium in groundwater.
R188	Alrakabi et al. [62]	India	The study focuses on investigating the elemental concentration of uranium in ground water and canal water in the Bathinda district of Punjab state, India. The X-ray fluorescence technique is used for analysis.	The study suggests that agrochemical processes occurring in calcareous soils in the region are the favored potential source of uranium in ground water. The concentrations of certain elements, such as Br, Sr, and U, were found to be high in shallow ground water samples collected from hand pumps, indicating a correlation with total salt content.
R192	Yamamoto et al. [63]	Kazakhstan	This study focuses on the levels of uranium isotopes (234U, 235U, and 238U) in well water samples collected from settlements around the SNTS.	The concentration of 238U in the well water samples varied widely, ranging from 3.6 to 356 mBq/L. Some water samples had 238U concentrations comparable to or higher than the WHO proposed guideline of 15 μg/L.
R194	Winde et al. [64]	South Africa	A study in South Africa links uranium-contaminated drinking water to leukemia and aims to investigate alternative exposure pathways.	This case study highlights the potential health risks associated with uranium-contaminated drinking water and its link to leukemia.
R200	Yadav et al. [19]	India	Evaluation the concentrations of uranium in drinking and ground water samples calculation the cumulative, age-dependent radiation doses to humans.	The uranium concentrations in the water samples ranged from 0.20 ± 0.03 to 64.0 ± 3.6 mg/L, with an average concentration of 11.1 ± 1.5 mg/L. These concentrations were found to be within the drinking water limit set by regulatory bodies.
R205	Wu et al. [65]	China	This study discussed the variations in uranium concentrations in a multi-aquifer system due to the interaction between surface water and groundwater.	Groundwater uranium concentrations exhibit spatial-seasonal variations related to pH, Eh values, and dissolved Ca^{2+}, HCO_3^-, and Fe (III) concentrations.
R216	Zoriy et al. [66]	Tajikistan	Over 130 water samples were collected from various sources such as rivers, lakes, wells, and drinking water points.	Out of nine drinking water samples near Taboshar, seven exceeded the World Health Organization's guideline value for uranium concentrations (30 μg/L).
R217	Wu et al. [67]	China	This study focuses on investigating the occurrence, behavior, and distribution of high levels of uranium (U) in shallow	High U groundwater occurs at the alluvial plains of Datong basin. Redox state, complexation and adsorption are

(*continued on next page*)

Table 2 (*continued*)

Code	First author	Country	Study design	Main result
			aquifers at the Datong.	responsible for U enrichment.
R223	Tanaskovic et al. [68]	Serbia	A total of 5 drinking water samples were analyzed in October 2001, and 4 samples were analyzed in April 2002. In September 2002, 11 samples were analyzed.	The analyzed drinking waters from the regions bombed by depleted uranium ammunition were safe from a radiological aspect. It is recommended to continue monitoring the radioactivity of potable waters in this region to ensure ongoing safety.

were comparable, and the uranium concentrations in the samples ranged from 3.2 to 60.5 ppb. However, the LF technique had some advantages over the FTA technique, such as simplicity, sensitivity, easy sample preparation, and faster analysis time. Further investigations are recommended to determine the source of uranium in drinking water and its potential health effects [30]. The uranium and heavy metals content was assessed in Sirhind Canal water and groundwater in the Malwa Belt of Punjab, and the uranium content in the surface water of Sirhind Canal downstream was below the detection limit in all tested villages. However, findings showed that groundwater in several districts had uranium levels ranging from 30.0 to 366.0 ppb [61]. In this country, other studies examined the distribution of uranium in drinking water sources (tap water, bore well water, and river water) from different states in India. They estimated the associated age-dependent radiation dose and highlighted the importance of assessing uranium content in drinking water for hydro geochemical prospecting and health risk assessment. The study found that about 54 % of the samples contain uranium less than one mg/l, and only four samples contain higher uranium content (i.e., more than ten mg/l) [31,61,62,71]. The results related to the amount of uranium in the water resources of India were contradictory. A significant fraction of the groundwater samples with uranium concentration that exceeded the permissible level recommended by the WHO for drinking water was observed in the Bathinda district of Punjab state, India [62]. Another study was conducted in five districts of Kerala and analyzed uranium and water quality parameters in drinking water sources in five districts by 830 samples from different sources during pre and post-monsoon. The concentration of uranium varied from <0.5 to 12.54 μg/L in pre-monsoon and <0.5–5.93 μg/L in post-monsoon is well within the standard limit, and the concentration of uranium was within the standard limit, indicating that the water was suitable for drinking [45]. The drinking water quality is vital for guaranteeing its security for human consumption, and radioactivity concentration is one of the variables that can influence the quality. The nearness of radionuclides in drinking water at specified concentrations can make it risky for utilization. A study measured the activity of gross alpha, gross beta, uranium, and radon in drinking water samples collected from different sources in South Lebanon. The measurements were conducted in wet and dry seasons to account for seasonal variations. The study found that the annual effective dose of only one sampled well (Aitaroun) exceeded the individual dose criterion (IDC) level set by the WHO. The reported annual effective dose for infants, children, and adults in this well was higher than the recommended limit. However, the radioactivity concentrations in other sampled locations were within acceptable limits [35]. The studies conducted in Tarragona, Spain, and Hungary, as well as the assessment in Kyrgyzstan, collectively highlight the presence of natural radioactivity in drinking water and its potential implications. In Tarragona, approximately 23 % of the drinking water samples exceeded the alpha-gross index parameter, indicating the presence of natural radionuclides. However, most of the samples (95.5 %) did not pose a health risk, with annual effective doses remaining below 0.1 mSv/year. In Hungary, the correlation between the uranium content of wells and river water underscored the impact of uranium mining on water sources. Additionally, the assessment in Kyrgyzstan revealed potential risks of contamination from uranium mining residues, particularly during floods and landslides. While the levels of radionuclides and trace metals were generally low in the water samples, high concentrations of iron, aluminum, and manganese were associated with elevated turbidity. These findings emphasize the importance of continued monitoring and assessment to ensure the safety of drinking water and to mitigate potential risks associated with natural radioactivity and human activities [21,38,40,72].

The issue of uranium contamination and health risks in Kosovo after the NATO war in 1999 should not be overlooked. A study analyzed 951 drinking water sources in Kosovo, revealing that over 98 % of the samples had uranium concentrations above 0.01μg/L, with concentrations up to 166 μgL-1. The mean concentration was 5 μg/L, and the median was 1.6 μg/L. The study found that 2.6 % of the analyzed samples exceeded the WHO maximum acceptable concentration of 30 μg/L, and 44.2 % exceeded the 2 μg/L German maximum acceptable concentrations recommended for infant food preparations. In another study, the levels of gross alpha and beta natural radio-activities in surface, underground, and drinking waters in Brazil exceeded the recommended levels in drinking water set by the WHO. These findings highlight the importance of monitoring and addressing uranium concentration and its potential health risks in affected regions. However, further studies are needed due to the high background radiation in the area [50,60]. Winde et al. [64] conducted a study in South Africa to assess the connection between uranium-contaminated drinking water and leukemia. The research revealed that contaminated drinking water was the primary exposure pathway for residents, leading to uranium uptake rates that exceeded recommended limits. Household water filtering was recommended as a short-term solution to reduce uranium levels in underground water. The study underscores the potential health risks associated with uranium-contaminated drinking water and the importance of implementing measures to address this issue, particularly in affected regions such as South Africa.

3.5. Uranium levels based on isotopes

Several studies have investigated the presence of uranium isotopes in different water sources and their potential health risks. In Central Poland, the activity concentrations of 234U and 238U in the examined waters varied from <0.013 (LLD) to 16.8 mBq/dm^3 and from <0.013 (LLD) to 45.5 mBq/dm^3, respectively. Another study used strontium isotopes to evaluate the spatial variation of groundwater recharge at the Rifle Site, a former U-mill tailings site adjacent to the Colorado River. The study found that the vadose zone pore-water contribution to the aquifer ranged from 0 % to 38 % and was almost entirely controlled by the micro-topography of the site. In Germany, a binding U guideline value in drinking water of 10 μg/L was established due to the nephrotoxic and ototoxic potential [29,41,43,63].

The hydrochemistry and isotope compositions of groundwater in Xinjiang, NW China, were evaluated by the Shihongtan sandstone-hosted uranium deposit, and the groundwater was categorized into three hydrochemical facies, each with different characteristics. The data suggested that the uranium in groundwater in the area was related to migration, water-rock interaction, and mixing of meteoric water with connate waters contained in sediments [32]. The speciation of uranium in water samples from a test site called Gessenwiese showed uranium speciation in the samples was dominated by the uranium (VI) sulfate species UO_2SO_4 (aq), and no evidence for the existence of the so-called “free uranyl” was seen in the samples by TRLFS. However, it could be

possible that a signal from free uranyl was suppressed by the intensive signal from the UO_2SO_4 (aq) species. The uranium can enter economic loops and eventually reach the food chain, so understanding its speciation is essential for assessing potential risks [42]. A study nationwide found higher uranium levels in Swiss mountainous drinking water sources compared to other places. The cause was the rocks in the ground, but there was no relation between uranium levels in the water and other substances. Uranium levels in Swiss drinking water varied greatly, ranging from undetectable amounts to nearly 100 μg per liter. Among 5548 samples, 98 % were below the WHO's 2004 limit of 15 μg/L, and 99.7 % were below the 2011 limit of 30 μg/L. The text highlighted uranium in Swiss drinking water, mainly in snow-capped areas, but most people were not exposed to high levels. Also, certain areas may need to reduce uranium levels in the water supply. More research is needed, particularly in the Bernese Alps, where there is no available data currently [33]. Another study looked into the higher amounts of uranium found in the water on and below the surface of the Swiss Plateau. Two springs on the mountainside of Mont-Verry have a lot of uranium and were observed for almost two years to see if the amount of uranium changed depending on the season. Samples of water were collected from springs, streams, and drains. Drainage pipes draining farmland north of Mont-Vory contained even higher concentrations of uranium. Radiocarbon dating of the uranium-rich peat strata revealed an age of less than 8.1 thousand years, indicating that the wetland was formed in an impermeable clay layer after the last Ice Age. A potential source of uranium is the Aralin gabbro which often contains uranium ore and occurs on the Swiss plateau due to glacial transport from the Alps. Another possible explanation is the presence of coal seams with increased gamma dose rates in the Lisbach region. However, the actual origin of uranium enrichment in Swiss plateau peat remains unclear [39].

In some cases, groundwater sources may already be contaminated with uranium, and the contaminated water will be used as a source of drinking water without proper treatment. The survey by Ref. [34] et al. assessed the radioactivity in groundwater in Srinagar City using uranium and radon as indicators. The study found that the average uranium concentration was below the permissible level, while the radon concentration in some groundwater samples outmatched the permissible limits set by USEPA. This information can be important for health professionals studying lung cancer incidence in the region, as radon is a leading cause of lung cancer worldwide [73].

The concentrations of uranium, thorium, and their daughters in water tests (reservoir water, well water, dehydrator, desalter, and drinking water) were collected from oil sites in northern Iraq. The survey found that most of the delivered water from the oil areas isn't reasonable for any coordinated reason based on suggested values and the calculated yearly successful dosage. The uranium concentration in well water tests extended from 0.32 to 3.50 ppm, whereas the uranium concentration in-store water tests extended from 0.80 to 2.05 ppm. Based on the results, the uranium concentration was higher than the WHO level in a few trials but lower than the Determined Constrain of Canada (DRL) esteem in most tests [36].

The influence of hydraulic connection on the distribution of uranium in the Gas Hure Salt Lake in China was investigated. The study collected water samples from various sources (spring, stream, well water, intercrystalline brine, and water from the drilling hole) around the lake with hydrochemistry and isotope techniques. The measure of uranium in water varies depending on the sample, and the uranium concentration ranged from 2.09 to 289.67μg/L [37].

4. Conclusion

This systematic review investigated the uranium in drinking water supply sources in the world by meta-analysis approach and focuses on examining the amount of uranium present in drinking water sources in the world. The research includes a variety of primary sources such as original articles, preprints, and peer-reviewed journals and reports from PubMed, Web of Science, Science Direct, Google Scholar, and gray literature. Meta-analysis was conducted on 12 studies using the random effects model. The average uranium concentration was 0.15 μg/L, below WHO guidelines for drinking water. The test of heterogeneity between studies was not significant, indicating consistent results. The U concentrations in various water sources from different countries show significant variations, with the highest concentration found in surface water from South Africa (0.29 μg/L) and the lowest in groundwater from the USA (0.01 μg/L). Providing a safe source of drinking water has become a challenge due to various anthropogenic pollutants in water sources. Radioactive pollution is considered one of the top sources of concentration in surface waters such as rivers and streams. These pollutants are critical due to their detrimental impacts on public health and the environment. The presence of radioactive pollutants, especially the presence of uranium in water has become a global concern. The results of the present investigation demonstrated that an elevated uranium concentration occurred in surface water.

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CRediT authorship contribution statement

Samaneh Abolli: Writing – original draft, Methodology, Investigation. **Niloufar Borhani Yazdi:** Conceptualization. **Mohammad Khanizadeh:** Visualization, Validation. **Kosar Salemi:** Writing – review & editing, Formal analysis. **Maryam Zare Bidoki:** Validation, Data curation. **Ehsan Abouee Mehrizi:** 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.

Data availability

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

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