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A Review of Uranium and Co-occurring Heavy Metals in Groundwater and Soil of Chhattisgarh, India: Hydrogeochemical Controls and Human Health Risk Implications.

Seema Mor

seemamor099@gmail.com

Department of Physics Sanskaram University https://orcid.org/0009-0002-8421-6249

Babita Hooda

Department of Physics Sanskaram University

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A Review of Uranium and Co-occurring Heavy Metals in Groundwater and Soil of Chhattisgarh, India: Hydrogeochemical Controls and Human Health Risk Implications.

Seema Mor, Babita Hooda*
Department of Physics
Sanskaram University, Jhajjar, Haryana (India)
seemamor099@gmail.com
*Corresponding author:
babitaphy@gmail.com

Abstract

Groundwater serves as a major source of drinking water in many parts of India, including the Chhattisgarh. In recent years, its quality has been increasingly affected by the presence of uranium and associated heavy metals. Uranium, a naturally occurring radioactive element, can enter groundwater through both natural geogenic processes as well as anthropogenic activities, while toxic metals such as arsenic, cadmium, lead, chromium, and nickel further degrade water quality. This review critically examines the occurrence, distribution, hydrogeochemical behavior, and health risk implications of uranium and associated heavy metals in groundwater and soil systems. The analysis indicates that uranium concentrations in groundwater frequently exceed recommended limits in several regions of India, driven by factors such as pH, redox conditions, and carbonate complexation that enhance its mobility. The simultaneous presence of multiple toxic elements increases the potential for cumulative health risks, particularly in populations dependent on untreated groundwater. Despite numerous regional studies, integrated assessments addressing both groundwater and soil contamination remain limited, especially in the Chhattisgarh. This study highlights the need for systematic monitoring, advanced analytical approaches, and comprehensive risk assessment strategies to support sustainable groundwater management and protection of public health.

Keywords

Uranium contamination; quality of groundwater; contamination by heavy metals; hydrogeochemistry; radioactive elements; environmental physics; human health risk assessment

1. Introduction

In many regions of central India, groundwater serves as the principal source of drinking water for domestic, agricultural, livestock purposes. In recent years, increasing levels of uranium in groundwater have become a matter of environmental and public health concern. elevated concentrations of uranium in groundwater have emerged as a significant environmental and public health concern in several regions of India **(CGWB, 2019; Singh et al., 2022).** This problem is further complicated by simultaneous presence of other toxic heavy metals, creating a complex contamination scenario **(Kumar et al., 2018).**

The World Health Organization recommends a guideline value of 30μg/L for uranium in drinking water **(WHO, 2017).** However, several regions have reported uranium concentrations exceeding this limit. In India, elevated uranium concentrations in groundwater have been reported in states such as Punjab, Haryana, Rajasthan, and parts of central India **(CGWB, 2019; Kumar et al., 2018).** The presence of uranium in drinking water is particularly concerning due to its potential chemical toxicity and radiological hazards. Unlike many common contaminants, uranium exhibits both chemical toxicity and radiological hazards, making its presence in drinking water particularly alarming. This problem becomes more complex when uranium co-occurs with other heavy metals such as arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni). These co-existing contaminants may interact within

groundwater systems and contribute to cumulative or synergistic health effects **(Sharma et al., 2022).** The mobility and distribution of these metals in groundwater are largely influenced by physicochemical parameters such as pH, electrical conductivity (EC), and total dissolved solids (TDS), which control geochemical reactions within aquifer systems. From the perspective of hydrogeochemistry and environmental physics, understanding processes that control the migration, mobilization, and accumulation of uranium and associated heavy metals in groundwater systems is essential for assessing long-term environmental and human health risks.

This review focuses on Balod District of Chhattisgarh, India, where groundwater plays a crucial role in sustaining rural communities. Previous studies conducted in nearby regions have reported the presence of uranium and associated heavy metals in groundwater systems **(Sar et al., 2018; Sahu et al., 2020; Pritee Pandey et al., 2022).** In addition to groundwater contamination, soil can act as a secondary reservoir for heavy metals and may contribute to cumulative human exposure through soil–water interactions.

By synthesizing previously published studies on uranium and heavy metal contamination in groundwater and soils, this review aims to provide an integrated understanding of contamination trends, hydrogeochemical controls, and potential human health implications in the Balod region. The findings highlight existing knowledge gaps and emphasize the need for systematic monitoring and integrated water–soil assessments to support sustainable groundwater management and public health protection strategies.

This review article is entirely based on previously published literature. No original groundwater or soil samples were collected or analyzed in the present study. All tables, figures, and statistical summaries were derived or interpreted from secondary data reported in earlier studies and are presented solely for comparative and analytical purposes. These observations highlight the importance of region-specific investigations, particularly in areas like Balod, where groundwater dependency is high and contamination studies are limited.

2. Framework for systematic review research

2.1 Literature search strategy

This review was conducted using a systematic literature search approach to identify relevant studies on uranium contamination and co-occurring heavy metals in groundwater, with a particular focus on India and the Balod District of Chhattisgarh. Scientific databases including Scopus, Google Scholar, Web of Science, Springer Link, Science Direct, and UGC-CARE indexed journals were used to collect research articles, technical reports, and regulatory documents.

Keywords and Boolean search combinations used during the literature search included: “uranium in groundwater,” “heavy metal contamination,” “Balod Chhattisgarh,” “hydrogeochemistry,” and “toxic metals risk assessment.” The sources considered for this review included peer-reviewed journal articles, government technical reports, World Health Organization (WHO) guidelines, and publications from the Central Ground Water Board (CGWB).

Only literature published between 2000 and 2025 was considered to ensure that the analysis reflects current environmental conditions and public health concerns.

2.2 Data Extraction and Reliability Assessment

Relevant information was extracted from each selected study to facilitate comparative analysis. The key parameters considered included:

- Study location and sampling period
- Analytical techniques used for uranium and heavy metal determination
- Physicochemical water quality parameters

- Reported uranium and heavy metal concentration ranges
- Documented environmental or human health implications

Where possible, the results from different studies were compared to identify spatial patterns, seasonal variations, and methodological consistency. Greater emphasis was placed on studies employing well-established analytical techniques such as laser fluorimetry and alpha spectrometry, which are widely used for uranium detection in groundwater.

2.3 Review Framework

The review was structured to progressively move from global perspectives to national and regional evidence, and finally to localized findings from Balod District. The thematic framework of the review included the following components:

1. Global trends in uranium contamination in groundwater
2. Groundwater contamination studies reported in India
3. Site-specific investigations from Chhattisgarh and surrounding regions
4. Co-occurrence of uranium and heavy metals in groundwater systems
5. Hydrogeochemical controls and seasonal influences affecting metal mobility
6. Environmental and human health risk implications
7. Research gaps and future challenges

2.4 Inclusion and Exclusion Criteria

To ensure the reliability and relevance of the reviewed literature, specific inclusion and exclusion criteria were applied during the study selection process. Only peer-reviewed journal articles, government technical reports, and publications from recognized international organizations such as the World Health Organization (WHO) and the Central Ground Water Board (CGWB) were included in the review. Studies focusing on uranium contamination and co-occurring heavy metals in groundwater systems were given primary consideration.

Studies were included if they reported quantitative data on uranium or heavy metal concentrations in groundwater or soils, along with supporting hydrogeochemical parameters. Research conducted in India, particularly in central India and neighboring regions of Chhattisgarh, was prioritized to maintain regional relevance.

Studies that lacked reliable analytical data, did not report clear sampling or analytical methodologies, or were not published in credible scientific sources were excluded. In addition, duplicate records and non-scientific sources such as blogs or unverified online materials, were excluded from the analysis.

3. Review of the Literature

3.1 Uranium in Groundwater: A Global Concern

Uranium occurrence in groundwater and drinking water has been reported across various regions of the worldwide, including Europe (Finland and Germany), Africa (Kenya), and South Asia (India). These regions represent diverse hydrogeological settings, such as crystalline bedrock aquifers, sedimentary formations, and alluvial plains. The distribution and mobility of uranium are primarily governed by natural geogenic processes, including rock-water interaction, mineral weathering, and redox conditions, along with anthropogenic activities, such as excessive groundwater extraction. This global perspective highlights the widespread nature of uranium contamination and its significance as an environmental and public health concern. The global distribution of these areas is shown in **Figure 1,** providing a comprehensive understanding of uranium contamination patterns and associated health risks.

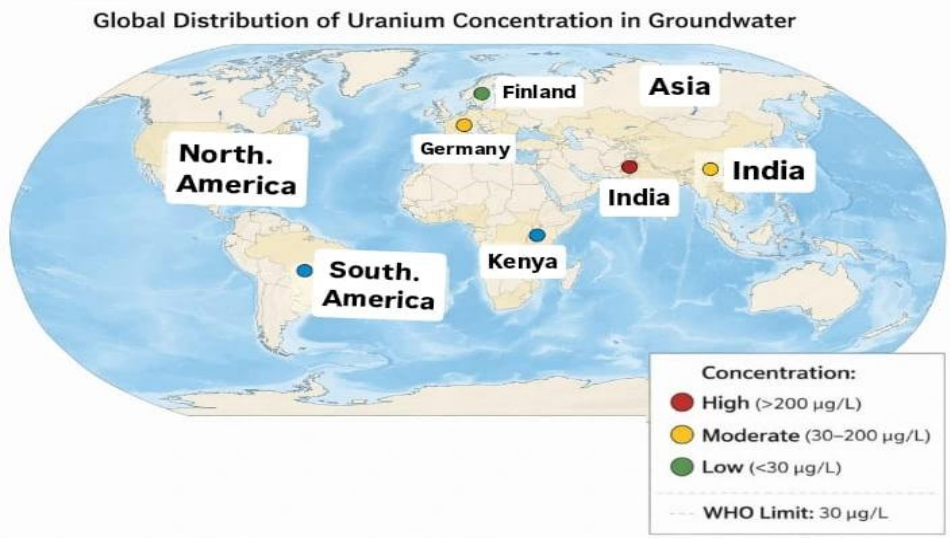


Figure 1. Global location map showing selected study regions across North America, Europe, Asia, and Africa, including the United States, Germany, Finland, India and Kenya

Kurttio et al. (2002) conducted an epidemiological study in Finland to investigate the renal effects of uranium exposure through drinking water. The study adopted a targeted and systematic sampling approach by selecting populations that consumed uranium-rich groundwater. Biochemical and clinical analyses, including urine and blood parameters, were used to assess kidney function. The findings indicated that prolonged exposure to uranium may result in subtle renal dysfunction, emphasizing its chemical toxicity. However, groundwater systems show much wider variability, with interquartile ranges between 6–135 µg/L and maximum concentrations reaching up to 1920 µg/L in Finland, highlighting the strong influence of geogenic factors and hydrogeochemical conditions on uranium mobilization. These findings demonstrate the wide variability of uranium concentrations and confirm its global environmental significance. **Smedley and Kinniburgh (2023)** reported the global occurrence of uranium in natural waters across diverse geographical regions, including North America (USA and Canada), Europe (Finland, Norway, and Switzerland), Asia (South Korea), and Africa (Burundi). The study was based on a systematic data synthesis approach, compiling and analyzing data from multiple regions worldwide. Their findings highlighted that uranium concentrations vary significantly depending on hydrogeochemical conditions in natural waters are generally low, typically less than 4µg/L in river water and around 3.3µg/L in open seawater, usually remaining below 5µg/L. In contrast, significantly higher uranium concentrations have been reported in groundwater systems. **Kilavi et al. (2021)** investigated the quality of drinking water and associated human health risks in Kwale County, Kenya. The study adopted a random sampling strategy, collecting water samples from both surface and groundwater sources in areas surrounding Mrima Hill and the Kwale heavy mineral sand deposits. The concentrations of heavy metals, including uranium, were analyzed using inductively coupled plasma mass spectrometry (ICP-MS). Water quality was evaluated using the weighted arithmetic index method, while human health risks were assessed through deterministic and probabilistic risk assessment models. The results indicated that while uranium concentrations remained within permissible limits, other heavy metals such as chromium and cadmium exceeded national and international standards. The study further revealed that both carcinogenic and non-carcinogenic risks were significant, suggesting that the water was unsuitable for human consumption and highlighting the impact of both geogenic and anthropogenic sources. **Riedel and Kübeck (2018)** investigated the occurrence of uranium in groundwater using a large hydrogeochemical dataset comprising more than 8000 samples collected from over 2000 locations. The study adopted a systematic data-driven approach, integrating statistical analysis with geochemical modeling to understand the factors controlling uranium mobility. Their findings demonstrated a strong correlation between uranium concentrations and groundwater chemistry parameters such as electrical conductivity and alkalinity, indicating that mineral weathering and desorption processes play a significant role in uranium release. Furthermore, the study revealed that redox conditions are a key controlling factor, with higher uranium concentrations observed under manganese- and nitrate-reducing environments, whereas iron- and sulfate-reducing conditions tend to limit uranium mobility by acting as sinks. In addition, anthropogenic influences such as agricultural activities, including fertilizer application and irrigation, were found to contribute to uranium occurrence

in groundwater. Overall, the study concluded that uranium distribution is governed by complex interactions between geochemical and environmental factors rather than a single controlling mechanism. **Coyte and Vengosh (2018)** examined large-scale uranium contamination in groundwater resources in India through regional hydrogeochemical analysis. The study incorporated compiled datasets and field observations, reflecting a mixed analytical approach. The results indicated that uranium mobilization is enhanced under alkaline and oxidizing conditions, along with intensive groundwater extraction, leading to widespread contamination in alluvial aquifers. The comparative summary of uranium concentration ranges, dominant sources, and associated characteristics across different regions is presented in **Table 1.** And variation in minimum and maximum uranium concentration across different regions compared with WHO permissible limit illustrated in **Figure 2.**

Region/Country	Min (µg/L)	Max (µg/L)	WHO/BIS Limit (µg/L)	Dominant Source	Reference
Finland	~0.1	~1920	WHO: 30	Geogenic (granite bedrock, groundwater)	Kurttio et al. (2002)
Global (Review) America, Europe, Asia, Africa	~4	~200	WHO: 30	Geogenic + hydrogeochemical processes	Smedley & Kinniburgh (2023)
Kenya (Kwale County)	~0.5	~80	WHO: 30	Geogenic+ anthropogenic (mining activities)	Kilavi et al. (2021)
Germany	~0.01	~200	WHO: 30	Hydrogeochemical controls (redox, alkalinity)	Riedel & Kübeck (2018)
India	~1	~300	WHO: 30 / BIS: 30	Geogenic + agricultural influence (bicarbonate, nitrate)	Coyte & Vengosh (2018)

Table 1. Global occurrence of uranium in groundwater and associated characterstics

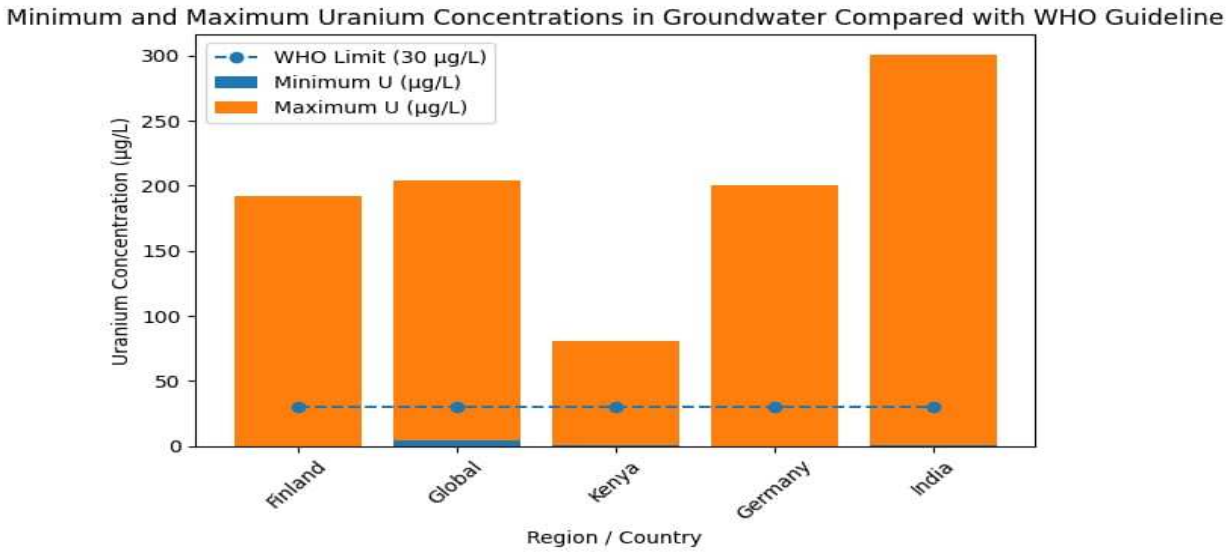


Figure 2. Comparison of minimum and maximum uranium concentration with WHO permissible limit

The compiled global data indicate that uranium contamination in groundwater is a widespread phenomenon primarily governed by lithological characteristics and hydrogeochemical conditions, with additional contributions from anthropogenic activities in certain regions. The observed variability in concentration levels across different countries highlights that uranium mobility is controlled by factors such as redox conditions, pH, and carbonate complexation rather than a single uniform mechanism. This is important as it demonstrates that groundwater quality assessments based on generalized assumptions may not accurately reflect actual contamination scenarios, thereby influencing risk evaluation and management strategies. However, most existing studies are region-specific and lack integrated, comparative analyses that consider both geogenic and anthropogenic interactions at a broader scale. Additionally, limited long-term monitoring and insufficient linkage between hydrogeochemical processes and health risk assessments remain key gaps, indicating the need for more comprehensive and multidisciplinary approaches in future research.

3.2 Uranium in Indian Groundwater

The occurrence of uranium in groundwater has been widely reported in several regions of India and is considered an important environmental and public health concern. Numerous studies have documented spatial variability in uranium concentrations in groundwater, which is largely influenced by geological formations, hydrogeochemical conditions, and anthropogenic activities. The spatial distribution of uranium contamination reported in previous studies across different regions of India is illustrated in **Figure 3.**

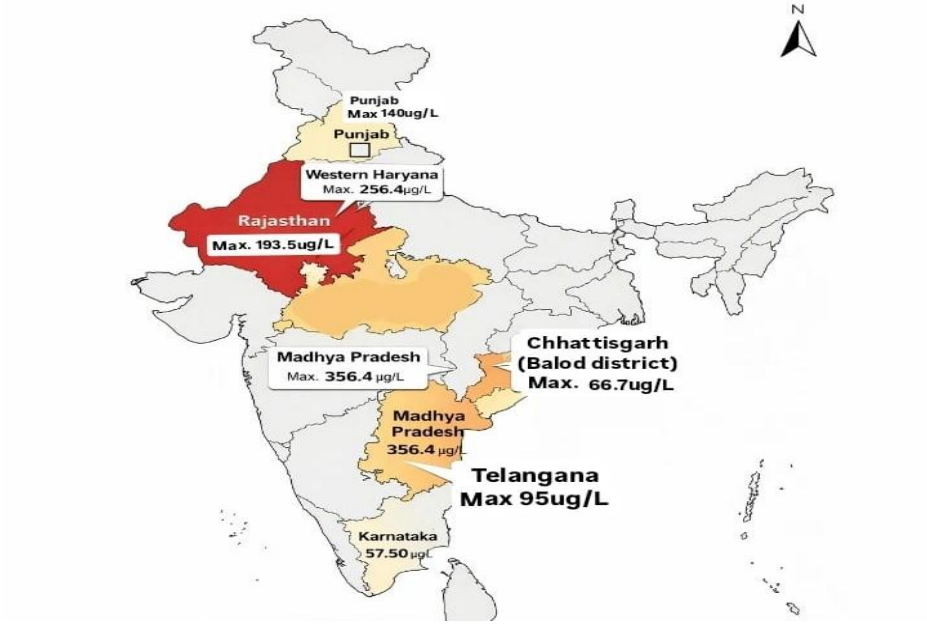


Figure 3. Spatial distribution of reported uranium contamination in groundwater across different regions of India based on published studies.

The occurrence of uranium in groundwater has become an important environmental and public health concern in several regions of India. Numerous studies have reported spatial variability in uranium concentrations, which is largely influenced by geological formations, hydrogeochemical conditions, and anthropogenic activities. For instance, a study conducted in Punjab by **Singh et al. (2020)** analyzed 120 groundwater samples collected using a systematic sampling approach from wells and hand pumps distributed across the study area and reported uranium concentrations ranging from 5 to 140 µg/L. Approximately 23% of the samples exceeded the guideline value of 30 µg/L recommended by the World Health Organization (WHO). The elevated concentrations were mainly attributed to geogenic sources, intensive agricultural practices, and the presence of carbonate-rich groundwater which enhances uranium mobility.

Similarly, investigations in western Haryana by **Singh et al. (2014)** collected 98 groundwater samples using a random sampling strategy to evaluate uranium occurrence in the region. The reported uranium concentrations ranged between 0.3 and 256.4µg/L, with nearly 32% of the samples exceeded the WHO permissible limit, indicating potential health risks associated with long-term consumption of contaminated groundwater. The study suggested that uranium mobilization in the region is strongly influenced by alkaline groundwater conditions and water–rock interactions in alluvial aquifers. High uranium concentrations have also been reported from Madhya Pradesh. In the Shahdol district, **Garima et al. (2024)** analyzed 50 groundwater samples collected using a stratified sampling approach considering different hydrogeological settings. Uranium concentration ranged from 18.2 to 356.4µg/L, with nearly 82% of the samples exceeding the WHO guideline value. The authors attributed the elevated levels primarily to coal mining activities, geogenic uranium-bearing minerals, and enhanced water–rock interactions within the aquifer system. In Rajasthan, a comprehensive assessment by **Kumar et al. (2025)** examined 205 groundwater samples collected through a systematic regional sampling strategy. The reported uranium concentrations ranged between 0.52 and 193.5µg/L. Approximately 18% of the samples exceeded the recommended WHO limit. The study highlighted that high total dissolved solids (TDS) and alkaline hydro chemical conditions significantly enhance uranium solubility and transport in groundwater. Studies from Chhattisgarh, particularly in the Balod district, have also documented the presence of uranium in groundwater systems. Investigations by **Sar et al. (2018)** and later assessments by **Sahu and Ghosh (2025)** analyzed 29 groundwater samples collected using a random sampling approach across different villages. Uranium concentrations ranged from 0.10 to 66.7µg/L, with nearly 30% of the samples exceeding the WHO guideline value. The occurrence of uranium in this region has been associated mainly with geogenic sources and seasonal hydrogeochemical variations.

Further evidence from Telangana indicates uranium enrichment in groundwater within hard-rock aquifers. A study by **T. Raghavendra et al (2020)** analyzed 37 groundwater samples collected using a systematic sampling design, reporting uranium concentrations ranging from 9 to 95µg/L, with approximately 28% of samples exceeding the WHO guideline limit. The authors emphasized the role of hydrogeochemical processes and aquifer lithology in controlling uranium distribution. Likewise, research conducted in Karnataka by **Bevinathalapura Shankarappa et al. (2024)** examined 67 groundwater samples collected through stratified sampling across different aquifer zones; with uranium concentrations varying from 0.20 to 57.50µg/L. Around 15% of the samples exceeded the WHO permissible limit. The elevated concentrations were mainly linked to granitic lithology and prolonged groundwater–rock interaction. Overall, these findings indicate that uranium contamination in groundwater across India is controlled by a complex interplay of geological formations, hydro chemical conditions, and human activities. The spatial heterogeneity observed across different states highlights the importance of region-specific monitoring and management strategies to safeguard drinking water quality and minimize potential health risks.

A summary of uranium concentrations reported in groundwater from different regions of India, including the number of samples analyzed, minimum and maximum concentrations, percentage of samples exceeding the WHO guideline value, and major controlling factors, is presented in **Table 2.** These studies highlight significant regional variations in uranium concentrations and demonstrate the influence of hydrogeochemical processes such as water–rock interaction, alkaline groundwater conditions, and high total dissolved solids on uranium mobility in aquifer systems

State / Region	No. of Samples (n)	Min (µg/L)	Max (µg/L)	Range (µg/L)	% Samples >30 µg/L	WHO Limit (µg/L)	Major Controlling Factors	Reference
Punjab	120	5	140	135	~23%	30	Agricultural fertilizers, geogenic sources, carbonate-rich groundwater	Singh et al.,2020
Western Haryana	98	0.3	256.4	256.1	~32%	30	Geogenic sources groundwater-rock, alkaline groundwater conditions	Singh et al.,2014

Madhya Pradesh	50	18.2	356.4	167.91	82	30	Coal mining, geogenic, uranium, groundwater-rock interaction	Garima et al., 2024
Rajasthan	205	0.52	193.5	19.9	18%	30	High TDS increase uranium solubility in groundwater	Kumar et al, 2025
Chhattisgarh (Balod)	29	0.10	66.7	70.9	~30%	30	Geogenic sources, seasonal variation	Sar et al., 2018; Sahu & Ghosh, 2025
Telangana	37	9	95	86	~28%	30	Hard rock aquifers	T Raghavenrda et al, 2020
Karnataka	67	0.20	57.50	4.40	~15%	30	Radiation dose due to uranium in groundwater	Bevinathalapura Shankarappa,et al. 2024

Table 2. Uranium concentrations in groundwater across different regions of India and comparison with WHO limit (30µg/L)

The Compiled Data presented in Table2 indicate that uranium concentrations in groundwater vary significantly across different regions of India. These findings suggest that uranium contamination of groundwater is a widespread issue in several parts of India. To provide a comparative overview of uranium contamination levels across different regions, the maximum reported uranium concentrations from the reviewed studies were compared with the World Health Organization (WHO) drinking water guideline value of 30µg/L, as illustrated in **Figure 4.** The comparison clearly indicates that in several regions, the reported concentrations exceed the recommended safe limit, suggesting potential environmental and public health concerns associated with long-term consumption.

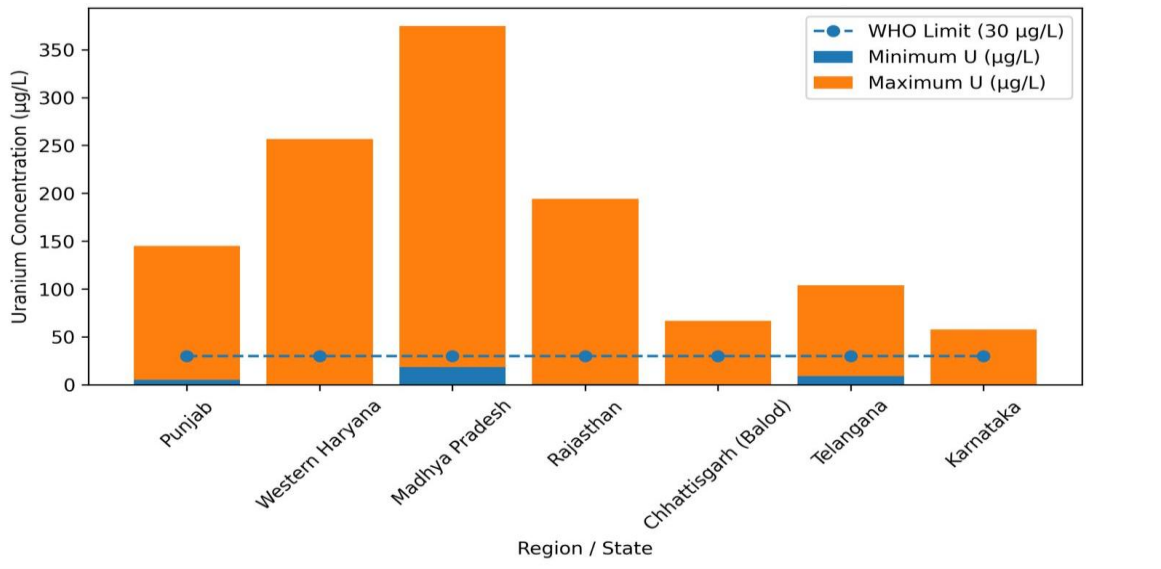


Figure 4. Minimum and maximum uranium concentrations in groundwater compared with WHO guideline

The compiled data indicate that uranium contamination in groundwater across different regions of India exhibits significant spatial variability primarily controlled by lithological characteristics, hydrogeochemical conditions, and localized anthropogenic influences. The variation in concentration levels reflects the role of factors such as pH, total dissolved solids, and water–rock interactions in governing uranium mobility. This is important because a considerable number of groundwater samples exceed the WHO permissible limit, indicating potential risks to human health, particularly in regions with high dependence on groundwater for drinking purposes. Understanding these patterns is essential for accurate risk assessment and effective groundwater management strategies. However, most existing studies are region-specific and lack integrated assessments that consider hydrogeochemical processes, seasonal variability, and long-term exposure risks simultaneously. Additionally, there is limited continuous monitoring data and insufficient evaluation of the interaction between uranium and co-occurring heavy metals, highlighting the need for more comprehensive and multidisciplinary research approaches.

3.3 Occurrence of Uranium in Groundwater of Chhattisgarh

Groundwater contamination by uranium has been reported in several districts of Chhattisgarh, indicating spatial variability across the region. Previous studies have identified uranium occurrence in districts such as Balod, Raipur, Kanker, and Bastar. These investigations suggest that the presence of uranium in groundwater is largely controlled by geological formations, hydrogeochemical processes, and water–rock interactions. The spatial distribution of the reported study locations across Chhattisgarh is illustrated in **Figure 5.**

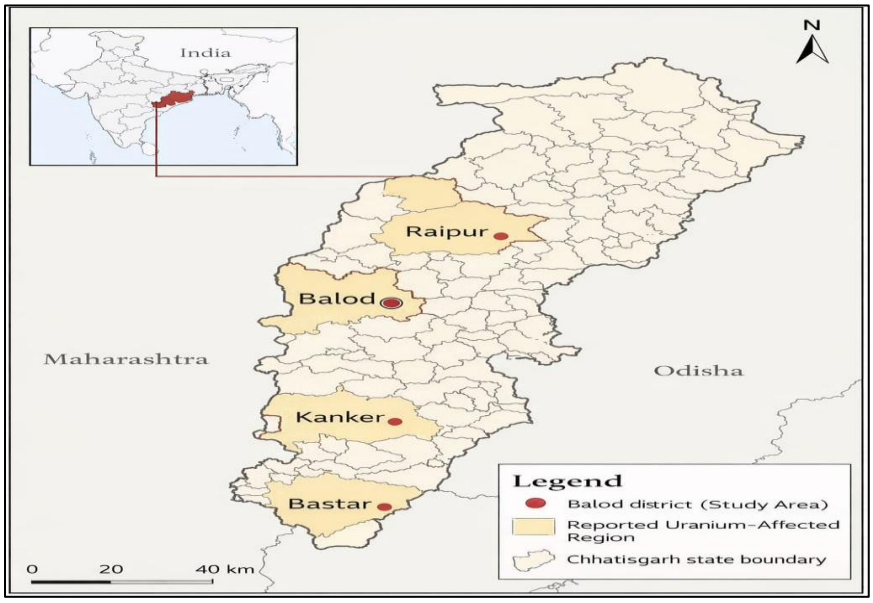


Figure 5. Location map showing reported uranium occurrence districts (Balod, Raipur, Kanker, Bastar) in Chhattisgarh, India

Groundwater is the primary source of drinking water for a large population in Chhattisgarh, India, and several studies have examined the occurrence and distribution of uranium in groundwater systems in the region. One of the early investigations was conducted out by **Sar et al. (2018)** in Balod district, where a total of 25 groundwater samples were analyzed to evaluate uranium concentration and potential health risks. The study reported uranium concentrations ranging from 0.6 to 78.9 µg/L, indicating that a few sampling locations exceeded the guideline value of 30µg/L recommended by the World Health Organization. Elevated uranium levels were primarily attributed to geogenic sources and rock–water interaction processes controlling uranium mobility in the aquifer system. Subsequently, **Sahu and Ghosh (2025)** further examined groundwater quality in the same district using 29 groundwater samples. Their results indicated uranium concentrations ranging from 0.10 to 66.7µg/L, where the

majority of the samples were within the permissible limit, although a few locations showed comparatively higher concentrations. The authors suggested that the lithological characteristics of the aquifer and hydrogeochemical processes play an important role in controlling uranium distribution in groundwater. In another study, **Sahu et al. (2020)** analyzed 48 groundwater samples from the Kanker district to understand the seasonal behavior of uranium within groundwater systems. The reported uranium concentrations ranged from 0.5 to 87.9µg/L, and the study highlighted that uranium distribution varies seasonally, with relatively higher concentrations observed during the dry season. The authors attributed this variation to groundwater residence time and geochemical conditions influencing uranium mobilization. A hydrogeochemical investigation was conducted by **Pritee Pandey et al. (2022)** in Raipur district and evaluated 73 groundwater samples collected during the pre- and post-monsoon seasons. The uranium concentrations in groundwater were reported to range from 3.7 to 13µg/L, which were below the guideline value recommended by the World Health Organization. The study emphasized the role of hydrogeochemical processes and the mobilization of uranium in the presence of complexing anions within the aquifer system. Similarly, **Singh et al. (2022)** assessed groundwater quality and associated health risks in Bastar district by analyzing 70 groundwater samples. The uranium concentration in the groundwater samples ranged from 0.50 to 26.4 µg/L, and multivariate statistical analysis indicated that rock–water interaction and hydrogeochemical processes were the major factors controlling uranium occurrence in groundwater. In addition, the study reported potential non-carcinogenic health risks associated with long-term exposure to uranium-contaminated groundwater in certain locations. In the reviewed studies, groundwater samples were collected from wells and hand pumps across different districts of Chhattisgarh using appropriate sampling strategies depending on the objectives of the investigations. These approaches generally included random and systematic sampling to obtain representative groundwater samples from the study areas. Overall, these studies highlight the spatial variability of uranium concentrations in groundwater across different districts of Chhattisgarh and emphasize the importance of hydrogeochemical processes and geological factors in controlling uranium mobilization. The major findings of the reviewed studies are summarized in **Table 3**.

Study area	No. of samples	Min (µg/L)	Max (µg/L)	Range (µg/L)	WHO limit (µg/L)	Key findings	Major controlling factors	Health risk observation	Reference
Balod district	25	0.6	78.9	0.6-78.9	30	Uranium detected in groundwater samples; one village showed concentration exceeding WHO limit	Geogenic sources, rock–water interaction	Chemical toxicity risk through drinking water ingestion	Sar et al., 2018
Balod district	29	0.10	66.7	0.10-66.7	30	Most groundwater samples were below the permissible limit except a few locations	Lithological control, hydrogeochemical processes	Non-carcinogenic risk observed in some samples	Sahu & Ghosh, 2025
Kanker district	48	0.5	87.9	0.5-87.9	30	Uranium distribution varied seasonally; higher values observed during dry season	Groundwater residence time, geochemical conditions	Potential chemical toxicity risk with prolonged exposure	Sahu et al., 2020

Raipur District	73	3.7	13	3.7-13	30	Uranium concentration evaluated in pre-and post monsoon using hydrogeochemical analysis	Mobilization of uranium with complexing anions and hydrogeochemical processes	Elevated uranium concentrations may affect groundwater quality and require monitoring	Pritee Pandey et al., 2022
Bastar District	70	0.50	26.4	0.50-26.4	30	Uranium detected in groundwater samples across the district	Rock-water interaction, hydro chemical processes	Non-carcinogenic health risk observed in several samples	Singh et al., 2022

Table3. Summary of reported uranium concentrations in groundwater of Chhattisgarh, India

As shown in Table 3, uranium concentration in groundwater varies significantly across different districts of Chhattisgarh, with certain locations exceeding the guideline value of 30µg/L recommended by the World Health Organization. The occurrence and mobility of uranium is mainly controlled by geological formations, hydrogeochemical conditions, and groundwater-rock interaction. The reported uranium concentration in groundwater (Chhattisgarh District) illustrated as **Figure 6.**

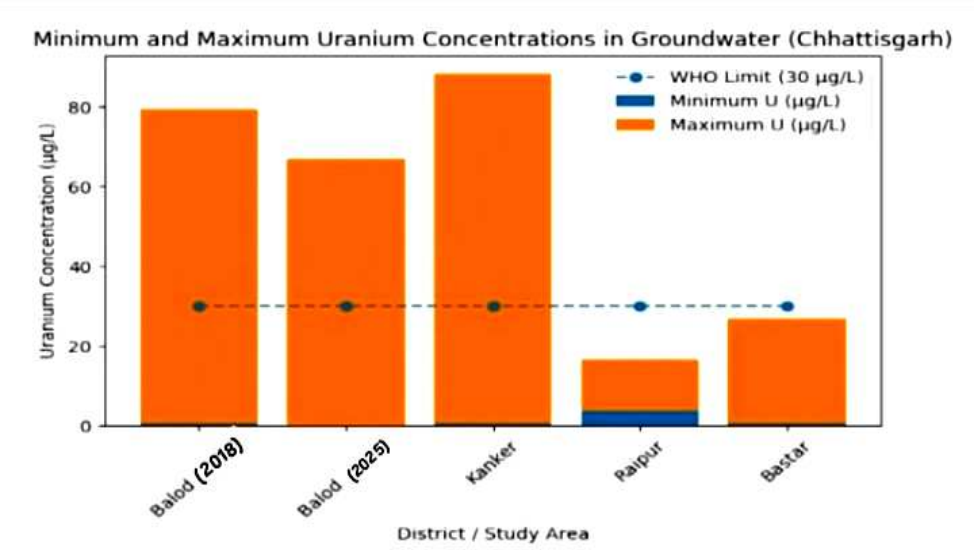


Figure 6 Reported minimum and maximum uranium concentration (µg/L) with WHO permissible limit in groundwater of selected Chhattisgarh districts

The reviewed studies indicate that uranium concentrations in groundwater across Chhattisgarh exhibit spatial and temporal variability, influenced by lithological characteristics, hydrogeochemical conditions, and groundwater–rock interactions. This is important because several locations report uranium concentrations near or above the WHO permissible limit, suggesting potential risks to human health in groundwater-dependent populations. However, although some studies consider seasonal variation, there is a lack of continuous long-term monitoring to capture detailed temporal trends. Moreover, most studies are limited to groundwater and lack integrated analysis of soil–water interactions. The limited understanding of uranium behavior in association with other heavy metals further highlights the need for comprehensive and multidisciplinary research approaches.

3.4 Co-occurrence with heavy metals

Numerous studies have examined the co-occurrence of heavy metals in groundwater across different regions of India. These investigations have included areas such as Delhi, Tamil Nadu, Haryana, Hisar, and the Durg–Balod belt in Chhattisgarh. Mapping the geographic distribution of these study locations helps to understand the spatial coverage of research related to heavy metal interactions in groundwater systems. The locations of the reported studies are illustrated in **Figure 7,** providing a spatial overview of regions where co-occurrence with heavy metals has been investigated.

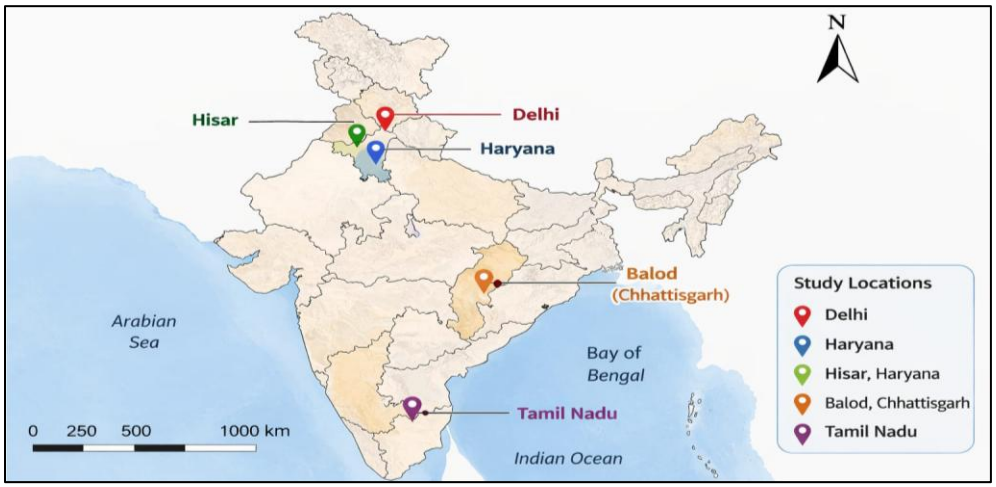


Figure 7. Location map of reported study from areas for heavy metals in groundwater across India

An important characteristic of groundwater contamination is that uranium rarely occurs in isolation from other elements. It is often found in combination with heavy metals including lead (Pb), cadmium (Cd), and arsenic (As). These contaminants exhibit high toxicity and, when present alongside uranium, they create a situation of multiple exposures. Lead has been widely recognized as a neurotoxin element that can adversely brain development and cognitive ability in children. Cadmium accumulates in the kidneys and bones, causing skeletal deformities and renal dysfunction. Arsenic is a well- established carcinogen element linked to cancers of the skin, lung, and bladder cancers. National studies have shown that heavy metal contamination is widespread in India. For Example, **V. Mohan et al. (2018)** reported that nearly 718 districts in India had groundwater affected by one or more toxic metals. **Sharma et al. (2022)** highlighted urban groundwater in Delhi with elevated lead and cadmium, while **Narayanan et al. (2025)** reported industrial discharge- related contaminate in Tamil Nadu. For Balod, where uranium hotspots have been verified, the likelihood of co-contamination with metals makes the groundwater quality issue even more complex and serious. **Yadava et al. (2013)** quantified heavy metal concentrations in groundwater near the proposed nuclear power project site in Fatehabad district, Haryana, finding elevated concentrations of metals such as Zinc, copper, nickel, iron, chromium, cadmium, and cobalt, which may pose health risks to the local population. **Garg et al. (2014)** in addition to uranium, this study also assessed concentrations of additional heavy metals in Hisar city's groundwater, providing analysis of water quality and potential health risks. Furthermore, **Prasad et al. (2020)** investigated groundwater quality in the Durg-Balod belt of Chhattisgarh and reported the presence of trace metals including lead, cadmium, arsenic, and mercury in groundwater samples from region. Groundwater samples in these studies were collected using various sampling strategies, including stratified, random, and systematic sampling approaches, to obtain representative data across different locations. The samples were analyzed using advanced techniques such as AAS and ICP-MS. These studies generally determined metal concentrations using advanced analytical techniques such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). The major findings from these investigations are summarized in **Table 4**

S. No.	Reference	Study Area	Sample Source	Parameter / Metal	Reported Value / Range (µg/L)	BIS Limit (µg/L)	Key Findings	Exceedance
1	V. Mohan et al., 2018	India	Groundwater	Toxic metals (Pb, Cd, As etc.)	NR	As per metal	Nationwide assessment reported ~718 districts affected by toxic metals in groundwater	NR
2	Sharma et al., 2022	Delhi	Urban groundwater	Pb	3–10	10	Elevated Pb detected in urban groundwater	Yes/No
				Cd	1–3	3	Cd present in several sampling sites	Yes/No
3	Narayanan et al., 2025	Tamil Nadu	Groundwater near industrial zones	Heavy metals	As per metal	As per metal	Industrial discharge associated with groundwater contamination	NR
4	Yadava et al., 2013	Haryana	Groundwater wells	Zn	3000	5000	Elevated Zn, Cu, Ni, and Cr near proposed nuclear power site	No
				Cu	2000	1500	Cu exceeded permissible limits in some samples	Yes
				Ni	70	20	Ni concentrations exceeded drinking water standards	Yes
				Cr	50	50	Cr near permissible limit	No
				Cd	3	3	Cd close to permissible limit	No
5	Garg et al., 2014	Hisar	Groundwater	U	30	30	Uranium and other heavy metals evaluated for groundwater quality	NR
6	Prasad et al., 2020	Durg–Balod Belt, Chhattisgarh	Groundwater	Pb	20	340	Trace metals measured in groundwater near mining belt	No
				Cd	5	120	Cd detected but below permissible limit	No
				As	5	150	Arsenic present in low concentrations	No
				Hg	1	40	Hg levels within permissible limits	No

Table 4. Studies reporting co-occurrence of uranium and heavy metals in groundwater in India

The comparison between reported heavy metal concentrations and permissible drinking water limits indicates that some elements such as Cu and Ni exceed recommended limits in certain regions. A graphical representation of the reported concentrations relative to the Bureau of Indian Standards limits is shown in **Figure 8**.

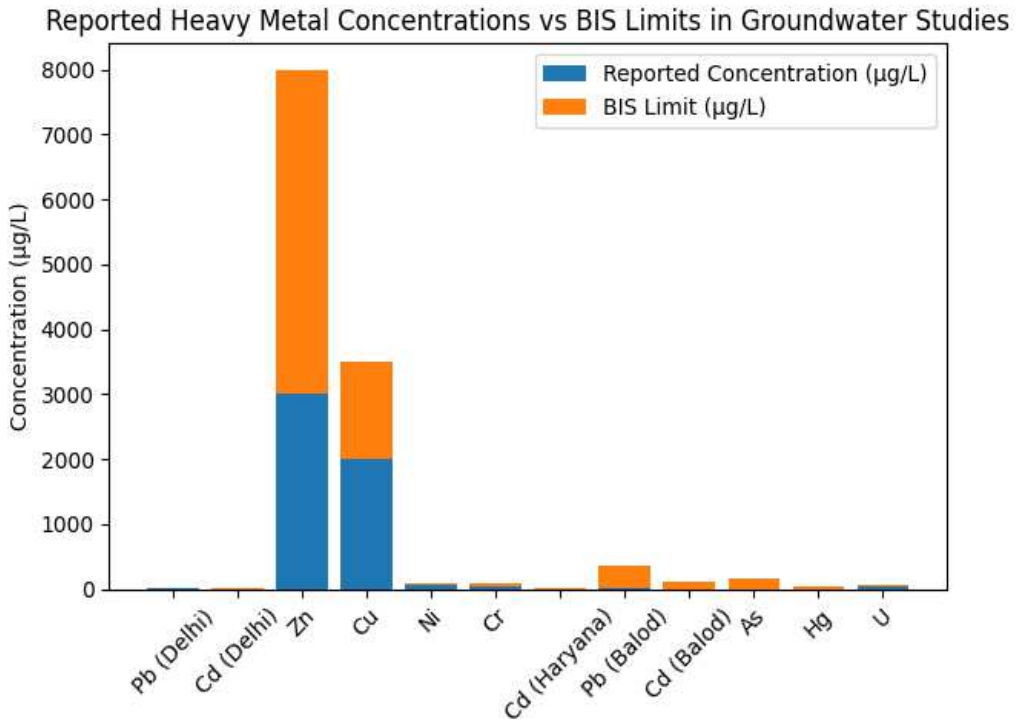


Figure 8. **Comparison of reported heavy metal concentrations with BIS drinking water limits in selected groundwater studies in India**.

The reviewed studies indicate that the co-occurrence of uranium with heavy metals such as Pb, Cd, Cu, Ni, and Cr in groundwater across different regions of India reflects the combined influence of geogenic processes and localized anthropogenic activities. The reported exceedance of certain metals beyond BIS permissible limits in specific areas suggests that groundwater contamination is not limited to a single element but represents a multi-contaminant system. This is particularly significant as the presence of multiple toxic elements may lead to enhanced health risks through cumulative exposure, especially in regions affected by industrial discharge and mining activities. However, most of the available studies focus on reporting concentration levels and lack detailed evaluation of the geochemical interactions and combined toxicity of uranium and co-existing heavy metals. Additionally, there is limited integration of multi-element risk assessment approaches, indicating a need for more comprehensive studies to better understand contamination behavior and its implications for groundwater quality and human health.

3.5 Heavy Metal Concentrations in Agricultural Soils of India

The spatial distribution of reported studies on heavy metal contamination in agricultural soils across India is illustrated in **Figure 9.** Previous studies have been conducted in different regions, including the Mewat district (Haryana), peri-urban agricultural areas of Haryana, eastern coastal paddy cultivation regions, the Brahmaputra Valley, and northern alluvial soil regions. These studies highlight the variability of heavy metal concentrations in soils influenced by agricultural practices, irrigation sources, soil characteristics, and anthropogenic activities.

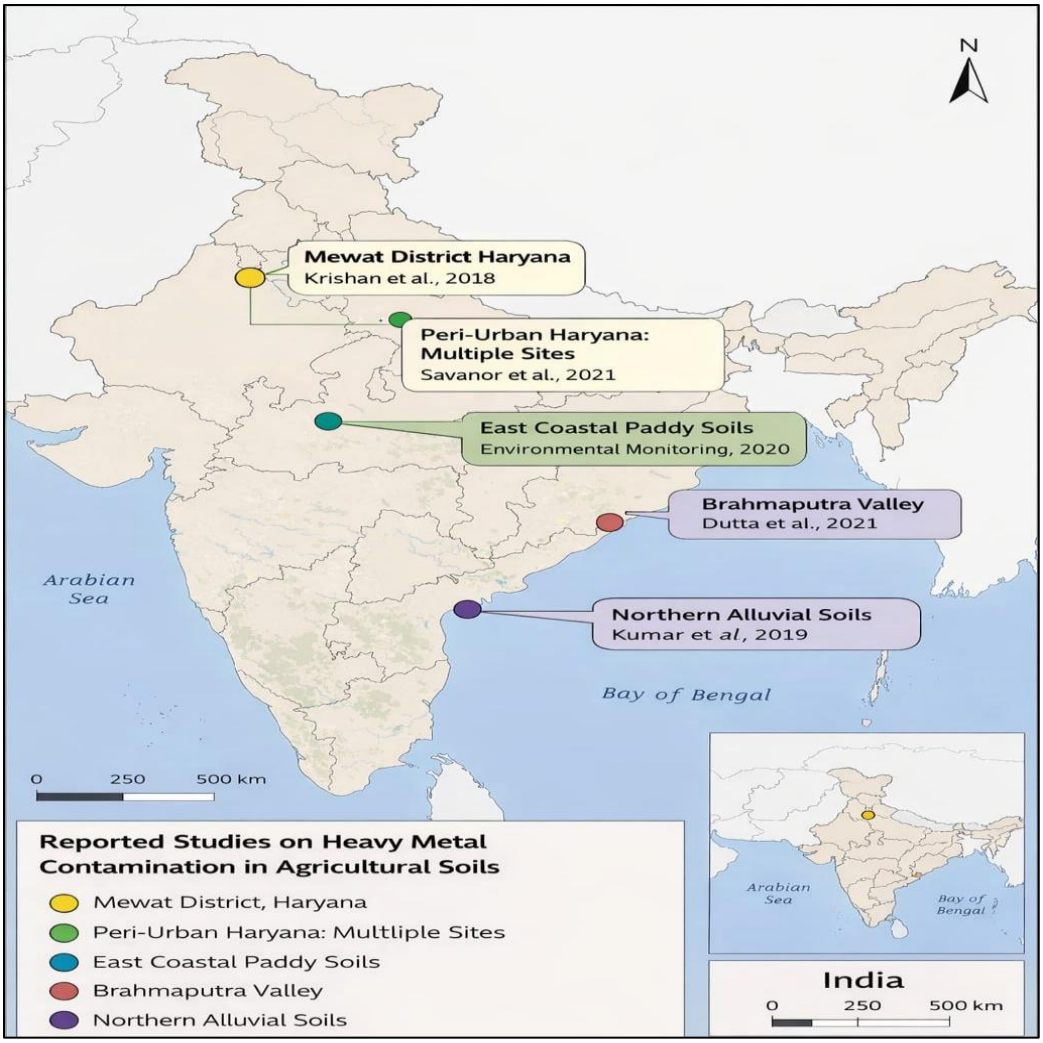


Figure 9. Study locations of heavy metal contamination in agricultural soils across India

Several studies have reported the occurrence and distribution of heavy metals in agricultural soils across different regions of India. For example, **Krishan et al. (2018)** investigated heavy metal enrichment in agricultural soils in the Mewat district, Haryana, and observed moderate levels of lead (Pb) was mainly associated with agricultural inputs and local lithology. Similarly, **Savanoor et al. (2021)** examined peri-urban soils in Haryana and identified significant spatial variation in cadmium (Cd) concentrations, which was largely influenced by irrigation practices and anthropogenic activities. In the eastern coastal regions, soil monitoring studies conducted in paddy cultivation areas documented chromium (Cr) levels and evaluated ecological risks under intensive agricultural practices. Furthermore, **Dutta et al. (2022)** analyzed surface soils (0–20 cm depth) from intensive vegetable-growing regions of the Brahmaputra Valley and reported the presence of multiple heavy metals, including Pb, Cd, Cr, and Ni, along with risk assessment indices. The major findings from these studies, including minimum, maximum, mean concentrations, and permissible limits, are summarized in **Table 5.**

Metal	Min (mg/kg)	Max (mg/kg)	Mean (mg/kg)	SD	Range	WHO/BIS Permissible Limit (mg/kg)	Study Location	Reference
Pb	12.4	38.6	24.3	6.5	26.2	100	Mewat, Haryana	Krishan et al., 2018
Cd	0.4	1.8	0.9	0.3	1.4	3	Peri-urban Haryana	Savanoor et al., 2021
Cr	1.3	7.8	4.6	1.9	6.5	90	EastCoast Paddy Soils	Environmental Monitoring Study
Ni	3.3	14.3	8.4	2.7	11.0	50	Brahmaputra Valley	Dutta et al., 2022
As	5.2	18.7	10.5	3.4	13.5	20	Northern Alluvial Soils	Kumar et al., 2016

Table 5. Summary of reported heavy metal concentrations in agricultural soils of India with reference to WHO/BIS permissible limits

Table 5 presents the minimum, maximum, mean, standard deviation, and range of selected heavy metals reported in agricultural soils across different regions of India. The average concentrations of Pb, Cd, Cr, Ni, and As were generally observed to be below their respective WHO/BIS permissible limits as shown in **Figure 10.** Among the analyzed metals, Pb exhibited relatively higher mean concentrations compared to other analyzed metals, whereas Cd showed relatively lower values. The spatial variability in metal concentrations can be attributed to differences in lithology, agricultural inputs, irrigation sources, and other anthropogenic activities. Although current concentrations are generally within permissible limits, the progressive accumulation of heavy metals in agricultural soils may pose long-term ecological and human health risks, particularly through soil–water interactions and potential transfer into the food chain.

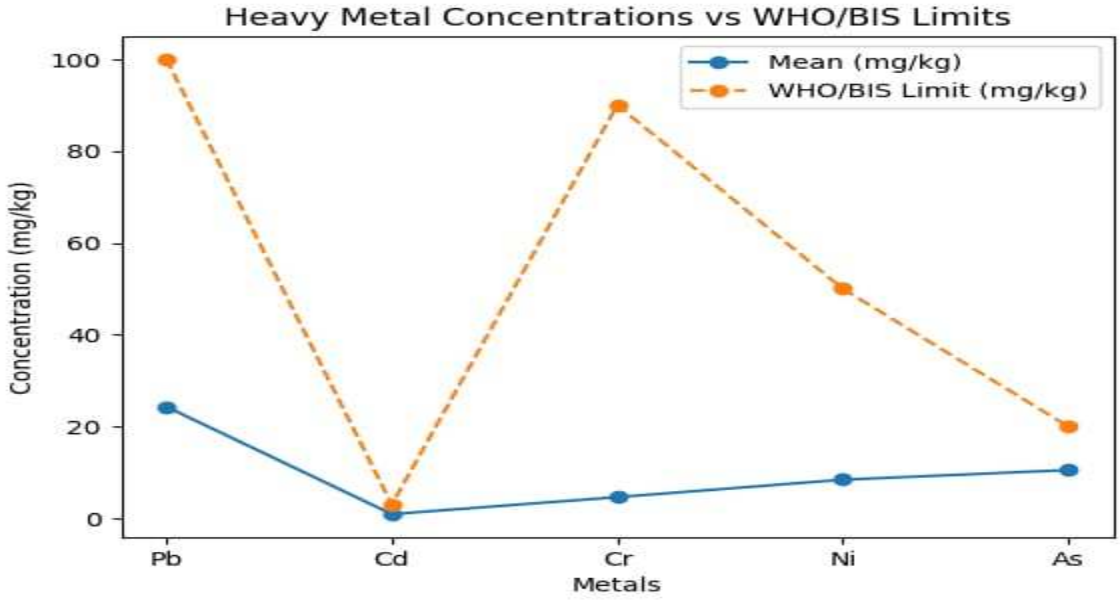


Figure 10. Mean heavy metal concentrations compared with WHO/BIS permissible limits

The figure compares mean concentrations of Pb, Cd, Cr, Ni, and As in agricultural soils with their respective WHO/BIS permissible limits. The reported mean concentrations are generally lower than the prescribed guideline limits, indicating that the studied soils are presently within acceptable safety thresholds. However, continuous monitoring remains essential due to the potential for long-term accumulation and geochemical transformations.

The presence of heavy metals in agricultural soils may influence uranium mobility in groundwater systems through adsorption–desorption processes, redox reactions, and competitive ion exchange mechanisms. Therefore, understanding soil metal concentrations provides a critical geochemical framework for assessing uranium co-occurrence and associated human health implications in regions such as Balod district, Chhattisgarh.

The compiled data on heavy metal concentrations in agricultural soils across different regions of India indicate considerable variability, primarily influenced by agricultural practices, irrigation sources, and local lithological characteristics. Although the reported mean concentrations of metals such as Pb, Cd, Cr, Ni, and As are generally within WHO/BIS permissible limits, the observed accumulation patterns suggest a potential risk of gradual enrichment in soil systems. This is particularly important as agricultural soils act as a critical interface controlling the transfer of contaminants into crops and subsequently into the food chain. The findings highlight that even low to moderate concentrations may pose long-term ecological and human health risks through continuous exposure and soil–water interactions. However, most studies are limited to concentration-based assessments and lack integrated evaluation of metal bioavailability, crop uptake, and their linkage with groundwater contamination, indicating the need for more comprehensive and multidisciplinary investigations.

3.6 Geochemical and seasonal factors

The mobility and spatial variability of uranium and co-occurring associated metals present in groundwater are strongly influenced by geochemical conditions and seasonal variability. The occurrence and movement of these contaminants are not random but are primarily controlled by hydrogeochemical parameters. Factors including parameters like pH, electrical conductivity (EC), total dissolved solids (TDS), alkalinity, and the carbonate and phosphate ions play a key role in controlling the mobility and chemical forms of uranium and associated metals. For instance, uranium becomes more soluble under alkaline conditions, where it forms uranyl-carbonate complexes, which enhances its transport in groundwater systems. Similarly, the redox potential determines whether metals such as arsenic or cadmium remains dissolved or precipitate as solid phases. Seasonal variations further influence contaminant concentrations through processes such as evaporation, recharge, and water- rock interaction. **Punetha, Patni K. et al. (2020)** reported that uranium concentrations often increase during the pre-monsoon season when groundwater levels decline and evaporation concentrate dissolved contaminants. Conversely, groundwater recharge after the monsoon leads to dilute groundwater temporarily reducing uranium concentrations. These observations highlight the importance of seasonal monitoring rather than relying on single-time sampling for groundwater quality assessment. Similarly, **Tiwari et al. (2019)** highlighted that alkaline pH and elevated bicarbonate concentrations promote uranium desorption from aquifer sediments, thereby increasing its concentration in groundwater. **Patel Singh (2022)** also observed higher uranium levels during pre-monsoon periods compared with post-monsoon conditions due to evaporation and reduced recharge. According to the United state geological survey **USGS (2022)**, granitic and sedimentary terrains are major natural sources contributing to uranium enrichment in groundwater. The combined influence of hydrogeochemical parameters and seasonal variations on uranium mobility in groundwater systems is illustrated schematically in **Figure 11.**

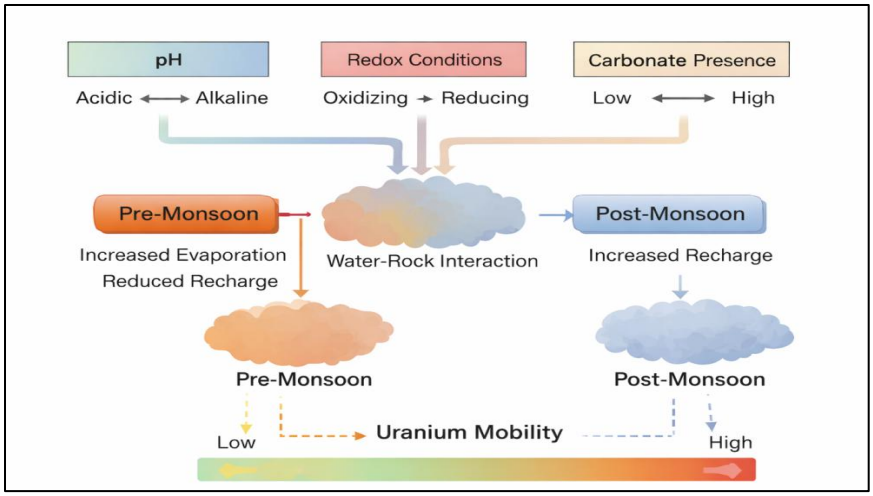


Figure 11. Conceptual representation of geochemical and seasonal factors controlling uranium mobility within groundwater environments

From the author's perspective, understanding the geochemical and seasonal controls on uranium and associated heavy metals is essential for accurately assessing groundwater contamination. This study is important because it highlights how variations in parameters such as pH, redox conditions, and carbonate chemistry, along with seasonal changes, directly influence contaminant mobility and distribution. However, most previous investigations have primarily focused on groundwater alone and often rely on single-time sampling, which does not capture seasonal variability. There is also a lack of integrated studies that simultaneously consider both water and soil systems, despite their strong interaction in controlling metal mobility. In the context of Balod district, where both groundwater and agricultural soils are interconnected, this gap becomes particularly significant. Therefore, this review emphasizes the need for integrated and seasonally resolved studies to better understand uranium–heavy metal behavior and to improve risk assessment and groundwater management strategies.

3.7 Human health implications

The health impacts of uranium and heavy metals in groundwater are severe and multi- dimensional. Uranium primarily targets the kidneys, where it accumulates and interferes with normal filtration functions. Even at levels below those of radiological concern, chemical toxicity can cause nephritis and other kidney disorders. Heavy metals add additional layers to the health burden. Exposure to arsenic is commonly linked to skin lesions, respiratory diseases, and increased risk of cancers. Cadmium leads to brittle bones, kidney failure, and lung problems. Lead poses serious risks to children, impairing their cognitive development and causing irreversible neurological damage. The combined exposure to uranium along with heavy metals, as seen in Balod and similar districts, creates a situation in which health risks are not simply additive but may be synergistic. This means that the overall toxicity is greater than the sum of its parts, making multi-contaminant exposure a far more serious public health issue. The Indian Council of Medical Research **(ICMR, 2020)** highlights that chronic uranium exposure may impair kidney function and alter biochemical pathways. **Garg et al. (2022)** discussed the nephrotoxic effects of uranium intake via contaminated drinking water, emphasizing the necessity for detailed health risk evaluation in areas with elevated uranium concentrations. **Malik et al. (2023)** highlighted the possible health risk impacts linked with uranium and heavy metal exposure in Haryana, including reneal impairment and other chronic health issues. **Tanwer et al. (2023)** addressed the radiological risks associated with uranium in groundwater, suggesting that long- term exposure could lead to various health complications. **Rani et al. (2025)** provided insights into seasonal variations of uranium and other heavy metals in groundwater, which could influence their bioavailability and potential health impacts. **Yadava et al. (2013)** discussed the health risks posed by higher levels of heavy metals like zinc, copper, and cadmium in groundwater near the proposed nuclear power project site in Fatehabad district. **UNICEF (2020)**

emphasized that children are particularly susceptible to heavy-metal exposure due to their higher water intake per body weight.

3.8 Challenges and research gap

The occurrence of uranium and associated heavy metals in environmental systems has received increasing attention in recent years because of their potential impacts on public health and ecosystems. Several studies in India have reported increased uranium concentrations in groundwater; however, the data remain spatially limited and often focus on single environmental compartments. In regions such as Balod district in Chhattisgarh, previous investigations have primarily evaluated uranium in groundwater and assessed associated health risks. Although these studies provide valuable information, comprehensive environmental evaluations that integrate both groundwater and agricultural soil systems remain still limited. The interaction between soil-groundwater plays a crucial role in controlling the mobilization, transport, and accumulation of uranium and other heavy metals, especially in agricultural regions, where geochemical conditions and anthropogenic activities may influence contaminant distribution.

Furthermore, existing studies often report only concentration data without addressing the relationships between uranium and other heavy metals or the geochemical and environmental mechanisms that controls their behavior. Spatially comprehensive monitoring and multi-element analyses are scarce, limiting the understanding of long-term contamination patterns and potential sources. Additionally, advanced radiological assessments using techniques such as HPGe gamma spectrometry in soils remain unexplored for the study area. Hence, there is a clear need for integrated future investigations involving simultaneous analysis of uranium and heavy metals in both soil and groundwater, combined with hydrogeochemical characterization and statistical approaches. Such studies will provide baseline environmental data, improve the understanding of contaminant dynamics, and support informed groundwater and soil management strategies in the region.

Future Research Direction

Considering the existing research gaps, future investigations should adopt a more integrated and comprehensive approach. Studies should simultaneously assess uranium and associated heavy metals in both groundwater and agricultural soils to better understand the interactions between these environmental compartments. Incorporating hydrogeochemical parameters, such as pH, electrical conductivity, total dissolved solids, and alkalinity, can provide insight into the geochemical processes controlling the mobility and accumulation of contaminants.

Advanced analytical techniques, including LED fluorimetric spectrometry for uranium determination and HPGe gamma spectrometry for radiological assessment, are recommended to obtain more reliable and accurate data. Furthermore, statistical approaches such as Pearson correlation, principal component analysis (PCA), and cluster analysis should be applied to identify potential sources of contamination and relationships among multiple metals. The implementation of these methods will not only provide a baseline environmental dataset for the region but also guide environmental risk assessment, groundwater management, and soil protection strategies. Such integrated research can bridge the existing gaps and significantly enhance the understanding of uranium and heavy metal contamination dynamics in Balod district and similar regions.

4. Analytical techniques for the determination of uranium and co-occurring heavy metals in groundwater and soil

4.1 Inductively coupled plasma-optical emission spectroscopy (ICP-OES)

Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP-OES) is widely applied for the determination of trace and major elements in environmental samples such as groundwater and soil. This method is based on excitation of atoms and ions in a high-temperature argon plasma, resulting in the emission of element-specific wavelengths that allow quantitative determination of metals. The application of ICP-OES for groundwater quality assessment and trace metal determination has been reported by **Yadav et al. (2013).** A similar environmental

monitoring approach using ICP-OES for metal analysis in groundwater was discussed by **Kumar and Kansal (2025).** Further studies have highlighted the suitability of ICP-OES for multi-element environmental analysis in groundwater systems **(Sahu et al., 2020).** The importance of ICP-OES in hydrochemical investigations of contaminated water resources has also been emphasized by **Garg et al. (2022).**

Sharma et al. (2015) applied ICP-OES to assess uranium concentrations in groundwater and reported elevated levels in granitic and hard-rock aquifers. In a regional groundwater quality assessment, **P.S. et al. (2019)** used ICP-OES to quantify uranium along with iron and manganese and highlighted the influence of aquifer lithology on metal mobilization. **Rao et al. (2017)** employed this technique to study uranium distribution in drinking water sources and observed that prolonged water–rock interaction played a significant role in uranium enrichment. Their findings emphasized the usefulness of ICP-OES in large-scale monitoring studies. Further investigations by **Gupta et al. (2022)** analyzed heavy metal concentrations in river water, sediment, and groundwater of Kanpur (Uttar Pradesh, India), reporting detectable levels of Fe, Cu, As, and Pb in groundwater samples and highlighting the need for routine monitoring due to potential health risks. **Shinde et al. (2020)** used ICP-OES to quantify heavy metals including Fe and Mn in groundwater along the Sukhna River and found that several metal concentrations exceeded permissible standards, underscoring the utility of ICP-OES for multi-element water quality assessment. More recently, **Joshi et al. (2022)** confirmed that ICP-OES remains a practical and cost-effective tool for environmental assessment of uranium in groundwater systems.

4.2 Inductively coupled plasma-mass spectrometry (ICP-MS)

Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) is considered one of the most sensitive analytical techniques for trace-level determination of metals and radionuclides in environmental samples. The technique allows detection of elements at extremely low concentrations due to its high sensitivity and low detection limits. The application of ICP-MS for groundwater uranium analysis has been reported Quality assurance and quality control (QA/QC) procedures are essential to ensure the accuracy and reliability of trace metal analysis using ICP-MS in environmental studies. In groundwater investigations, strict QA/QC protocols including calibration standards, procedural blanks, and duplicate sample analysis are commonly applied during ICP-MS measurements. For example, **Krishan et al. (2018)** reported that instrumental calibration and periodic quality control checks were performed to maintain analytical precision during multi-element determination in groundwater samples. Similarly, **Pritee Pandey et al. (2022)** emphasized the use of replicate analyses and method blanks to minimize analytical uncertainties during trace metal determination. **Prasad et al. (2025)** utilized reliable analytical techniques for the determination of uranium in drinking water, supporting its application in environmental monitoring and health risk assessment.

Detection limits achieved for metals analyzed by ICP-MS are generally very low, allowing ultra-trace level determination in groundwater samples. For instance, **Savanoor et al. (2021)** reported detection limits of approximately 0.01 µg L^{-1} for Cd, 0.02 µg L^{-1} for Pb, 0.03 µg L^{-1} for Cr, and around 0.05 µg L^{-1} for uranium, demonstrating the high sensitivity of ICP-MS for environmental monitoring studies. Comparable detection capabilities for trace metals in groundwater were also described by **Garg et al. (2022)** during hydrochemical investigations of contaminated aquifers.

Balaram and Rani et al (2022) Global and Indian studies show that geogenic uranium occurs with other geochemical parameters such as iron and manganese, and advanced analytical methods including ICP-MS are frequently used for accurate quantification of uranium and other trace elements.

To ensure analytical accuracy, certified reference materials (CRMs) are widely used for validation of ICP-MS measurements. Environmental monitoring studies have commonly used standard reference water materials such as NIST SRM-1643 or equivalent certified standards for quality control during trace metal analysis. The use of CRMs for validation of analytical methods in groundwater metal determination has been discussed by **Kumar et al. (2018),** who reported satisfactory agreement between measured and certified values.

Recovery experiments are also conducted to assess method accuracy of the analytical method. In most groundwater studies using ICP-MS, reported recovery rates for trace metals typically range between 90 % and 110 %, indicating

acceptable analytical precision and reliability of the method. Similar recovery ranges for multi-element analysis in environmental samples were reported by **Sahu et al. (2020),** confirming the suitability of ICP-MS for trace-level determination of uranium and associated metals in groundwater systems. **Kilavi et al 2021** reported uranium concentrations were within permissible limits, the carcinogenic risk values exceeded the acceptable limit of 10^{-4}, indicating significant health risks due to combined heavy metal exposure.

4.3 Alpha spectrometry

Alpha spectrometry is an important radiometric method used for the determination of alpha-emitting radionuclides such as uranium isotopes in environmental samples. The technique involves radiochemical separation followed by measurement of alpha particle energies using semiconductor detectors. The application of alpha spectrometry for radiological assessment of groundwater has been reported by **Prasad et al. (2020).** Similar studies focusing on radionuclide analysis in environmental samples were conducted by **Dutta et al. (2022).** Additional investigations have also highlighted the usefulness of alpha spectrometry for evaluating uranium distribution in water resources **Sahu and Ghosh, (2025).**

Alpha spectrometry is a specialized analytical technique used for the determination of uranium isotopes and assessment of their radiological impact. It is particularly important for distinguishing between chemical toxicity and radiological exposure associated with uranium in drinking water. In a detailed radiological assessment **Ghosh et al. (2024)** used alpha spectrometry to measure uranium isotopes in groundwater and calculated age- dependent ingestion doses, finding uranium concentrations well below international limits and associated effective doses ranging from approximately 0.6 to 19.5μSv/y across age groups. Methodologically, alpha spectrometry allows for peak deconvolution and interference correction, as highlighted by **Harrison et al. (2016),** ensuring reliable isotope ratio determination even in complex groundwater matrices. Together, these studies demonstrate that alpha spectrometry is an effective tool for assessing both the concentrations of uranium isotopes and the radiological health risks associated with groundwater consumption. **Rana et al. (2016)** examined natural uranium concentrations in groundwater around the Tummalapalle uranium mining and processing facility in Andhra Pradesh, India, and assessed the resulting radiological risks and ingestion doses for local populations**. Sharma et al. (2018)** documented the spatial distribution of uranium in alluvial aquifers of northwest India, showing that hydrogeological conditions such as shallow water tables and aquifer lithology significantly influence dissolved uranium levels in groundwater**. Barman et al. (2022)** assessed harmful heavy metals including uranium in shallow aquifers of Nagaon district (Assam, India), quantifying spatial distributions and associated health risks for both adults and children. Further applications by **Yadav et al. (2020)** focused on evaluating radiological risks in uranium-affected groundwater systems.

4.4 Laser-based techniques (laser fluorimetry/ laser-induced fluorimetry/ LED fluorimetry)

Laser fluorimetry is recognized as a highly sensitive analytical method widely applied for uranium determination in groundwater due to the strong fluorescence characteristics of the uranyl ion (UO_2^{2+}). Studies from Balod District, Chhattisgarh, observed uranium levels varying between 0.10 to 66.7μg/L using laser-based spectroscopic techniques, with some locations exceeding WHO permissible limits **(Sahu & Ghosh, 2025)**. These techniques are particularly suitable for rapid screening and localized hotspot identification. The application of laser fluorimetry for uranium detection in groundwater samples has been reported by **Yadava et al. (2013).** Similar studies **Sharma et al. (2022)** investigating uranium concentration in drinking water using fluorimetric techniques was conducted. The usefulness of this method for rapid monitoring of uranium contamination has also discussed by **Singh et al. (2022).**

In an extensive groundwater survey, **Pritee Pandey et al. (2022)** reported that laser-based measurements provided consistent results with laboratory-based techniques, supporting their reliability for routine monitoring. Their study emphasized the advantage of minimal sample preparation. **Tiwari et al. (2016)** reported the application of laser-induced techniques for the detection and quantification of uranium in environmental samples. Their study demonstrated that pulsed laser-induced plasma could effectively identify uranium signatures in complex matrices, highlighting the potential of laser-based methods for rapid, minimally invasive uranium analysis in soils and water.

This approach provided an alternative to conventional radiochemical techniques, offering faster analysis with reduced sample preparation.

Several studies have investigated the occurrence of uranium and associated heavy metals in groundwater and their potential health impacts. **T. Raghavendra et al. (2014)** analyzed groundwater samples from the Peddagattu and Seripally regions and reported the distribution of uranium using laser fluorimetry, demonstrating the effectiveness of the technique for detecting trace levels of uranium in groundwater. Similarly, **George C.-Y. Chan et al. (2016)** applied laser-induced breakdown spectroscopy for isotopic determination of uranium in environmental samples, highlighting advanced spectroscopic techniques for uranium analysis.

Further methodological improvements in uranium detection were discussed by **D. P. S. Rathore et al. (2024),** who demonstrated reliable determination of uranium in natural waters using laser-induced fluorimetry (LED fluorimetry), particularly under challenging conditions such as the presence of fluoride and humic substances in groundwater. In northern India, **K. Chahal and S. Kumar et al. (2023)** evaluated radiological risks and chemical toxicity associated with uranium-contaminated drinking water in Mahendergarh district of Haryana and reported potential health concerns due to long-term exposure.

Similarly, **A. Kumari, B. Babita et al. (2023)** analyzed natural uranium concentrations in groundwater from Jhajjar district, Haryana using LED fluorimetry and observed spatial variability in uranium levels influenced by hydrogeochemical conditions.

4.5 Atomic absorption spectroscopy (AAS)

Investigations by **A. G. Urmila and Annu (2016)** assessed heavy-metal contamination in soils of Jhajjar district, indicating the potential contribution of soil-derived metals to groundwater contamination. Using multivariate statistical techniques, **V. Panghal et al. (2023)** evaluated groundwater and surface soil contamination in Gurugram, Haryana, and identified geogenic and anthropogenic sources influencing heavy-metal distribution. Additionally, **V. Duggal et al. (2021)** assessed uranium concentrations in drinking water from Hisar district and estimated radiological risks associated with long-term consumption. Collectively, these studies highlight the importance of advanced analytical techniques, hydrogeochemical evaluation, and health risk assessment for understanding uranium distribution and associated heavy-metal contamination in groundwater systems across India.

Atomic Absorption Spectroscopy (AAS) has been widely applied for the determination of trace metals in environmental samples due to its reliability and relatively simple instrumentation. The method provides) adequate sensitivity for monitoring heavy metals in groundwater and soil samples. For instance, **Mohan V. et al. (2018)** reported the use of AAS for the determination of trace metals in environmental samples and highlighted its suitability for routine monitoring studies. The detection limits reported for AAS analysis generally range between 0.001–0.01 mg L^{-1} for Cd**,** 0.005–0.02 mg L^{-1} for Pb**,** and 0.01–0.05 mg L^{-1} for Cr and Ni**,** depending on the analytical conditions and instrument configuration. Similar environmental monitoring applications of AAS for heavy metal determination have been discussed by **Bevinathalapura Shankarappa et al. (2024).** Quality assurance procedures such as calibration standards, procedural blanks, and replicate sample analysis are commonly implemented to ensure analytical accuracy, and recovery rates for heavy metals typically range between 90% and 105%**,** indicating acceptable analytical performance.

4.6 Health risk assessment (HQ, HI, cancer risk and dose) reviewed studies

Health risk assessment has been widely employed in groundwater studies to evaluate the potential adverse effects of uranium and associated heavy metals on human health. In reviewed studies, both non-carcinogenic and carcinogenic risks have been assessed using standard indices such as Hazard Quotient (HQ), Hazard Index (HI), lifetime cancer risk, and radiological dose estimation**.** The Hazard Quotient (HQ) is commonly used to estimate non-carcinogenic risk by comparing the average daily intake of a contaminant with its reference dose.

B. K. Gurona et al. (2024) evaluated health risks associated with uranium contamination in groundwater using Monte Carlo simulation, estimating hazard quotient (HQ), cancer risk (CR), and uncertainty in exposure parameters

through probabilistic modelling. Similarly, **N. Narwal et al. (2024)** investigated heavy metal contamination in groundwater and assessed the potential impact on public health by calculating hazard quotient (HQ), hazard index (HI), and carcinogenic risk values for different exposure pathways. Using a probabilistic risk assessment approach, **Kumar and Maurya et al. (2025)** analyzed heavy metal contamination in groundwater of Gaya, Bihar, and estimated HQ, HI, and cancer risk using Monte Carlo simulation, highlighting uncertainties in human exposure. In central India, **Rajesh Ahirwar et al. (2025)** mapped groundwater contamination in industrial and landfill-affected areas and evaluated associated non-carcinogenic risks (HQ and HI) and carcinogenic risks (CR) to assess potential health hazards. Hydrogeochemical modelling combined with risk assessment was performed by **P. Samala et al. (2022)** in the Basundhara coal mining region, where the authors estimated HQ and HI values for heavy metal exposure through drinking water consumption. Similarly, **Vignesh Akshitha et al. (2022)** applied geostatistical techniques to evaluate heavy metal contamination in hard-rock aquifers and calculated hazard quotient (HQ), hazard index (HI), and cancer risk (CR) to determine potential health impacts. A regional study by **Vidisha Upadhyay et al. (2024)** investigated the transfer of heavy metals from soil to groundwater in northern India and assessed human health risks through HQ, HI, and carcinogenic risk estimations. Recent work by **Abishek S. R. et al. (2025)** evaluated hydrogeochemical variability and estimated non-carcinogenic risk (HQ and HI) and carcinogenic risk (CR) associated with heavy metals in groundwater. Risk indices such as hazard quotient (HQ) and hazard index (HI), and lifetime cancer risk are frequently used to assess non-carcinogenic and carcinogenic risks associated with metal exposure. The application of health risk assessment models in groundwater contamination studies has been reported by **Garima et al. (2024).** Similar studies evaluating health risks due to uranium and heavy metals were conducted by **Tanwer et al. (2023).** The importance of dose assessment in evaluating radiological health risks from drinking water has also been emphasized by the **Indian Council of Medical Research (2020).**

When multiple contaminants coexist, the Hazard Index (HI) is used to evaluate cumulative non-carcinogenic risk. Many reviewed studies documented HI values greater than the permissible limit, suggesting enhanced health risks due to combined exposure to uranium and heavy metals such as arsenic, lead, and cadmium **(Brindha et al 2020; Singh et al., 2017).** The lifetime cancer risk associated with uranium ingestion has also been assessed in several studies. Although uranium is primarily known for its chemical toxicity, prolonged ingestion has been linked to elevated cancer risk in certain regions. Cancer risk values reported in the reviewed literature often exceeded the acceptable range of 10^{-6} to 10^{-4}, indicating potential carcinogenic concern for long-term consumers of contaminated groundwater **(Sahu et al., 2020; Singh et al., 2022).** In addition to chemical toxicity**,** radiological health risks have been evaluated through the estimation of annual effective dose due to uranium ingestion. Several studies reported dose values within international safety limits; however, some regions exhibited values approaching or exceeding the recommended limit of 0.1 mSv $year^{-1}$, highlighting the need for continuous monitoring **(Prasad et al., 2020; Singh et al., 2022).**

Overall, the reviewed studies emphasize that health risk assessment indices such as HQ, HI, cancer risk, and dose estimation are essential tools for understanding the potential human health implications of uranium-contaminated groundwater. These approaches provide a scientific basis for risk management strategies and support the identification of high-risk zones requiring immediate mitigation measures. The present review synthesizes health risk assessment methodologies and reported risk levels from earlier studies, while future investigations will focus on site-specific estimation of HQ, HI, cancer risk, and radiological dose using newly collected groundwater and soil samples.

4.7 Multi-metal cumulative health risk in reviewed studies

Several independent studies have applied multi-metal cumulative health risk assessment to evaluate the combined impacts of uranium and co-occurring heavy metals in groundwater. Although similar risk indices such as HQ, HI, and cumulative risk indices were used, these studies were conducted in different geographical regions, hydrogeological settings, and contamination scenarios**,** resulting in varied health risk outcomes.

Brindha et al. (2020) assessed cumulative health risks in hard-rock aquifers of southern India and reported elevated risk levels due to the combined presence of uranium and arsenic. Furthermore, investigated by **P. Samala et al. (2022)** Saturation Indices calculated for minerals such as uraninite and calcite reveal undersaturation, which promotes uranium mobility under prevailing oxidizing conditions.

Sahu et al. (2020) investigated uranium-bearing groundwater in central India and highlighted that the combined exposure to uranium and associated heavy metals significantly increased non-carcinogenic health risks. Their study emphasized that cumulative risk indices provide a more realistic assessment than single-metal evaluations, especially in regions with prolonged groundwater dependence. Similarly, **Venkatesh et al. (2020)** examined groundwater from semi-arid regions and demonstrated that long-term consumption of multi-metal contaminated water led to elevated cumulative health risk, even when individual metal concentrations were within permissible limits. **Kumar et al. (2018)** expanded cumulative risk analysis to include a broader range of heavy metals and reported higher overall health risk in untreated groundwater sources compared to treated drinking water supplies. Further investigation by **Singh et al. (2022)** emphasized the need for integrated risk assessment models in environmental health studies. **Garg et al. (2025)** conducted detailed carcinogenic and non-carcinogenic risk assessments based on contaminant concentrations in groundwater from semi-arid regions.

Collectively, these studies confirm that while the health risk assessment methodology remains consistent, the study locations, contaminant profiles, and population exposure scenarios differ, demonstrating that cumulative health risk assessment is essential for accurately evaluating human health impacts in uranium-contaminated groundwater systems.

4.8 Hydrogeochemical model interpretation

Hydrogeochemical model interpretation plays a crucial role in understanding the origin, mobilization, and distribution of uranium and co-occurring heavy metals in groundwater systems. Various graphical and geochemical models such as Piper diagrams, Gibbs plots, and geochemical speciation models are widely used to evaluate groundwater evolution and the geochemical processes controlling contaminant mobility. These approaches help explain how water–rock interaction, redox conditions, carbonate complexation, and mineral dissolution influence the release and transport of uranium and associated trace metals in aquifers, thereby affecting groundwater quality and potential human exposure through drinking water.

Several studies have applied hydrogeochemical tools to identify the processes governing uranium occurrence in groundwater. For instance, **Sahu et al. (2020)** investigated uranium-bearing groundwater in central India and used Piper trilinear diagrams to classify hydrochemical facies, reporting that uranium-rich groundwater was commonly associated with bicarbonate-dominated alkaline water types. Similarly, **Brindha et al. (2020)** examined groundwater from hard-rock aquifers and observed that enhanced mineral dissolution under alkaline conditions significantly contributed to uranium mobilization.

To further understand the mechanisms controlling groundwater chemistry, **Singh et al. (2017)** applied Gibbs diagrams and demonstrated that water–rock interaction was the dominant process influencing uranium enrichment in aquifer systems. Comparable findings were reported by **Venkatesh et al. (2020),** who studied semi-arid groundwater environments and observed that evaporation combined with water–rock interaction intensified uranium concentrations in groundwater. In addition, **Kumar et al. (2016)** suggested that groundwater chemistry in uranium-affected regions is largely controlled by geogenic processes rather than atmospheric inputs.

Geochemical speciation and saturation modeling have also been widely used to understand uranium behavior in groundwater systems. For example, **Sahu et al. (2020)** applied PHREEQC modeling and reported that oxidizing conditions, alkaline pH, and elevated carbonate concentrations favor the formation of soluble uranyl–carbonate complexes, thereby increasing uranium mobility in groundwater.

In addition to uranium mobilization, hydrogeochemical processes are often linked with the occurrence of other trace metals in groundwater. For instance, **Sahoo et al. (2020)** used bivariate plots and ionic ratios to identify silicate weathering and carbonate dissolution as major contributors to the co-occurrence of uranium and fluoride in groundwater. Similarly**, Venkatesh et al. (2020)** associated hydrogeochemical processes with the presence of arsenic and other heavy metals, highlighting the potential for multi-metal contamination in groundwater systems. Such geochemical associations can significantly influence cumulative human health risks when contaminated groundwater is used as a drinking water source. Overall, hydrogeochemical model interpretation provides an important framework for linking geochemical processes with uranium mobilization, associated heavy metal

contamination, and groundwater exposure pathways. Understanding these relationships is essential for evaluating potential health risks using indices such as hazard quotient (HQ), hazard index (HI), multi-metal cumulative risk index (MMCRI), cancer risk, and radiological dose. Such integrated interpretations are valuable for identifying high-risk zones and supporting effective groundwater management and public health protection strategies shown in **Figure 12.**

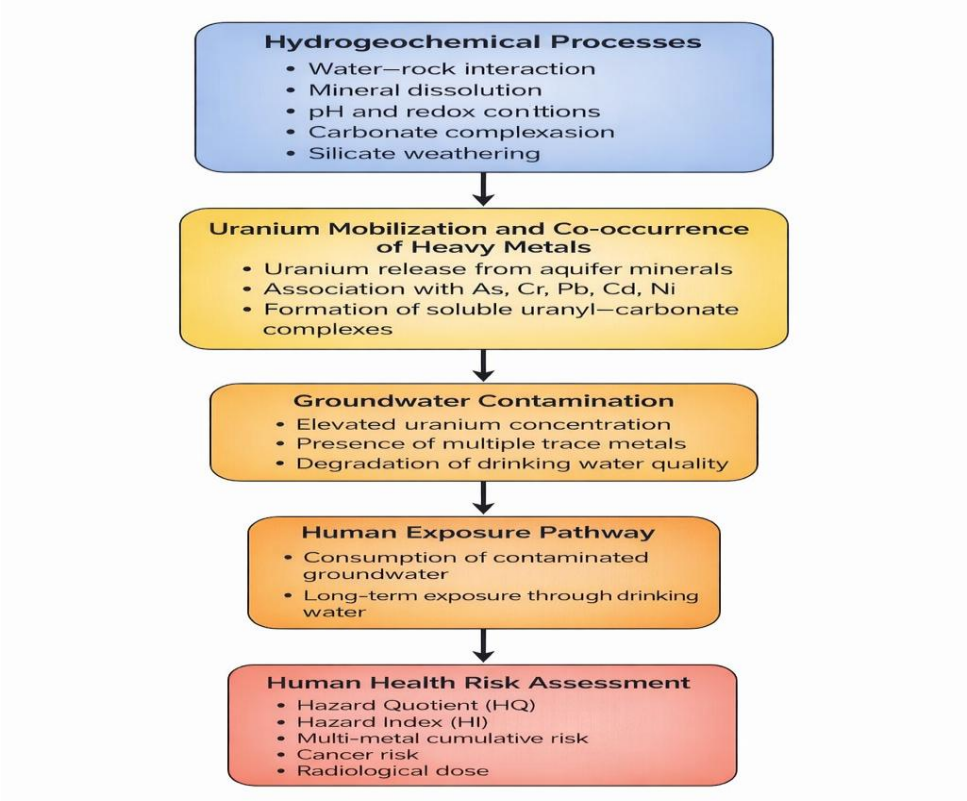


Figure 12. Conceptual framework of hydrogeochemical controls on uranium mobilization, co-occurring heavy metals in groundwater, and associated human health risks.

Conclusion

This review summarizes the current understanding of the occurrence, hydrogeochemical behavior, and potential health implications of uranium and co-occurring heavy metals in water and soil environments, with particular reference to studies conducted in India and similar geological settings. The reviewed literature indicates that uranium contamination in groundwater and soil is largely influenced by natural geogenic processes such as mineral dissolution, water–rock interaction, carbonate complexation, and prevailing redox conditions. These hydrogeochemical processes control the mobilization and transport of uranium from geological formations into groundwater systems, thereby affecting environmental quality and human exposure pathways.

In addition to uranium, several studies have reported the presence of toxic heavy metals such as arsenic, cadmium, chromium, lead, and nickel in water and soil matrices. The co-occurrence of these contaminants is of particular concern because it can significantly degrade environmental quality and increase cumulative human health risks. Soil may also act as a secondary reservoir for contaminants, facilitating their gradual transfer into groundwater through leaching processes.

Various analytical techniques, including ICP-MS, ICP-OES, Atomic Absorption Spectroscopy (AAS), laser-induced fluorimetry, and alpha spectrometry, have been widely employed in environmental studies for the determination of

uranium and associated metals. These techniques, combined with hydrogeochemical modeling approaches, provide valuable insights into the mechanisms controlling contaminant mobility and distribution in environmental systems.

From a public health perspective, long-term exposure to uranium and co-occurring heavy metals through contaminated groundwater and soil poses significant risks to human populations, particularly in rural regions where untreated groundwater is widely used for drinking purposes. Health risk assessment approaches such as hazard quotient (HQ), hazard index (HI), cancer risk estimation, and radiological dose evaluation are essential tools for evaluating potential health impacts associated with chronic exposure.

Overall, this review highlights the importance of integrated environmental assessments that consider both groundwater and soil contamination pathways in order to better understand uranium mobilization and associated heavy metal risks. Such integrated approaches are essential for identifying vulnerable regions, improving environmental monitoring strategies, and supporting the development of effective groundwater management and public health protection measures. Future research should focus on site-specific investigations, particularly in regions such as the Balod district of Chhattisgarh, where comprehensive assessments of uranium occurrence in groundwater and soils and their potential health implications remain limited.

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We are pleased to submit our review manuscript entitled “A review of Uranium and Co-occurring Heavy Metals in Groundwater and Soil of Chhattisgarh, India: Hydrogeochemical controls and Human health Risk Implications” for favor publication in Environmental Science and Pollution Research esteemed journal.

Author Contributions

Seema Mor, conceptualized the study, conducted the literature review, analyzed and synthesized the data, and prepared the manuscript. Dr. Babita Hooda reviewed and edited the draft and provided valuable guidance.

Conflict of Interest

The authors declare no conflict of interest.

Consent to Publish

All authors (Seema Mor and Babita Hooda) have read and approved the final manuscript and agree to its publication.

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Data Availability

No new data were generated or analyzed in this study. All information presented in this manuscript is based on previously published studies and has been appropriately cited.

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