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Assessing Uranium Contamination in Groundwater: A Comprehensive Review for India

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***Abstract*:U contamination in groundwater is a growing environmental and public health concern in India, particularly in areas with U-rich geological formations. Its presence in groundwater is influenced by natural processes such as rock-water interaction and leaching, as well as anthropogenic activities like industrial waste discharge and phosphate-based fertilizers. Prolonged U exposure poses serious health risks, primarily affecting kidney function, bone development, and reproductive health due to its chemical and radiological toxicity. This study reviews U contamination levels, influencing factors, and detection methods such as ICP-MS, alpha spectrometry, and laser-induced fluorimetry. Studies reveal that U levels in some regions exceed WHO and BIS safety limits. River osmosis, ion exchange, adsorption, and bioremediation have proven effective in mitigating contamination. Sustainable groundwater management, periodic monitoring, and policy interventions are crucial for reducing risks and ensuring safe drinking water. This review emphasizes the need for strategic interventions to safeguard public health.**

***Author Keywords*: U contamination, Groundwater pollution, Radiological toxicity, Water treatment, Public health. India.**

I. INTRODUCTION

Water covers 71% of the Earth's surface, mostly in seas and oceans. About 3.4 million people (mostly children) die per year due to water-related diseases [1]. On Earth, 97.2% of water is salty, and only 2.8% is freshwater, of which 20% constitutes groundwater. Once groundwater gets contaminated, it can not be restored by stopping the pollutants from their source. According to WHO, about 80% of diseases in human beings are caused by contaminated water [2]. Water quality is influenced by many contaminants, such as organic, inorganic, microbial, and radioactive pollution [3–5]. Uranium (U) is a potent radioactive contaminant due to its chemo and radiological properties [6, 7]. The primary sources of U contamination in groundwater are geogenic in nature, such as the weathering of rock, which contains radioactive elements, dissolution of another mineral, and controlled by groundwater fluctuation, as well as anthropogenic activities [1, 2, 8–10]. The release of bicarbonate during the monsoon season can affect the saturation index of U, leading to its mobilization [10].

Additionally, using fertilizers in agricultural activities may contribute to higher U concentrations in groundwater [8, 11]. It is important to note that the concentration of U in groundwater can vary with different seasons, with the highest levels observed during the northeast monsoon season [11–15]. Overall, the primary source of U contamination in groundwater in India is natural geological processes, but human activities can also play a role in exacerbating the issue [13, 16–20]. Many researchers are tracking the mobilization of Uin water bodies, especially in groundwater, at the international and national levels. As far as India is concerned, many researchers have measured the U concentration in groundwater. Considering all detailed studies, the main objective of this study is to review the levels and the significant impact of U measurement and tracking in sources.

II. MATERIALS AND METHODS

Literature Survey

This study adopts a comprehensive approach to assessing U contamination in groundwater across India. A systematic review of existing literature, government reports, and scientific publications was conducted to understand U's sources, distribution, and health impacts in groundwater. Data on U concentration levels were gathered from various hydrogeological studies and monitoring programs, focusing on regions exceeding the WHO and BIS permissible limits. To evaluate uranium concentration, advanced analytical techniques such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Alpha Spectrometry, Laser-Induced Fluorimetry, and Kinetic Phosphorescence Analysis were examined for their effectiveness in detecting U at trace levels. Additionally, various remediation strategies, including reverse osmosis, ion exchange, adsorption, and bioremediation, were analyzed to determine their efficiency in removing U from groundwater. The findings of this review aim to provide insights for improved groundwater management, policy implementation, and public health interventions in affected regions.

III. RESULTS AND DISCUSSION

Sources of U in Groundwater

U in groundwater occurs due to both sources, viz., natural (geogenic) and artificial (anthropogenic). The primary natural sources are granite, shale, phosphorite, and sedimentary rocks due to the weathering and dissolution of U-rich minerals such as uraninite, zircon, and monazite, which release U into groundwater [21–23]. The soil also plays a vital role in releasing the U from U-bearing rocks, which release U into groundwater through leaching, especially under oxidizing conditions [24–29]. High bicarbonate content in water enhances U solubility [25]. Oxidizing conditions play a favourable role in the conversion of insoluble U(IV) to soluble U(VI), making it mobile in water [30–34]. Higher pH (Alkaline) levels can also increase U mobility in groundwater [35–38]. A geothermal system creates hot springs that can introduce U into groundwater [39–42]. In the case of anthropogenic sources, several sources have been recorded. For example, a phosphate-containing rock used in fertilizers has U as an impurity and can leach into groundwater [43–47]. U mining and milling waste can contaminate groundwater through tailings and leachates [48–52]. Nuclear power plants, metal processing industries, and coal-fired power plants release U into the water environment [53]. Fly ash from coal-burning power plants contains U, which can leach into groundwater [48–50, 53–55]. Improper disposal of radioactive waste and past nuclear weapons testing can contribute to U contamination [56].

U content in India's groundwater

U contamination in groundwater is a growing concern in various regions of the world, including India at the national level, where the majority rely on groundwater as a fresh and contaminated-free source for drink. The main concern of U presence in drinking water is due to its radio and chemo toxic properties, which may lead to carcinogenic to human beings [4, 57–64]. This contamination can be attributed to natural factors and anthropogenic activities causing a human health effect. Several studies have been done on the health concerns arising from the consumption of U-containing drinking water at international and national levels [6, 65, 73–82, 66, 83, 84, 67, 67–72]. A state-wise U concentration list and map are presented in Table 1 as a part of the current study.

Uranium contamination in India's groundwater varies widely across different states, with some regions showing alarmingly high concentrations. Areas in Karnataka, Haryana, Punjab, and Rajasthan report some of the highest levels, with Chikkaballapura (Karnataka) reaching up to 8649 ppb and Kolar exceeding 2985 ppb. Meanwhile, states like Kerala, West Bengal, and Odisha generally have lower uranium levels, staying below 50 ppb in most cases. The variation in uranium content is largely due to differences in geological formations, mining activities, and local water chemistry. Particularly concerning are the high readings in Punjab and Haryana, where multiple districts record levels above 500 ppb, posing potential health risks. Similarly, parts of Madhya Pradesh, Andhra Pradesh, and Uttar Pradesh also show elevated concentrations, highlighting the need for ongoing monitoring. Given these findings, ensuring safe drinking water through better groundwater management and filtration methods is crucial for affected areas.

A comprehensive study on U occurrence in shallow aquifer in India has been conducted by Central Ground Water Board in 2020. This is single study report which published the concentration of U in groundwater at state level. A total of 14377 groundwater samples were collected from well water sources across India. The U concentration ranges from 0.0 to 2876 ppb representing that U contents in groundwater prominently change by several orders of magnitude. The most affected states which have crosses the permissible limits (30 ppb) prescribed by WHO [85] are Punjab (24.2%), Haryana (19.6%), Telangana (10.1%), Delhi (11.7%), Rajasthan (7.2%), Andhra Pradesh (4.9%), Uttar Pradesh (4.4%) respectively.

Uranium in groundwater and human health

Consumption of U-contaminated groundwater is highly harmful to human health due to U's chemo-radiological properties. The comprehensive list of risks due to U is presented in the form of a flowchart, denoted in Figure 1. Understanding potential harms related to U use requires an accurate assessment of U contamination in groundwater [10, 86]. Apart from its radioactivity, U presents a serious risk for chemical toxicity. Chronic consumption raises the risk of cancer and damages the kidneys. U's presence in groundwater seriously threatens human health due to its dual toxic nature—both chemical and radiological. Assessing the risks associated with U exposure requires precise groundwater testing, as contamination levels can vary significantly [87]. While U's radioactivity is concerning, its chemical toxicity is often the primary cause of health issues, particularly prolonged exposure. Chronic ingestion has been linked to kidney damage and an increased risk of cancer [87–91]. Detecting U in groundwater relies on advanced analytical techniques, such as inductively coupled plasma mass spectrometry (ICP-MS), lab-based spectroscopy, and portable field-testing devices. However, these methods can be costly, complex, and require specialized training. LED fluorimeter is very rugged from many instruments and requires minimum maintenance [56]. Due to U's radioactive properties, its health effects have been widely studied. While naturally occurring and depleted U primarily cause chemical toxicity, enriched U presents an additional radiological hazard [92]. Among U compounds, those highly water-soluble, such as U hexafluoride, uranyl nitrate, and U tetrachloride, pose the most significant systemic risks [92–94]. Research has also suggested a possible link between U exposure and thyroid dysfunction [95, 96]. A study of 3,125 individuals living in areas with high U concentrations in drinking water found elevated thyroglobulin antibody levels associated with a higher incidence of thyroid cancer [95]. However, no correlation was found with anti-thyroid peroxidase levels [95]. The effects of U on human reproduction remain poorly understood. Some findings indicate that U toxicity may disrupt reproductive function by lowering sex hormone levels, reducing fertility, affecting gene expression related to reproduction, and even increasing the likelihood of identical twin births [95–98]. Given these potential health risks, regular monitoring and mitigation strategies are crucial to prevent long-term exposure to U-contaminated water.

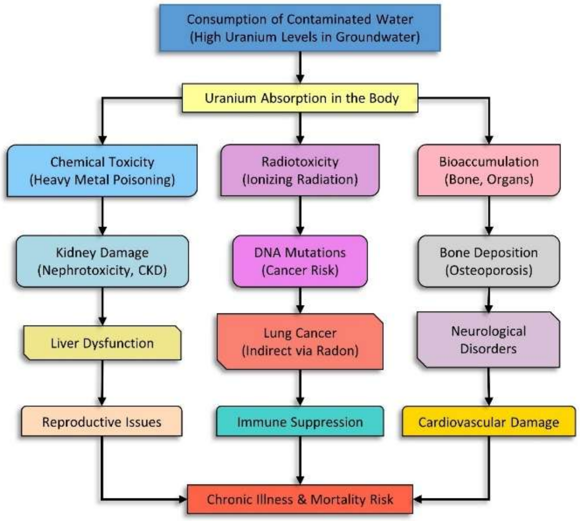

Figure 1. Impact of U on Humans

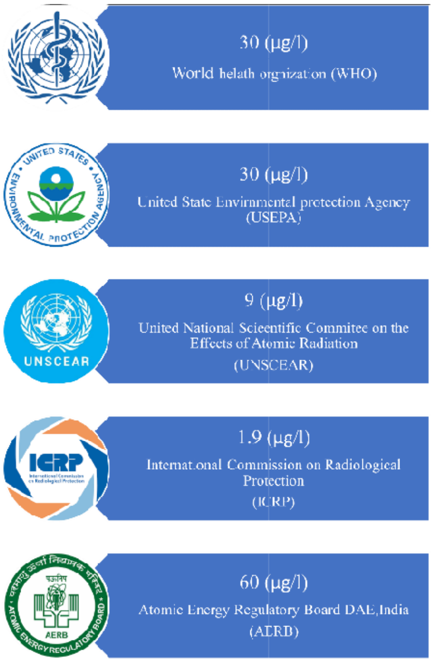

Figure 2. The permissible limit of U concentration

The researchers' investigation was helped by the extensive review of local, national, and worldwide literature that was conducted before selecting the current subject. The literature review provided the essential background and focus for the research topic. Table 1 provides an overview of some relevant research on this subject.

Methods for U determination

Various approaches have been employed to estimate U concentrations in water sources, often utilizing multiple methods to ensure accuracy and reliability. Numerous studies have explored analytical techniques for U detection, including spectrophotometry, fluorometry, and kinetic phosphorescence, alongside radiological analysis techniques such as spectroscopy. Additionally, U quantification in water samples is conducted using mass spectrometry-based applications like accelerator-MS, AES-MS, and ICP-MS [169–171]. Selecting a suitable detection method depends on several factors: sample type, instrument precision, cost, spectral interferences, and overall accuracy. Advanced techniques such as bioremediation, MF-HT adsorption, nanoparticle technology, LED fluorimetry, Raman spectroscopy, ICP-MS, HR-ICP-MS, and MC-ICP-MS have also been explored for U analysis [169, 172–175]. Researchers commonly employ liquid scintillation counting and alpha-particle spectroscopy to study U in groundwater. These methods allow for precise measurements of U isotopes, with alpha-particle spectrometry and liquid scintillation counting particularly useful in determining U activity levels [176–180]. ICP-MS is widely used to measure isotope and activity ratios, providing insights into the natural variations in groundwater U levels. U Activity Ratios (UAR) help quantify the balance between parent and decay-product U isotopes, while radiation chemistry techniques further refine isotopic U measurements. The combined use of these methods enhances our understanding of U distribution in groundwater systems [176, 181–184].

Remedial technologies

Different countries use various water treatment methods to remove U from water. Reverse Osmosis (RO) is highly effective in removing U and other heavy metals from drinking water [185, 186]. Adopting an Ion Exchange resin to remove U ions from water selectively will work effectively [187, 188]. Adsorption methods like activated alumina and zeolite-based filters can trap U [189–193]. New trends are evolving in nanotechnologies, such as nano-adsorbents, such as graphene oxide and biochar, which are emerging solutions for better efficiency in U removal [194–197]. Chemical methods include lime or ferric chloride to precipitate U for removal [198]. Bioremediation techniques like microbial reduction [199] and phytoremediation [200] are emerging in U removal and establishing surveillance programs to track U levels in groundwater sources. Enforcing limits based on WHO and national standards. Informing people about U risks and safe water practices. Regular health check-ups for populations in affected areas to monitor kidney function and radiation exposure effects.

TABLE 1

List of literature survey at national level of U concentration groundwater

Sr. No	States	District	Uranium Conc. (ppb)			Reference
			Min	Max	Mean	
1.	**Andhra Pradesh**	Nalgonda,	0.2	68	18.5	[99]
2.		Tummalapalle	0	20	0.4	[100]
3.		Tummalapalle	0.38	79.7	-	[101]
4.		peddagattu/Seripally	0.6	521.15	-	[102]
5.		Vishakhapatnam	0.6	12.3		[103]
6.	**Assam**	Guwahati	0.08	5.32	-	[104]
7.		Nalbari	0.6	10.3	2.75	[75]
8.	**Bihar**	Aurangabad	0.1	107.4	11.4	[105]
9.		Gaya	0.1	238.2	18.9	
10.		Jahenabad	0.3	45	7.7	
11.		Nawada	0.2	76	9.5	
12.		Nalanda	0.2	59.6	5.1	
13.		Patna	0.1	14.5	2.3	[106]
14.	**Chhattisgarh**	Balod	0.56	78.93	-	[107]
15.		Bastar	0.5	26.4	6.97	[108]
16.		kankar	0.5	87.9	6.8	[109]
17.		Durg	0.638	45.7	-	[110]
18.		Raipur	0.1	3.7	1.0	[111]
19.		Bijapur	0.21	10.04	2.05	[112]
20.		Bemetara	0.68	96.08	-	[113]
21.	**Haryana**	Hisar	1.2	274	32.5	[84]
22.		Mahendragarh	0.56	57.53	18.87	[71]
23.		Fatehabad	0.3	48	-	[114]
24.		West Haryana	0.93	290	49	[115]
25.		West Haryana	0.3	256.4		[116]
26.		Panchkula	1.7	12.28	5.89	[117]
27.		Sirsa	0.93	290	-	[115]
28.		Panipat	14.9	123.3	-	[118]
29.		Sonipat and Panipat	9.1	155.1	-	[118]
30.	**Himachal Pradesh**	Chamba	0.5	90.46	6.51	[70]
31.		Kangra	0.26	29.5	-	[119]
32.		Hamirpur	0.26	29.5	-	[119]
33.		Himachal Pradesh	0.56	10.11	2.17	[120]
34.		Kangra	0.98	6.14	-	[120]
35.		Himachal Pradesh	0.12	19.43	2.57	[70]
36.		Siwaliks	1.08	19.68	-	[121]
37.		Shimla	0.61	10.11	-	[120]
38.		Kullu	0.3	2.5	-	[122]
39.	**Jharkhand**	Jaduguda	0.5	28	-	[123]
40.		Jaduguda	0.03	11.6	-	[124]
41.		Deoghar	0.3	11.3	4.51	[13]
42.		Bagjata	0.5	11.2	-	[125]
43.		Banduhurang	0.5	27.5	-	[125]
44.		Godda	0.1	14.1	1.3	[126]
45.		Sahibganj	0.22	24.04	4.23	[127]
46.	**Karnataka**	Bangalore	0.2	770.1	-	[79]
47.		Bangaluru	0.88	581.47	-	[128]
48.		Bangalore Urban	0.94	98.79	-	[129]

Sr. No	States	District	Uranium Conc. (ppb)			Reference
			Min	Max	Mean	
49.		Chikkaballapura	1000	8649	-	[130]
50.		Kolar	1000	2985.7	-	[130]
51.		Chamarajnagar	0.03	4.63	-	[131]
52.		Chikkaballapur	0.23	285.23	-	[132]
53.		Chamarajanagar	0.20	57.5	4.4	[133]
54.		Mysuru	0.34	242.93	-	[133]
55.		Kolar	0.3	1442.9	-	[134]
56.	**Kerala**	South Coast district	0.31	4.92	-	[135]
57.		Munnar & Cochin	0.132	2.542	-	[136]
58.		Alappuzha, Kollam & Thiruvananthapuram	0.82	7.32	-	[137]
59.		Kudankulam	0.2	6.6	2.0	[138]
60.		Ernakulam, Idukky	0.132	2.542	-	[139]
61.	**Maharashtra**	Aurangabad	0.012	16.673	0.068	[77]
62.		Bhandara	1.28	47.98		[140]
63.		Beed	0.03	32.85	2.58	[4]
64.		Buldhana	0.1	13.06	2.48	[141]
65.		Chandrapur	0.01	417.74	-	[65, 142]
66.		Mumbai	1.1	10.6	4.8	[143]
67.		Jalna	0.1	16.2	-	[5]
68.		Nagpur	2.7	30	-	[140]
69.		Raigad	0.1	1.4	-	[144]
70.		Jalgaon	1.2	26.8	15.2	[145]
71.		Dhule	1	28	14	[146]
72.	**Madhya Pradesh**	Shahdol	13.76	476.33	167.91	[147]
73.		Balaghat, Betul, Chhatarpur, Datia, Gwalior, Jhabua,Panna, Raisen, Seoni, Shivpuri	BDL	233.91	-	[140]
74.	**Odisha**	Ganjam	0.2	13.6	4.3	[148]
75.		Ganjam	0.3	16.4	-	[149]
76.	**Punjab**	Bathinda	9.72	186.6	-	[150]
77.		Amritsar	3.19	45.59	-	[151]
78.		Bathinda	11.7	113.7	-	[152]
79.		Bathinda, Mansa, Faridkot, and Firozpur	2	644	73.1	[80]
80.		Punjab (General)	1.24	45.42	14.91	[120]
81.		Southwest Punjab	0.13	676	76.27	[153]
82.		Southwest Punjab	0.5	579	73.5	[115]
83.		Southwest Punjab	0.5	579	-	[73]
84.	**Rajasthan**	North Rajasthan	2.54	133	38.48	[120]
85.		Jaipur and Dausa (Easthern Part)	5	145	49	[154]
86.		Tonk	0.21	173.72	8.58	[155]
87.	**Tamil Nadu**	Central Tamil Nadu	0.79	71.93	-	[87]
88.		Madurai	0.2	156.84	-	[12]
89.		Tirunelveli	0.5	65	29.5	[156]
90.		Kanniyakumari	0.2	10	0.4	[157]
91.		Tiruvannamalai	0.2	25.8	5.4	[158]
92.	**Telangana**	Hyderabad	0.6	82	-	[159]
93.	**Uttar Pradesh**	Eastern Uttar Pradesh	11	63.33	-	[160]
94.		Gorakhpur	0	21.6	2.78	[161]
95.		Khalilabad, Gorakhpur, Maharajganj, and Kushinagar	0.2	64	11.1	[162]
96.	**Uttarakhand**	Kedar Garhwal Himalayan	0.02	63.7	7	[163]
97.		Nainital	0.1	27.4	4.4	[164]
98.		Almora	0.1	23.1	4.3	[164]
99.		Pithoragarh	0.1	9.9	3.14	[165]
100.	**West Bengal**	Nadia	0.21	20.9	3.88	[166]
101.		Purulia	0.5	52	4.57	[167]
102.		Bongaon's	0.08	1.5	0.22	[168]

IV. CONCLUSION

This study found U distribution in the Maharashtra region. Many research studies show high natural U content in surface and groundwater resources in India. However, there's a lack of information on water-related health issues arising from U and other radioactive elements. Regular surveys and further investigation are needed to understand U human exposure. The observed amount of U in groundwater is influenced by two main factors: natural sources and anthropogenic sources. The study reviews the U sources, observed concentration, health effects, and remediation measures for regions that exceed the permissible limit. Regular surveillance programs like the National Uranium Project (NUP), which was established by BARC, Mumbai, to track U levels in groundwater sources, are highly beneficial due to health concerns. The time-to-time revision of the standard limit will be helpful based on radio and chemical risk purposes.

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