Assessment of Environmental Health Risks Associated with Cadmium (Cd) and Chromium VI (CrVI) Exposure from Community Water Sources in Ponre District, Bone Regency

Nur Azizah Aliardani[1]*, Anwar Mallongi[2], Agus Bintara Birawida[2], Owildan Wisudawan[2], Wahiduddin[3]

[1] *Masters of Environmental Health, Faculty of Public Health, Hasanuddin University, Makassar, Indonesia*
2 Department of Environmental Health, Faculty of Public Health, Hasanuddin University, Makassar, Indonesia
3 Department of Epidemiology, Faculty of Public Health, Hasanuddin University, Makassar, Indonesia

Abstract

Heavy metal contamination in groundwater poses a significant threat to environmental quality and public health, particularly in rural communities relying on well water for drinking. This study assessed the environmental health risks associated with cadmium (Cd) and hexavalent chromium (Cr VI) exposure in Pattimpa, Poleonro, and Bolli Villages, Ponre District, Indonesia. A quantitative environmental health risk assessment approach was applied, including hazard identification, exposure assessment, dose–response analysis, and risk characterization. Data on participant characteristics, water consumption patterns, and exposure duration were collected through structured interviews and field observations, while groundwater samples were analyzed for Cd and Cr VI concentrations. Participants were aged 4–60 years with body weights ranging from 14.3 to 87.3 kg. The average Cd concentration in groundwater was 0.001 mg/L in all villages. Cr VI concentrations were 0.001 mg/L in Pattimpa and 0.01 mg/L in Poleonro and Bolli Villages. Exposure duration ranged from 2 to 32 years, with daily water consumption of 1–2.5 L. Carcinogenic risk assessment indicated elevated Cd-related cancer risk in Pattimpa Village (ECR > 10^{-4}), while non-carcinogenic assessment showed potential health effects from Cr VI exposure in Poleonro Village (RQ ≥ 1). Continuous monitoring and mitigation strategies are needed to protect public health.

Keywords: Environmental health risk assessment, cadmium (Cd), chromium (Cr VI), groundwater contamination, exposure to drinking water

1. Introduction

Water pollution resulting from heavy metals remains a significant environmental concern with grave consequences for human health worldwide. While many heavy metals are essential in trace levels for proper physiological functions and development, excessive exposure can be detrimental. At elevated quantities, these chemicals exhibit toxicity and may accumulate in bodily tissues over time, resulting in significant health repercussions and potential mortality [1]. Moreover, heavy metals can naturally exist in aquatic environments at concentrations that may reach or surpass dangerous thresholds [2].

In Indonesia, water pollution is mostly caused by human activities including home waste disposal, agricultural practices, industrial processes, and mining operations. The swift expansion of industrialization and agriculture, coupled with escalating waste generation, has substantially contributed to the pollution of water resources by toxic compounds, such as pesticides and heavy metals [4]. Agricultural practices significantly contribute to environmental degradation via both biotic and abiotic processes, resulting in soil deterioration, erosion, and the pollution of adjacent ecosystems, including water bodies. The predominant reason is the excessive and incorrect application of fertilizers and pesticides. The excessive application of fertilizers beyond agricultural requirements diminishes efficiency and adversely affects environmental quality [5]. Moreover, numerous widely utilized herbicides have heavy metals, including cadmium (Cd) and chromium (Cr VI) [6].

Chromium (Cr) is a heavy metal commonly found in polluted water systems, where it can deteriorate water quality and adversely affect aquatic organisms. In aquatic species, chromium disrupts metabolic processes by blocking vital enzyme function, potentially leading to persistent toxicity and mortality. Exposure to chromium can lead to both immediate and chronic health consequences. Hexavalent chromium (Cr VI) is the most perilous kind due to its significant mobility and potent oxidative characteristics. Upon entering the human body, it might interfere with metabolic operations and block enzymes like benzopyrene hydroxylase, thereby inducing aberrant cell proliferation and elevating cancer risk [8].

According to Indonesian health standards, the permissible concentration of chromium (Cr VI) in drinking water is 0.01 mg/L [9]. Nonetheless, numerous investigations have indicated levels surpassing this criterion in groundwater. Alharbi [10] identified chromium values of 0.062 mg/L, 0.046 mg/L, and 0.038 mg/L in dug wells adjacent to the Talang Gulo dump in Jambi City, all exceeding the permitted limit. Research in the Pangkajene watershed indicated hazard quotient (HQ) values over 1, signifying significant ecological and health concerns associated with chromium exposure [11]. The severity of health effects resulting from chromium (Cr VI) is contingent upon parameters including its chemical form, exposure dosage, duration, and exposure route [12].

Cadmium (Cd) is a very poisonous heavy metal that poses considerable environmental and health risks. In contrast to essential elements, cadmium possesses no biological role and is classified as a non-essential metal. Its endurance enables accumulation in soil, water, and ultimately within the human body. Cadmium exposure is associated with renal impairment, oxidative stress, and carcinogenic consequences, with the World Health Organization categorizing it as a human carcinogen [13]. Prior research has indicated that cadmium levels in groundwater surpass recommended thresholds. Li et al. [14] detected cadmium concentrations of 0.11 mg/L, 0.08 mg/L, and 0.065 mg/L in drinking water wells, significantly exceeding the allowable limit of 0.005 mg/L.

Agricultural inputs, particularly fertilizers and pesticides, are acknowledged as significant contributors to heavy metal contamination in soil and groundwater. Numerous investigations have identified heavy metals, including lead (Pb) and cadmium (Cd), in pesticide categories such as organophosphates, pyrethroids, carbamates, and triazoles [15]. Moreover, inorganic fertilizers may include heavy metals, with documented amounts of Pb between 10.53 and 28.09 mg kg^{-1} and Cd from 0.07 to 0.52 mg kg^{-1} [16]. The persistent use of these materials can result in the long-term buildup of heavy metals in soil, which may subsequently infiltrate groundwater, especially in regions with permeable soils and extensive irrigation. These processes highlight the substantial impact of agricultural practices on groundwater pollution in rural areas.

In Ponre District, Bone Regency, local populations rely significantly on groundwater sources, including dug wells and boreholes, for daily activities such as drinking, cooking, and sanitation. In 2024, monitoring by the Lonrong Health Center detected cadmium (Cd) and chromium (Cr VI) in domestic water supplies, with concentrations between 0.0005 and 0.004 mg/L for Cd and 0.001 to 0.03 mg/L for Cr VI. Certain values surpass the maximum permissible limits established by Indonesian Ministry of Health Regulation No. 2 of 2023. Given that numerous water sources are situated adjacent to agricultural land characterized by intense fertilizer and pesticide application, agricultural practices are likely a significant factor in groundwater contamination in the region.

Consequently, assessing the potential health hazards linked to heavy metal exposure via drinking water is imperative. Environmental Health Risk Assessment (EHRA) is a systematic methodology to identify environmental dangers and evaluate the degree to which exposure may jeopardize human health. Through the assessment of pollutant concentrations, including cadmium (Cd) and chromium (Cr VI), and the evaluation of exposure patterns, EHRA facilitates informed decision-making in environmental health management. This study seeks to evaluate the environmental health concerns linked to heavy metal contamination in groundwater utilized by populations in Ponre District, especially in regions near agricultural operations.

METHODS

Research Methodology

This study utilized a cross-sectional design integrated with an Environmental Health Risk Assessment (EHRA) methodology to investigate potential health concerns linked to heavy metal exposure via drinking water. The EHRA methodology was utilized to assess risk levels within communities in Ponre District, Bone Regency, Indonesia. The evaluation adhered to the prescribed EHRA procedures, encompassing hazard identification, dose–response analysis, exposure assessment, risk characterization, and risk management. This method facilitates a systematic and quantitative assessment of environmental pollutants and their potential impacts on human health.

Study Area and Period

The research was conducted from September to November 2025 in Ponre District, Bone Regency, South Sulawesi, Indonesia. The evaluation concentrated on three villages: Pattimpa, Poleonro, and Bolli, where groundwater is the primary supply for everyday residential requirements, including drinking and cooking. These regions are predominantly agricultural, with several residential wells located adjacent to farmland, hence heightening the risk of groundwater contamination from agricultural inputs such as fertilizers and pesticides.

Study Population and Environmental Sampling

The study population encompassed both human and environmental elements. The human population comprised individuals potentially exposed to cadmium (Cd) and hexavalent chromium (Cr VI) via the intake of well water. A total of 177 persons were identified, consisting of 72 residents from Pattimpa Village, 59 from Poleonro Village, and 46 from Bolli Village. The environmental aspect encompassed groundwater sources utilized for drinking and cooking, particularly wells situated within a 95-meter radius of agricultural land. The distance was established based on prior research demonstrating that groundwater toxins can disperse up to approximately 95 meters from their origin [18]. A total of 15 wells were designated as sampling points: seven in Pattimpa Village, three in Poleonro Village, and five in Bolli Village.

Sampling Technique and Sample Size

Human subjects were chosen by purposive sampling based on established inclusion criteria. The sample size was calculated using the Slovin algorithm with a 10% margin of error, yielding 59 respondents. The respondents were proportionally distributed throughout the study sites: 24 from Pattimpa Village, 20 from Poleonro Village, and 15 from Bolli Village. Participants were expected to utilize well water for cooking and as their principal source of drinking water; individuals who did not consume well water or opted out of participation were eliminated. Random sampling was employed to determine well locations for environmental sampling, whilst total sampling was utilized to gather water samples from all qualifying wells. A total of 15 groundwater samples were collected for laboratory analysis.

Water Sampling Procedure

Groundwater samples were obtained in accordance with the Indonesian National Standard SNI 6989.58:2008. Sampling utilized 250 mL polyethylene bottles that were pre-treated through detergent washing, rinsing with clean water, acid cleaning with a 1:1 hydrochloric acid (HCl) solution, and triple rinsing with distilled water before drying and sealing. Before sampling, all apparatus and containers were cleaned thrice with the well water to avert contamination. Samples were collected at a depth of approximately 30 cm beneath the water surface utilizing a weighted sampler. For wells fitted with pumps or taps, water was permitted to flow for 1–2 minutes before collection to guarantee representativeness. Each specimen was designated with a distinct code and preserved in a refrigerated container during transit. To maintain heavy metal concentrations, samples were acidified with concentrated nitric acid (HNO_3) to get a pH below 2, and thereafter transported to the Makassar Environmental Health Laboratory (Labkesmas Makassar II) for examination

Data Collection

Data were obtained from both primary and secondary sources. Primary data comprised laboratory measurements of cadmium (Cd) and chromium (Cr VI) concentrations in groundwater, alongside individual exposure characteristics acquired through structured interviews. The questionnaire collected data on body weight, daily water consumption, frequency and duration of exposure, and length of residency, which were utilized to assess individual exposure levels. Secondary data were sourced from governmental records, health center reports, and pertinent scientific literature, encompassing environmental monitoring data and demographic information pertinent to the study area.

Exposure Assessment

The daily exposure dose, quantified as chronic daily intake (CDI) via oral ingestion, was computed utilizing the standard EHRA equation:

$$CDI = \frac{C_w \times IR \times EF \times ED}{BW \times AT}$$

Cw denotes the contaminant concentration in water (mg/L), IR signifies the ingestion rate (L/day), EF indicates the exposure frequency (days/year), ED represents the exposure duration (years), BW refers to body weight (kg), and AT is the average time (days). The averaging time for non-carcinogenic risk was computed as ED multiplied by 365 days.

Risk Characterization

Health hazards were assessed using two metrics: Excess Cancer Risk (ECR) for carcinogenic effects and Risk Quotient (RQ) for non-carcinogenic impacts.

The carcinogenic risk was assessed utilizing:

$$ECR = I \times SF$$

Where I denotes the intake value, and SF refers to the oral slope factor derived from the United States Environmental Protection Agency (US EPA) database. The slope factor values utilized in this investigation were 15 (mg/kg/day) for cadmium (Cd) and 0.27 (mg/kg/day) for chromium VI (Cr VI). An excess cancer risk (ECR) value exceeding 1×10^{-4} was deemed indicative of an unacceptable cancer risk.

The non-carcinogenic risk was assessed utilizing the Risk Quotient (RQ) formula:

$$RQ = \frac{I}{RfD}$$

where RfD denotes the oral reference dose. This study utilized reference values of 0.0005 mg/kg/day for cadmium and 0.0009 mg/kg/day for chromium VI, in accordance with US EPA recommendations. An RQ value exceeding 1 signifies a possible non-carcinogenic health hazard.

Risk Management Analysis

Upon determining that the risk characterization results revealed unacceptable risk levels, suitable risk management measures were recommended to mitigate exposure. These approaches aimed to decrease pollutant levels in drinking water and/or restrict the length and frequency of exposure for the population. Furthermore, safe concentration thresholds and permissible consumption rates were calculated utilizing typical EHRA risk management formulae to guarantee that exposure levels stayed beneath defined toxicological reference values.

Data Analysis and Visualization

Descriptive statistical techniques were employed to encapsulate respondent characteristics and exposure-related factors. Categorical variables were presented as frequencies and percentages, whilst continuous data were articulated as means and standard deviations or medians and ranges, contingent upon data distribution. All data processing and computations were executed with Microsoft Excel. Spatial analysis was performed utilizing Geographic Information Systems (GIS) to delineate sampling sites and depict the distribution of heavy metal concentrations. The geographical distribution patterns of cadmium (Cd) and chromium (Cr VI) were examined utilizing the Inverse Distance Weighted (IDW) interpolation method to discern potential trends within the study area. The findings were displayed through tables, graphs, and spatial maps to clearly illustrate pollutant levels and related environmental health hazards.

Ethical Consideration

This study complied with recognized ethical norms in health research. Essential ethical criteria encompassed acquiring informed consent from all participants, safeguarding confidentiality, preserving anonymity, and maintaining participants' right to withdraw from the study at any moment without facing negative repercussions. Ethical approval was obtained from the Health Research Ethics Committee of the Faculty of Public Health, Hasanuddin University (Approval No. 1684/UN4.14.1/TP.01.02/2025).

RESULTS

Participant Characteristics and Sampling Profile

Table 1. Demographic and socio-economic characteristics of participants in Pattimpa, Poleonro, and Bolli Villages, Ponre District, Indonesia, 2025 (N = 59)

Characteristics	**N=59**	**%**
Gender		
Male	23	39
Female	36	61
Age Group (Years)		
0-14	11	19
15-30	16	27
31-60	32	54
Education Level		
Not in School	3	5
Elementary School	22	37
Junior High School	10	17
High School/Vocational School	21	36
Diploma 3	1	2
Bachelor's Degree	2	3
Occupation Type		
Not Working	18	31
Farmer/Fisherman/Livestock Farmer	11	19
Housewife	22	37
Honorary Worker	3	5
Self-Employed	5	8

This study includes 59 respondents from the villages of Pattimpa, Bolli, and Poleonro. The predominant demographic of participants was female, accounting for 61%, whereas males constituted 39%. The majority of responders were aged 31–60 years (54%), followed by those aged 15–30 years (27%) and 0–14 years (19%). Respondents with elementary-level education constituted the predominant proportion (37%) of educational attainment. In terms of occupation, housewives constituted the largest percentage (37%), suggesting that numerous individuals were involved in informal or unpaid employment (Table 1). Groundwater sampling was conducted utilizing community wells that met the established inclusion criteria in the three communities. A total of 15 wells were chosen, comprising seven in Pattimpa, five in Bolli, and three in Poleonro. Each sampling site yielded approximately 1.6 liters of water for future laboratory analysis (Figure 1)

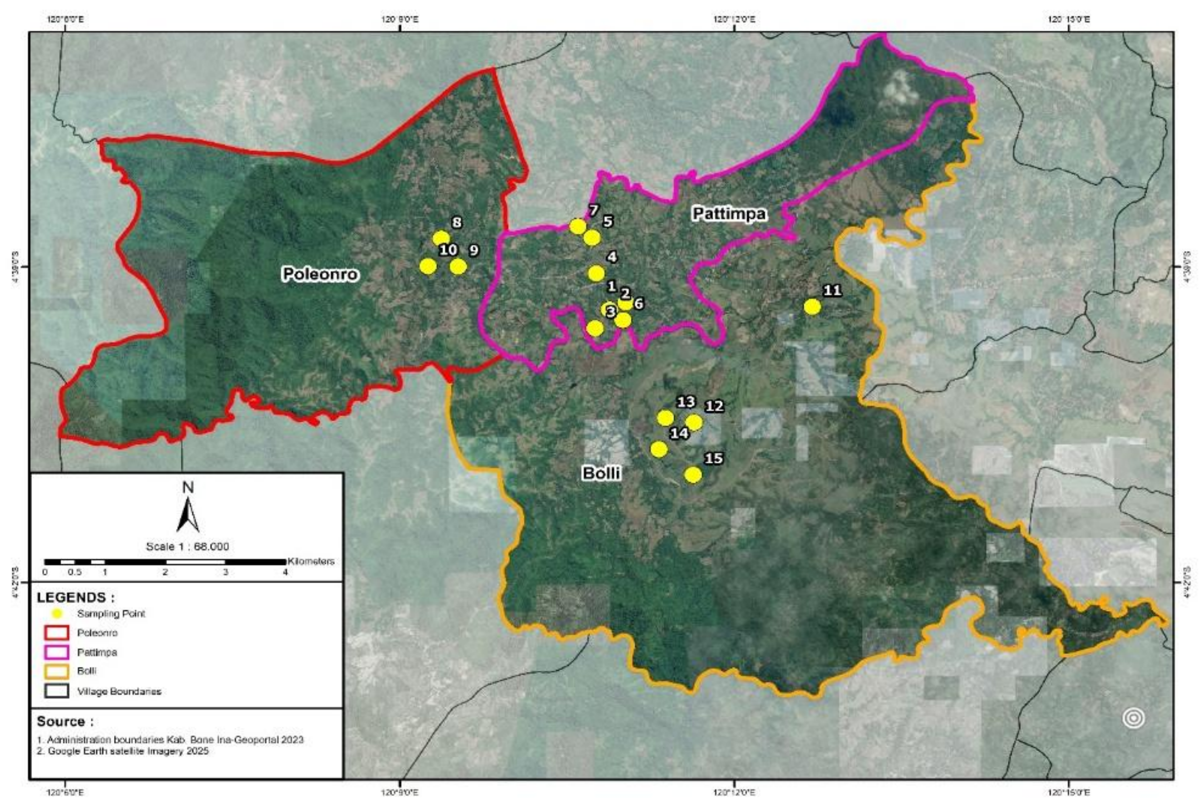
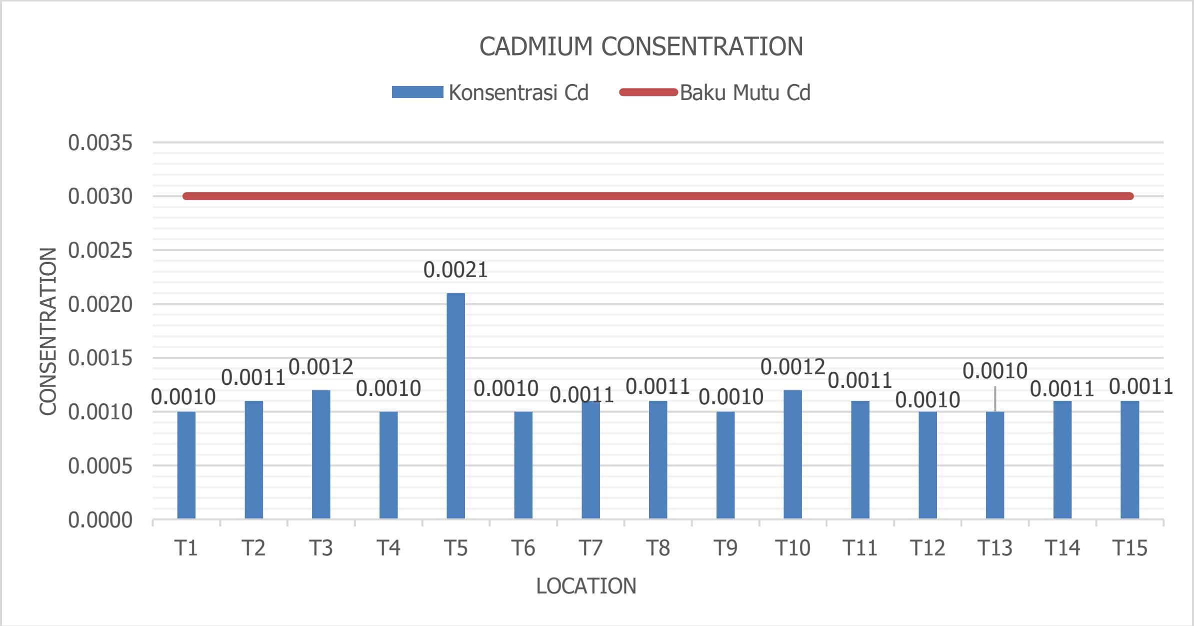


Figure 1. Geographical distribution and sampling locations of groundwater wells selected for analysis in Pattimpa, Poleonro, and Bolli Villages, Ponre District, Indonesia, 2025.



Heavy metal concentrations in groundwater

Figure 2. Flow diagram illustrating the sampling procedures and selection of groundwater wells included in the study across Pattimpa, Poleonro, and Bolli Villages, Indonesia, 2025.

The content of cadmium (Cd) in drinking water sources varied from 0.001 to 0.0021 mg/L throughout the research sites. The readings remained beneath the maximum permissible limit of 0.003 mg/L, signifying that cadmium levels conformed to acceptable criteria for potable water as per national legislation.

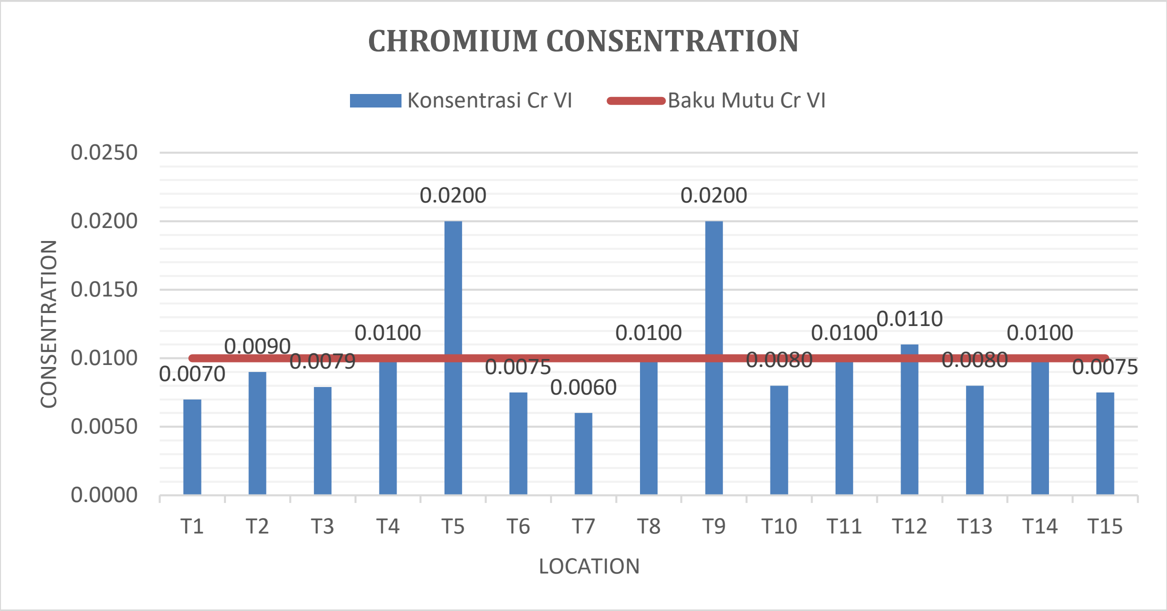


Figure 3. Measured concentrations of hexavalent chromium (Cr VI) in groundwater samples from community wells in Pattimpa, Poleonro, and Bolli Villages, Indonesia, 2025, in comparison with national drinking water quality standards.

Conversely, hexavalent chromium (Cr VI) values ranged from 0.006 to 0.02 mg/L. Numerous wells exhibited concentrations over the allowable limit of 0.01 mg/L, although others remained below acceptable parameters. This fluctuation indicates localized pollution patterns that may provide possible health hazards in some places (Figure 3). Moreover, variations in heavy metal concentrations were noted according to well depth. Shallow wells typically demonstrated elevated levels of Cd and Cr VI in comparison to deeper wells, indicating the impact of surface-related pollution sources (Table 2).

Table 2. Distribution of cadmium (Cd) and hexavalent chromium (Cr VI) concentrations in groundwater according to well depth in Pattimpa, Poleonro, and Bolli Villages, Ponre District, Indonesia, 2025

Sample Point	Location	Well Depth (m)	Heavy Metal Concentration (mg/L)	
			Cd	Cr VI
Pattimpa Village (n= 7)				
1	Desa Pattimpa	10	0.0010	0.0070
2		12	0.0011	0.0090
3		15	0.0012	0.0079
4		10	0.0010	0.0100
5		9	0.0021	0.0200
6		12	0.0010	0.0075
7		9	0.0011	0.0060
Poleonro Village (n= 3)				
8	Desa Poleonro	9	0.0011	0.0100
9		10	0.0010	0.0200
10		13	0.0012	0.0080
Bolli Village (n= 5)				
11		11	0.0011	0.0100

12	Desa Bolli	10	0.0010	0.0110
13		13	0.0010	0.0080
14		10	0.0011	0.0100
15		15	0.0011	0.0075

Source: Primary Data, 2025

Note: Quality Standards Cd= 0.003 mg/l, Cr VI= 0.01 mg/l

Exposure and intake projection

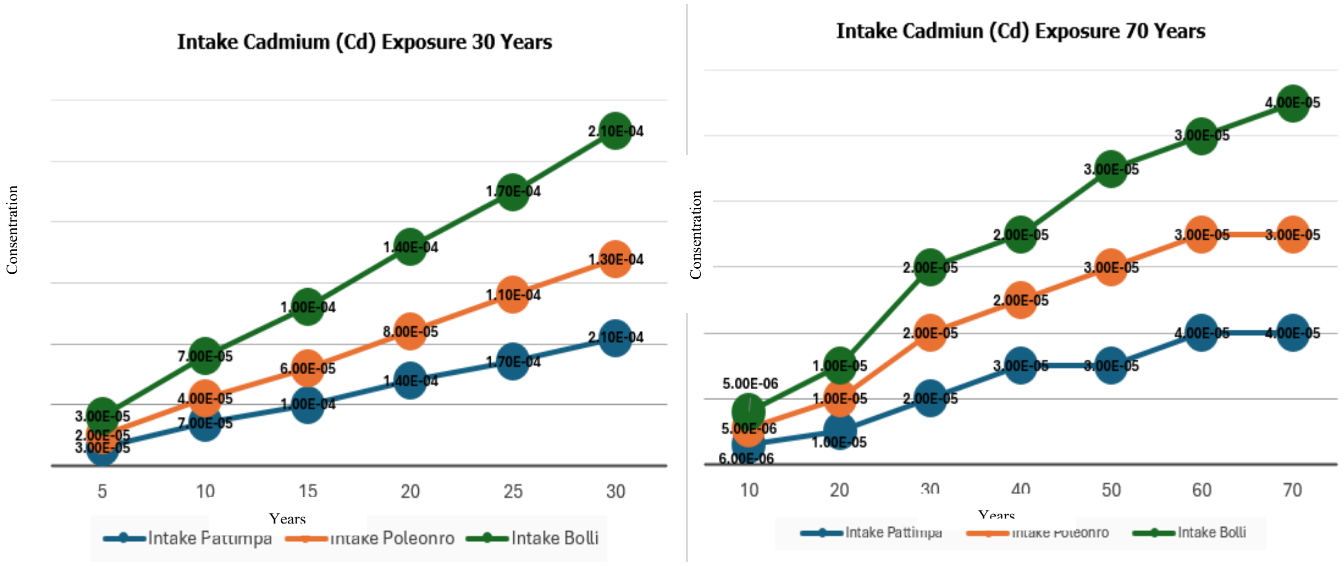


Figure 4: Projected cadmium (Cd) intake over time (10–70 years) and across exposure durations (5–30 years) among respondents consuming groundwater in Pattimpa, Poleonro, and Bolli Villages, Indonesia, 2025

The anticipated accumulation of cadmium exhibited a steady rise over time with extended exposure duration across all research sites. In Pattimpa Village, the average consumption increased markedly with prolonged exposure, and analogous upward trends were noted in Poleonro and Bolli Villages. This pattern was seen even in short-term estimates (5–30 years), underscoring the significant impact of cumulative exposure on total Cd intake (Figure 4).

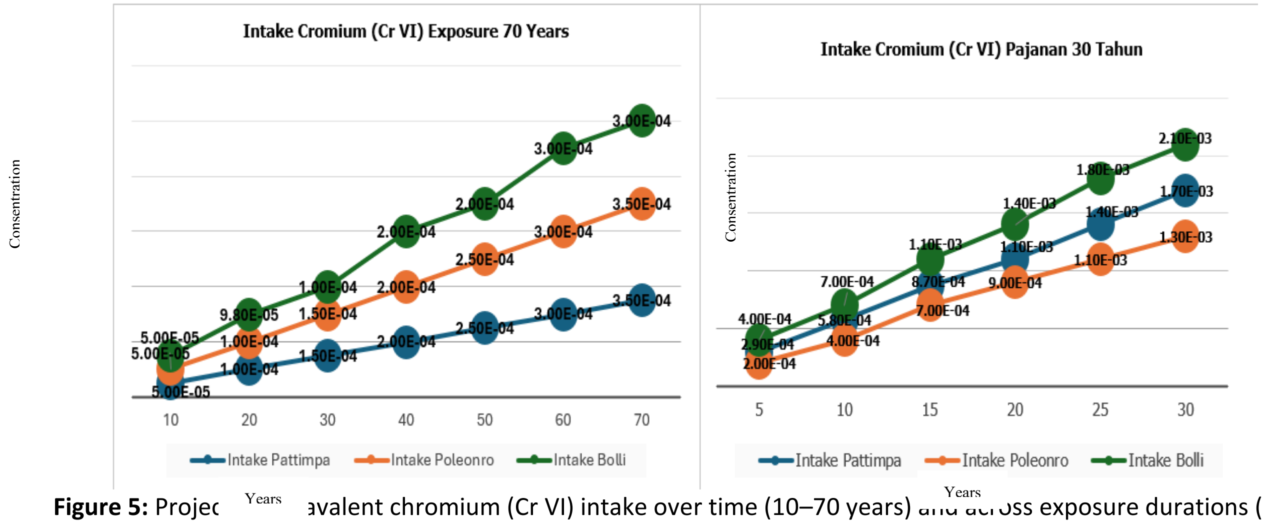


Figure 5: Projec[illegible]avalent chromium (Cr VI) intake over time (10–70 years) and across exposure durations (5–30 years) among respondents in Pattimpa, Poleonro, and Bolli Villages, Indonesia, 2025

A comparable trend was observed for Cr VI, with consumption levels consistently rising over time in all settlements.

Long-term forecasts (10–70 years) indicated rather steady exposure trends across locales; however, shorter-term projections (5–30 years) revealed a distinct rise in intake as the duration of exposure extended. Bolli Village exhibited the highest projected intake values among the three communities, signifying a somewhat elevated potential health risk (Figure 5).

Carcinogenic and non-carcinogenic risk assessment

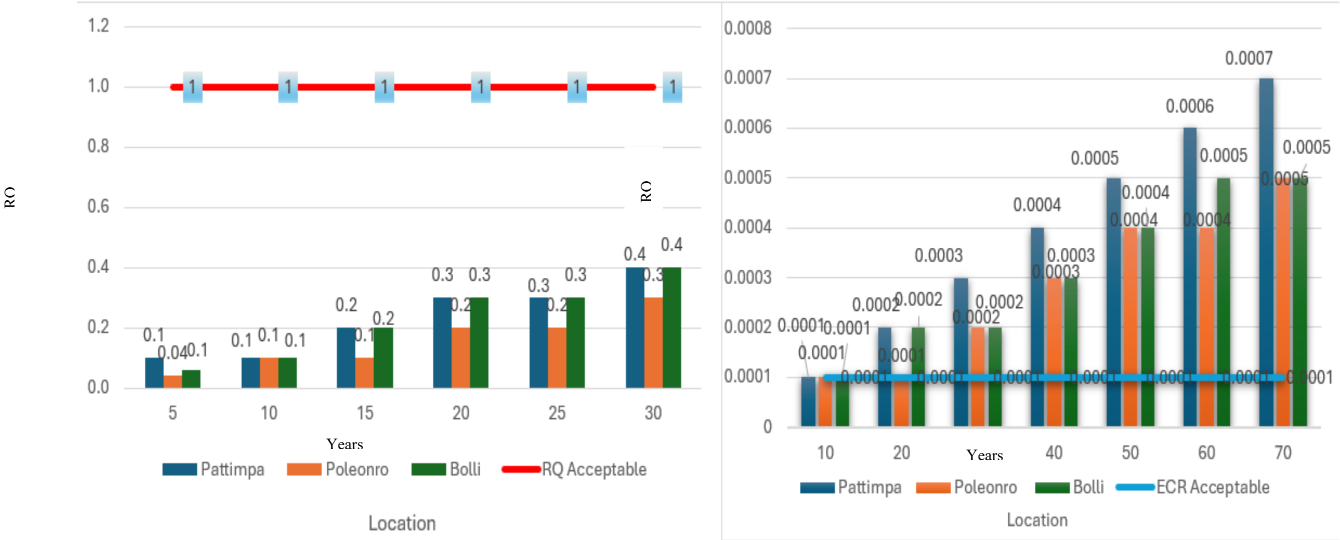


Figure 6: Carcinogenic (Excess Cancer Risk, ECR) and non-carcinogenic (Risk Quotient, RQ) risk estimates for cadmium (Cd) exposure across varying exposure durations among respondents in Pattimpa, Poleonro, and Bolli Villages, Indonesia, 2025

The carcinogenic risk assessment for cadmium exposure revealed a continuous increase in Excess Cancer Risk (ECR) values across all study regions over time. In Pattimpa Village, ECR values surpassed the permissible threshold ($>10^{-4}$), indicating a possible carcinogenic hazard. Simultaneously, ECR values in Poleonro and Bolli Villages were decreased however remained near the threshold of concern. The findings suggest that extended exposure to cadmium via drinking water may elevate cancer risk, especially in regions with elevated exposure levels. Nonetheless, the non-carcinogenic risk assessment revealed that all Risk Quotient (RQ) values for Cd were below 1 at the research sites, signifying that non-carcinogenic risks were within acceptable levels (Figure 6).

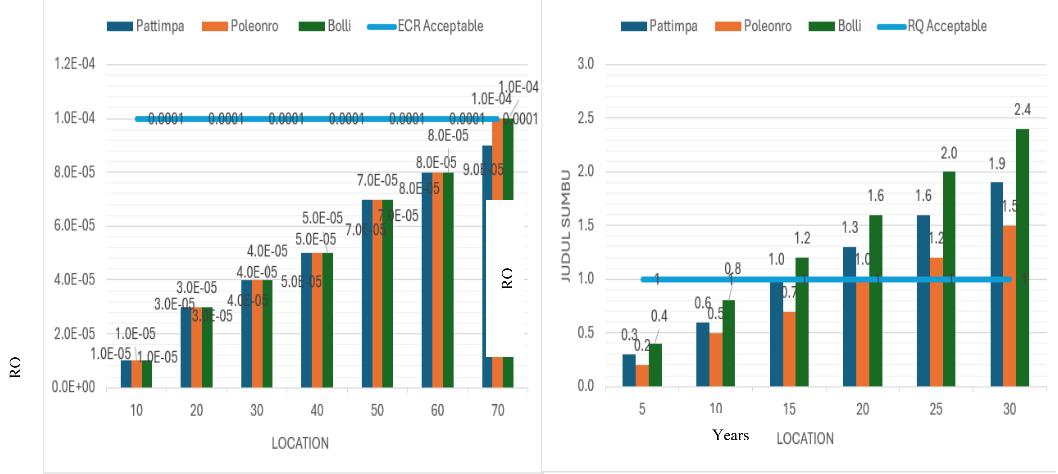


Figure 7: Carcinogenic (Excess Cancer Risk, ECR) and non-carcinogenic (Risk Quotient, RQ) risk estimates for hexavalent chromium (Cr VI) exposure across varying exposure durations among respondents in Pattimpa, Poleonro, and Bolli Villages, Indonesia, 2025

For Cr VI exposure, the carcinogenic risk (ECR) values were under tolerable thresholds ($\leq 10^{-4}$) across all villages, indicating no substantial carcinogenic risk. Nonetheless, the non-carcinogenic risk assessment indicated that RQ values were above 1 in multiple cases, especially with extended exposure durations. This signifies a potential danger of detrimental health effects, including possibly neurological consequences, linked to prolonged exposure to Cr VI (Figure 7).

DISCUSSION

Concentration of Heavy Metals Cadmium (Cd) and Chromium (Cr) VI

The deterioration of groundwater quality is frequently signaled by the presence of heavy metals, notably cadmium (Cd) and hexavalent chromium (Cr VI), primarily stemming from anthropogenic activities including industrial discharges, landfill leachate, overuse of fertilizers, and domestic wastewater. Although many heavy metals are necessary in low quantities for normal physiological functions, increased levels can be poisonous and present significant health hazards. These dangers are exacerbated by their propensity to bioaccumulate in biological tissues over time, resulting in prolonged health consequences [21]. Cadmium (Cd) and chromium (Cr) are recognized for their significant toxicity, capacity to deteriorate water quality, disrupt ecological equilibrium, and pose risks to human health, particularly upon entering food chains or potable water sources [22].

The examination of groundwater samples from 15 wells in Pattimpa, Poleonro, and Bolli Villages revealed disparate concentrations of cadmium (Cd) and chromium VI (Cr VI). Cadmium levels ranged from 0.001 to 0.002 mg/L, remaining beneath the maximum allowable limit of 0.003 mg/L established by the Indonesian Ministry of Health Regulation No. 2 of 2023. This signifies that Cd pollution in the studied area remains within acceptable limits. Comparable results have been observed in agricultural areas, where cadmium in groundwater is frequently linked to agricultural practices. Kumar [23] documented Cd concentrations ranging from 0.00276 to 0.00684 mg/L in groundwater adjacent to rice growing areas, whereas Zhang [24] identified Cd in the majority of groundwater samples from rural agricultural regions by Atomic Absorption Spectrophotometry (AAS).

Conversely, Cr VI values varied between 0.0079 and 0.020 mg/L, with some samples surpassing the regulation limit of 0.01 mg/L. The maximum concentration was documented in Poleonro Village at 0.021 mg/L. The findings indicate that some groundwater sources fail to comply with drinking water quality criteria and may present health hazards to the local populace. Prolonged exposure to Cr VI has been associated with numerous health complications, including dermatological conditions, respiratory problems, and carcinogenic effects [25]. In aquatic environments, chromium can disrupt metabolic functioning by blocking enzymes essential for normal biological processes [26].

The occurrence and dispersion of heavy metals in groundwater are influenced by both natural factors and anthropogenic activity. Agricultural methods, particularly the extensive application of phosphate fertilizers with cadmium impurities, are regarded as a significant source of contamination [27]. Excessive application of nitrogen fertilizers can reduce soil pH, thereby enhancing cadmium mobility. Topography influences runoff, with inclined terrain enabling drainage from agricultural regions onto adjacent communities [28]. Moreover, groundwater flow patterns affect the dispersion of contaminants, with wells situated nearer to agricultural areas frequently exhibiting elevated amounts [29]. The link among metals such as Cd, Co, Ni, and Cr suggests common anthropogenic sources, including fertilizers, livestock waste, and geological minerals [30]. Moreover, chromium occurs in many oxidation states, with Cr VI exhibiting greater mobility, solubility, and toxicity compared to Cr III, hence posing a greater risk to environmental and human health [31].

Body Weight (Wb)

Body weight is a critical factor in environmental health risk assessment as it directly influences the calculation of individual exposure doses. Anthropometric variables, especially body weight, affect the internal dosage received; persons with greater body weight often experience a lower dose intensity than those with lesser body weight [32]. The body weight of respondents in this study varied from 14.3 kg to 87.3 kg, with a mean of 58.7 kg. This average is below the standard adult body weight of 70 kg established by the US EPA but aligns with the average body weight figures recorded for Asian people, which are roughly 55 kg [33].

Body weight is affected by various factors, including dietary practices, lifestyle choices, cultural norms, hormonal circumstances, and environmental effects. Individuals with greater body weight may ingest larger quantities of water; nevertheless, their relative risk of exposure is frequently diminished due to dilution effects and the sequestration of pollutants in adipose tissue [34]. Conversely, those with lower body weight are more vulnerable to toxic consequences, as pollutants can more easily affect essential organs. Prior studies have underscored the significance of body weight in assessing exposure hazards, especially for heavy metals such as cadmium and chromium [35–37].

Intake Rate

The intake rate denotes the daily volume of water consumed and is a critical element in assessing exposure to pollutants. This study observed daily water intake varying from 1 to 2.5 L/day, with a mean of 2 L/day. In the research area's tropical climate, where numerous individuals engage in agricultural labor amidst elevated temperatures and humidity, water consumption is typically substantial. Prior research has indicated typical consumption levels of 3.45 ± 2.0 L/day in comparable environments, surpassing the standard reference amount of 2 L/day advised by the US EPA [38].

Consumption of water is a principal route by which environmental pollutants infiltrate the human body. The World Health Organization (WHO) often employs a standard intake value of 2 L/day in risk evaluations [39]. Elevated water consumption correlates directly with heightened exposure to pollutants, as demonstrated by Wang et al. [40], who indicated that larger intake volumes result in more heavy metal buildup and augmented health concerns.

Exposure Frequency

Exposure frequency denotes the annual number of days an individual encounters a particular contaminant and is crucial for calculating cumulative exposure. This study indicated that exposure frequency varied from 360 to 365 days annually, with a mean of 365 days, surpassing the US EPA recommended limit of 350 days per year. This signifies ongoing exposure, as groundwater is the principal supply of drinking water for the population. An elevated frequency of exposure heightens the probability of cumulative toxic effects, particularly for enduring pollutants like cadmium and chromium VI. Ongoing daily consumption may lead to bioaccumulation and prolonged health consequences. Prior research has similarly demonstrated that increased exposure frequency markedly heightens health hazards linked to environmental pollutants [41,42].

Exposure Duration

The deleterious effects of heavy metals are significantly determined by the concentration level and the length of exposure. The period of exposure in this study varied from 2 to 32 years, with a mean of 13 years. The US EPA posits that lifetime exposure scenarios often span 5–30 years for non-carcinogenic effects and 10–70 years for carcinogenic consequences [43]. Under prevailing exposure conditions, values of Cd and Cr VI were predominantly within permissible thresholds. Nonetheless, when evaluated throughout a lifetime, Cr VI exhibited possible health hazards, especially in carcinogenic evaluations, whereas Cd stayed within acceptable thresholds. The data suggest that prolonged exposure is essential in assessing health risk levels.

Intake

Intake denotes the quantity of pollutant entering the body per unit of body weight per day. The calculation is dependent on multiple variables, including contaminant concentration, intake rate, exposure frequency, exposure duration, body weight, and average time. The findings demonstrated that the carcinogenic intake values for Cd, at present exposure settings, were comparatively low and beneath the Slope Factor (SF) threshold, indicating tolerable risk levels. Likewise, Cr VI intake values were similarly beneath the SF standard. The non-carcinogenic intake values for both cadmium and chromium VI were below the Reference Dose (RfD), signifying an acceptable risk under current conditions.

Projections for lifetime exposure indicated a progressive rise in intake values over time. Intake levels of both Cd and Cr VI escalated with prolonged exposure duration, especially in Pattimpa and Bolli Villages. These data affirm that intake is significantly affected by exposure variables like concentration, intake rate, frequency, and duration. Prior research has consistently indicated analogous correlations between exposure factors and heightened health risks [44–49].

Limitations

This study has significant drawbacks. The cross-sectional approach restricts the capacity to deduce causal links between exposure and health outcomes. The low sample size and geographic scope may diminish the generalizability of the results. The exposure evaluation relied on contemporary measures and self-reported data, which may introduce variability and potential recall bias. Additionally, alternative exposure pathways, including dietary consumption and occupational exposure, were excluded from the analysis. Notwithstanding these limitations, the study provides significant insights on groundwater contamination and its related health hazards.

CONCLUSION

This study illustrates the possible environmental health hazards associated with exposure to cadmium (Cd) and hexavalent chromium (Cr VI) in groundwater inside villages in Ponre District. The participants' ages varied from 4 to 60 years, with body weights spanning from 14.3 to 87.3 kg, and the majority were female (61%). The examination of drinking water revealed that cadmium concentrations were below acceptable limits, whereas chromium VI levels surpassed regulatory norms in multiple areas. Exposure patterns revealed a prolonged and consistent reliance on groundwater, with exposure durations extending up to 32 years, daily water consumption varying between 1 to 2.5 liters, and exposure frequency occurring nearly every day. Risk assessment findings indicated that Cd exposure correlated with an elevated carcinogenic risk in Pattimpa Village (ECR > 10^{-4}), whereas Cr VI exposure presented a heightened non-carcinogenic risk in Poleonro Village (RQ ≥ 1). These findings underscore the necessity of continuous groundwater surveillance and the execution of specific mitigation strategies to diminish exposure and protect public health.

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Competing interests

The authors declare no competing interests.

Authors’ contributions

All authors have reviewed and endorsed the final version of this manuscript.

REFERENCES

1. Arunanidhi D, Aravinthasamy P, Subramani T, Kumar D, Venkatesan G. Chromium contamination in groundwater and Sobol sensitivity model-based human health risk evaluation from the leather tanning industrial region of South India. Environ Res. 2021;199:111238. doi:10.1016/j.envres.2021.111238.

2. Babich R, Craig E, Muscat A, Disney J, Farrell A, Silka L, et al. Defining drinking water metal contaminant mixture risk by coupling zebrafish behavioral analysis with citizen science. Sci Rep. 2021;11(1):17303. doi:10.1038/s41598-021-96244-4.

3. Nawaz H, Anwar-Ul-Haq M, Akhtar J, Arfan M. Cadmium, chromium, nickel and nitrate accumulation in wheat using wastewater irrigation and health risks assessment. Ecotoxicol Environ Saf. 2021;208:111685. doi:10.1016/j.ecoenv.2020.111685.

4. Rauf AU, Mallongi A, Daud A, Hatta M, Astuti RDP. Ecological risk assessment of hexavalent chromium and silicon dioxide in well water in Maros Regency, Indonesia. Gac Sanit. 2021;35(S1):S4–S8. doi:10.1016/j.gaceta.2020.12.002.

5. Vasseghian Y, Almomani F, Dragoi EN. Health risk assessment induced by trace toxic metals in tap drinking water. Chemosphere. 2022;286(Pt2):131821. doi:10.1016/j.chemosphere.2021.131821.

6. Kazemi A, Esmaeilbeigi M, Sahebi Z, Ansari A. Health risk assessment of total chromium in the qanat as historical drinking water supplying system. Sci Total Environ. 2022;807(Pt2):150795. doi:10.1016/j.scitotenv.2021.150795.

7. Xu H, Zhang H, Qin C, Li X, Xu D, Zhao Y. Groundwater Cr(VI) contamination and remediation: A review from 1999 to 2022. Chemosphere. 2024;360:142395. doi:10.1016/j.chemosphere.2024.142395.

8. Lin H, Luo X, Yu D, He C, Cao W, He L, et al. Risk assessment of As, Cd, Cr and Pb via the consumption of seafood in Haikou. Sci Rep. 2024;14:19549. doi:10.1038/s41598-024-70409-3.

9. Sanad H, Moussadek R, Dakak H, Zouahri A, Oueld Lhaj M, Mouhir L. Ecological and health risk assessment of heavy metals in groundwater within an agricultural ecosystem using GIS and multivariate statistical analysis. Water. 2024;16(17):2417. doi:10.3390/w16172417.

10. Alharbi T, El-Sorogy AS, Al-Kahtany K. Distribution and comprehensive risk evaluation of Cr, Cd, Fe, Zn and Pb from Al Lith coastal seawater, Saudi Arabia. Water. 2024;16(13):1923. doi:10.3390/w16131923.

11. Kumar S, Maurya NS. Analysis of heavy metal contamination in groundwater and associated probabilistic human health risk assessment using Monte Carlo simulation. J Water Health. 2025;23(5):630-647. doi:10.2166/wh.2025.348.

12. Krasnopyorova M, Gorlachev I, Kharkin P, Severinenko M, Zheltov D. Study of the trace element composition of drinking water in Almaty City and human health risk assessment. Int J Environ Res Public Health. 2025;22(4):560. doi:10.3390/ijerph22040560.

13. Ahmad T, Sa’ed HZ, Murad MA. Regional and national trends in tuberculosis research in SAARC countries: post-COVID bibliometric analysis. Int J Environ Res Public Health. 2024;21:1220. doi:10.3390/ijerph21091220.

14. Li Y, Zhang Q, Chen J, Wang H. Heavy metal contamination and human health risk assessment in groundwater of industrial regions. Environ Pollut. 2023;318:120839. doi:10.1016/j.envpol.2023.120839.

15. Zhang L, Liu Y, Wang X, Zhao J. Assessment of cadmium exposure and associated health risks in drinking water systems. Environ Sci Pollut Res. 2023;30:45871-45882. doi:10.1007/s11356-023-25938-5.

16. Chen Y, Huang Y, Liu H, Xu X. Spatial distribution and risk evaluation of heavy metals in groundwater of agricultural regions. Sci Total Environ. 2023;858:159725. doi:10.1016/j.scitotenv.2022.159725.

17. Wang J, Li H, Liu Z, Zhou Y. Human health risk assessment of groundwater contaminated by heavy metals in mining areas. Ecotoxicol Environ Saf. 2022;230:113171. doi:10.1016/j.ecoenv.2021.113171.

18. Li X, Chen Y, Zhao S, Wang Y. Source identification and health risk assessment of heavy metals in groundwater. Environ Geochem Health. 2022;44:1983-1998. doi:10.1007/s10653-021-01082-5.

19. Singh P, Singh AK, Singh VK. Health risk assessment of heavy metals in drinking water sources of rural India. Environ Monit Assess. 2022;194:297. doi:10.1007/s10661-022-09954-3.

20. Gao Y, Wang J, Zhang C. Distribution and risk assessment of heavy metals in groundwater in China. Chemosphere. 2022;286:131742. doi:10.1016/j.chemosphere.2021.131742.

21. Zhang X, Sun Y, Yang L. Groundwater contamination by cadmium and chromium in industrial areas. Environ Res. 2022;204:112017. doi:10.1016/j.envres.2021.112017.

22. Li P, Qian H, Wu J. Hydrogeochemical characteristics and human health risk of groundwater contaminants. Sci Total Environ. 2021;770:145324. doi:10.1016/j.scitotenv.2021.145324.

23. Kumar M, Ramanathan A, Tripathi R. Environmental risk assessment of heavy metals in groundwater systems. Environ

Earth Sci. 2021;80:356. doi:10.1007/s12665-021-09645-2.

24. Zhang H, Li Y, Chen Z. Cadmium exposure and kidney dysfunction risk in rural populations. Environ Sci Pollut Res. 2021;28:33814-33823. doi:10.1007/s11356-021-13214-6.

25. Liu Y, Chen H, Sun J. Chromium contamination in drinking water and associated health risks. Int J Environ Res Public Health. 2021;18:11430. doi:10.3390/ijerph182111430.

26. Zhao X, Zhang Y, Li J. Heavy metals in groundwater and potential human health risks. Environ Pollut. 2021;287:117645. doi:10.1016/j.envpol.2021.117645.

27. Chen L, Wang T, Wang Y. Assessment of drinking water contamination and associated health impacts. Water Res. 2021;189:116667. doi:10.1016/j.watres.2020.116667.

28. Gupta N, Yadav KK, Kumar V. A review of heavy metal contamination in groundwater and human health risk. Sci Total Environ. 2021;786:147441. doi:10.1016/j.scitotenv.2021.147441.

29. He X, Li P, Wu J. Groundwater contamination and health risk assessment in agricultural regions. Environ Sci Pollut Res. 2023;30:11982-11995. doi:10.1007/s11356-022-23245-4.

30. Zhang W, Yang X, Wang Y. Cadmium contamination in groundwater and ecological risk assessment. Chemosphere. 2023;319:137924. doi:10.1016/j.chemosphere.2023.137924.

31. Liu Z, Zhao L, Chen Y. Assessment of heavy metal pollution in groundwater using multivariate analysis. Water Res. 2023;234:119759. doi:10.1016/j.watres.2023.119759.

32. Yang H, Liu Q, Sun Y. Source identification and risk evaluation of chromium in groundwater systems. Environ Pollut. 2023;327:121569. doi:10.1016/j.envpol.2023.121569.

33. Wang S, Zhang L, Li Q. Health risk assessment of groundwater contaminated by heavy metals in rural communities. Environ Res. 2024;240:117324. doi:10.1016/j.envres.2024.117324.

34. Zhao H, Li Z, Zhang T. Human exposure to cadmium through drinking water and health implications. Sci Total Environ. 2024;906:167387. doi:10.1016/j.scitotenv.2024.167387.

35. Chen X, Liu H, Wang Q. Environmental distribution and risk evaluation of chromium in groundwater. Chemosphere. 2024;354:141566. doi:10.1016/j.chemosphere.2024.141566.

36. Zhang Y, Li M, Wang R. Assessment of groundwater quality and heavy metal contamination risk. Environ Monit Assess. 2024;196:745. doi:10.1007/s10661-024-12257-7.

37. Li J, Sun H, Wang L. Groundwater pollution by toxic metals and associated health risks in agricultural areas. Sci Total Environ. 2025;914:169852. doi:10.1016/j.scitotenv.2025.169852.

38. Chen P, Liu X, Zhang S. Human health risk assessment of toxic metals in groundwater systems. Environ Pollut. 2025;344:122657. doi:10.1016/j.envpol.2025.122657.

39. Kumar R, Singh AK, Singh P. Spatiotemporal assessment of heavy metal contamination in groundwater. Chemosphere. 2025;370:143247. doi:10.1016/j.chemosphere.2025.143247.

40. Wang Z, Li H, Zhao Y. Environmental health risk assessment of heavy metals in drinking water resources. Int J Environ Res Public Health. 2026;23:1021. doi:10.3390/ijerph23031021.

41. Wu J, Li P, Qian H, Duan Z. Groundwater quality and health risk assessment of heavy metals in arid and semi-arid

regions. Sci Total Environ. 2021;770:145332. doi:10.1016/j.scitotenv.2021.145332.

42. Adimalla N, Qian H. Groundwater chemistry, distribution and potential health risk appraisal of nitrate and heavy metals in semi-arid region. Chemosphere. 2021;267:128886. doi:10.1016/j.chemosphere.2020.128886.

43. Qasemi M, Afsharnia M, Zarei A, Farhang M, Allahdadi M, Darvishi Cheshmeh Soltani R. Health risk assessment of heavy metals in groundwater sources. J Environ Health Sci Eng. 2022;20:179–189. doi:10.1007/s40201-021-00747-0.

44. He S, Wu J, Li P. Human health risk assessment of groundwater contamination using Monte Carlo simulation. Environ Sci Pollut Res. 2022;29:30166-30179. doi:10.1007/s11356-021-17663-9.

45. Kumar V, Sharma A, Pandita S, Bhardwaj R, Thukral AK, Cerda A. A global meta-analysis of heavy metal contamination in groundwater and associated health risk. Sci Total Environ. 2022;806:150629. doi:10.1016/j.scitotenv.2021.150629.

46. Zhang Y, Wu J, Xu B. Human health risk assessment of groundwater contaminated by heavy metals in mining areas of China. Environ Geochem Health. 2022;44:4151-4165. doi:10.1007/s10653-022-01235-6.

47. Li Z, Ma Z, Kuijp TJ, Yuan Z, Huang L. A review of soil and groundwater contamination by heavy metals and associated health risk assessment. Sci Total Environ. 2023;868:161658. doi:10.1016/j.scitotenv.2023.161658.

48. Chen Y, Li F, Liu Q. Assessment of heavy metal contamination and human health risks in groundwater in agricultural areas. Environ Pollut. 2023;316:120512. doi:10.1016/j.envpol.2022.120512.

49. Wang L, Zhang X, Chen H. Source apportionment and health risk assessment of heavy metals in groundwater using multivariate statistical methods. Chemosphere. 2023;317:137824. doi:10.1016/j.chemosphere.2023.137824