A Systematic Review of Potential Health Risk Assessments for Nitrate Contamination in Different Water Resources in India

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Running title: Nitrate Contamination and Potential Health Risk Assessment in Indian Water: A Systematic Review

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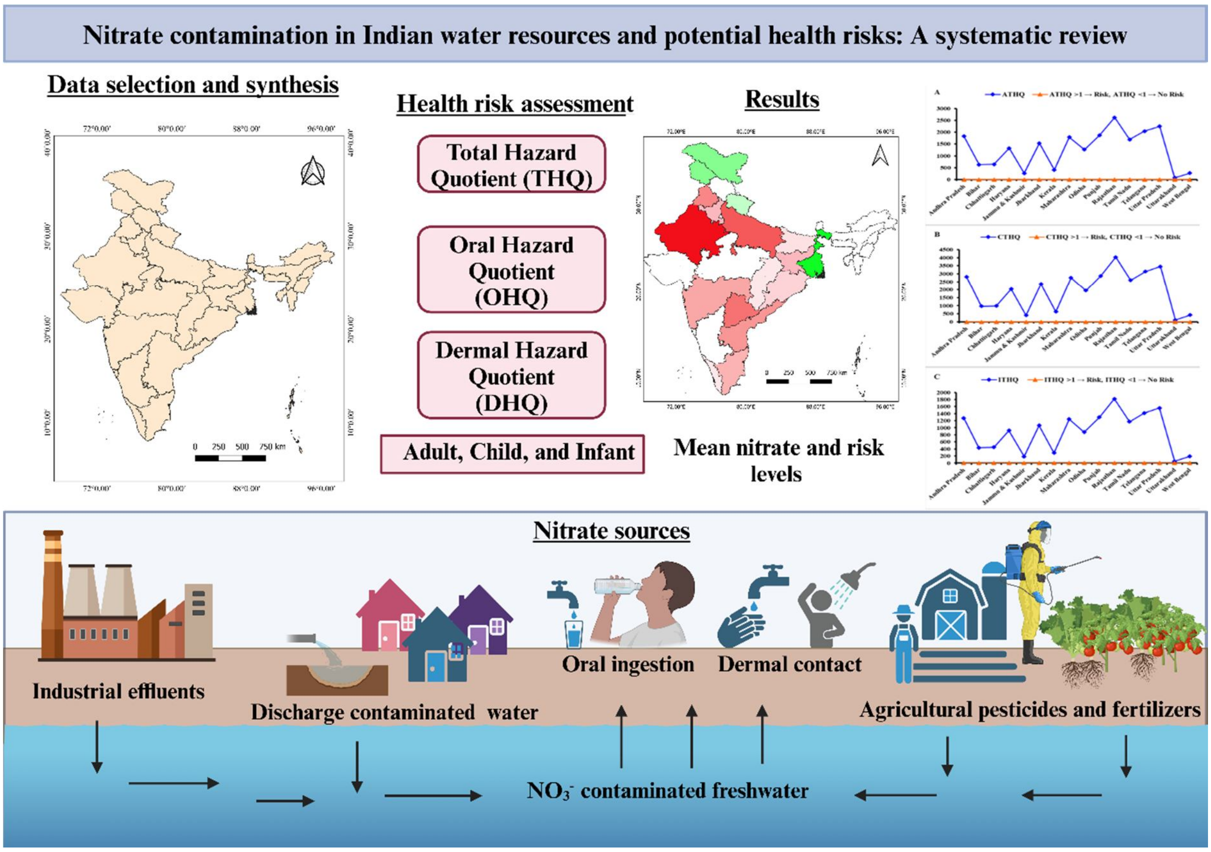
Abstract

Nitrate contamination of water resources has emerged as a critical public health issue in India. This study systematically reviews nitrate contamination in groundwater and surface water across 16 Indian states via the PRISMA guidelines. The study integrates data from 90 studies published between 2014 and 2024, offering the first meta-analysis that comprehensively evaluates nitrate distribution and associated health risks across diverse regions in India. The results revealed significant regional variations in nitrate concentrations, with states such as Rajasthan exhibiting high mean nitrate levels (80.43 mg L^{-1}), exceeding the BIS permissible limit of 45 mg L^{-1}. Minimum nitrate contamination was detected in Uttarakhand (2.21 mg L^{-1}). A comprehensive health risk assessment based on the US EPA model revealed that noncarcinogenic risk, calculated by the total hazard quotient (THQ), exceeded the acceptable limit (>1) for all age groups. The THQ was highest in children, followed by adults and infants, indicating a high noncarcinogenic risk. This study emphasizes oral ingestion as the dominant exposure route, whereas dermal absorption poses minimal risks (DHQ <1). These findings underscore the need for targeted interventions in high-risk states, including improved agricultural practices, enhanced wastewater management, and community-centric water quality monitoring. This review supports informed policymaking and aligns with sustainable development goals (SDG 3 and SDG 6) by addressing critical knowledge gaps and advocating for clean water and public health protection.

***Keywords*:** Groundwater; Health risk assessment; Nitrate contamination; SDG 3; SDG 6; Surface water



Graphical abstract

1 Introduction

Nitrate contamination of water resources is a growing environmental and public health concern worldwide (Abascal et al. 2022; Gutiérrez et al. 2018). Nitrate, a stable and water-soluble nitrogen compound (Li et al. 2019), enters aquatic systems through natural processes and anthropogenic activities (Gutiérrez et al. 2018; Verma et al. 2023). These include the extensive use of nitrogen-based fertilizers, improper disposal of organic waste, and untreated wastewater from urban and industrial sources (Shukla and Saxena 2020). Over the years, these activities have led to elevated nitrate levels in surface water and groundwater, with substantial implications for human health (Akhtar et al. 2021). Long-term exposure to elevated nitrate levels in drinking water has been associated with serious health concerns (Ward et al. 2018; WHO 2017). These include methemoglobinemia, also known as "blue-baby syndrome," which can be particularly harmful to infants (Rahman et al. 2021). Furthermore, it has also been linked to an increased risk of developing thyroid disorders and various types of cancers (Picetti et al. 2022; Ward et al. 2018). Despite these implications, the full extent of nitrate pollution and its potential health risks across Indian regions remain inadequately addressed.

India's diverse climatic conditions and intensive agricultural practices have contributed to varying degrees of nitrate pollution across states (Rahman et al. 2021). In different regions of India, elevated nitrate levels have been detected in groundwater samples (Verma et al. 2023). For example, levels reached 2000 mg L^{-1} in Muktsar and Haryana (Pant et al. 2020) and 700 mg L^{-1} in southern Haryana (Kumari and Rai 2020). The Bureau of Indian Standards (BIS) and the World Health Organization (WHO) have established guidelines on safe nitrate concentrations in water for human use, aiming to prevent short-term health effects such as methemoglobinemia and thyroid issues (BIS 2012; WHO 2017). However, these recommended limits are frequently exceeded in freshwater sources worldwide, including both developed (Kwon et al. 2021; Nakagawa et al. 2021) and developing countries (Panneerselvam et al. 2023; Ramalingam et al. 2022; Su et al. 2021). Therefore, analysing nitrate contents and evaluating health risk assessments are essential to ensure safe water supplies and public health.

Previous studies on nitrate contamination have focused primarily on localized assessments, which are often restricted to specific regions or water types (Table 1). These fragmented efforts limit the understanding of spatial and demographic contamination patterns, creating a significant research gap. Furthermore, while health risk assessments have been conducted in isolated studies (Khan et al. 2021; Panneerselvam et al. 2023; Ramalingam et al. 2022; Richards et al. 2022), a comprehensive synthesis that integrates findings across states is still lacking. The need for a unified, systematic analysis that evaluates nitrate contamination levels, identifies high-risk areas, and assesses potential health risks across different age groups is urgent.

Therefore, this study addresses these gaps through a systematic review and meta-analysis of nitrate contamination in Indian water resources, focusing on its distribution, sources, and associated health risks (Table 1). By integrating data from recent studies conducted between 2014 and 2024, this study provides an in-depth examination of nitrate pollution trends. It evaluates the noncarcinogenic risks for infants, children, and adults. The study employs key metrics such as chronic daily intake (CDI), the oral hazard quotient (OHQ), and the total hazard quotient (THQ) to quantify risks from oral and dermal exposure pathways. Unlike previous studies, this work offers a holistic perspective, revealing regional disparities and identifying priority areas for intervention.

The findings of this study are particularly significant in the context of global sustainable development initiatives. This research contributes directly to the United Nations Sustainable

Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), by advancing knowledge on water quality challenges and promoting sustainable water management. Furthermore, it aligns with SDG 3 (Good Health and Well-being) by identifying health risks associated with nitrate exposure and promoting public health protection, especially for vulnerable populations. The primary objectives of this study are to (a) assess nitrate concentrations from published research across various Indian water resources, (b) identify the predominant anthropogenic and natural sources of nitrate pollution, and (c) evaluate the noncarcinogenic health risks posed by nitrate exposure in different age groups (infants, children, and adults). By addressing these objectives, this study provides a robust evidence base to inform policymakers, researchers, and stakeholders, enabling them to design targeted interventions for sustainable water resource management and public health protection in India.

Table 1 Comparison of the present study with studies from other regions

Reference	Key findings	Significance of our study
(Lin et al. 2023)	This study conducted a systematic review and meta-analysis to examine the effects of nitrate contamination in drinking water on reproductive health and birth outcomes. It analysed global data to identify correlations between nitrate exposure and complications such as low birth weight, preterm birth, and congenital abnormalities.	Our study provides a more comprehensive assessment of nitrate contamination across different water resources in India. This study also calculated the potential health risk assessment in different age groups. We evaluate its impact on broader health concerns beyond reproductive health, offering region-specific insights and policy recommendations.
(Picetti et al. 2022)	This systematic review and meta-analysis explored the link between nitrate and nitrite contamination in drinking water and cancer risk. The study compiled data from multiple regions to assess the potential carcinogenic effects of nitrate ingestion.	Our study evaluates non-carcinogenic health risks associated with nitrate contamination, including ingestion and dermal effects. Additionally, we examine nitrate levels in various water sources, not just drinking water, to provide a more holistic risk assessment.
(Abascal et al. 2022)	This study presents a global-scale diagnosis of nitrate pollution in groundwater, emphasizing sources, distribution, and associated risks. It also reviews existing nitrate removal technologies, highlighting their efficiency and applicability.	Our study differs by focusing on India, providing localized data on nitrate contamination levels and their potential health risks. This makes our findings more relevant to policymakers addressing India's water quality challenges.
(Essien et al. 2022)	This systematic review and meta-analysis investigate the link between nitrate levels in drinking water and cancer risks, particularly gastrointestinal cancers. The study compiles epidemiological data to assess the long-term health effects of nitrate exposure.	Our study evaluates a broader spectrum of health risks. Additionally, our study assesses nitrate contamination in different types of water resources (not just drinking water). It considers its implications through ingestion and dermal exposure pathways in infants, children, and adults.
(Rawat et al. 2022)	This study systematically reviews and models groundwater nitrate contamination caused by agricultural activities. It examines how agricultural runoff contributes to nitrate pollution and discusses potential mitigation strategies.	Our study takes a more comprehensive approach by considering multiple contamination sources, including industrial and domestic activities. We also assess the overall health risks of nitrate contamination in various water resources, offering a broader perspective.

2 Methodology

2.1. Study area

The study included different states of India. India is located in South Asia and is surrounded by the Indian Ocean to the south, the Arabian Sea to the southwest and the Bay of Bengal to the southeast. It is located north of the equator between latitudes 8°4' N and 37°6' N and longitudes 68°7' E and 97°25' E, covering a total area of 3,287,263 sq. km. It consists of 28 states and eight union territories. We included 90 studies from 16 different states of India. These states included Jammu and Kashmir, Andhra Pradesh, Rajasthan, Haryana, Punjab, Telangana, Tamil Nadu, West Bengal, Kerala, Bihar, Chhattisgarh, Jharkhand, Uttar Pradesh, Uttarakhand, Odisha and Maharashtra (Figure 1).

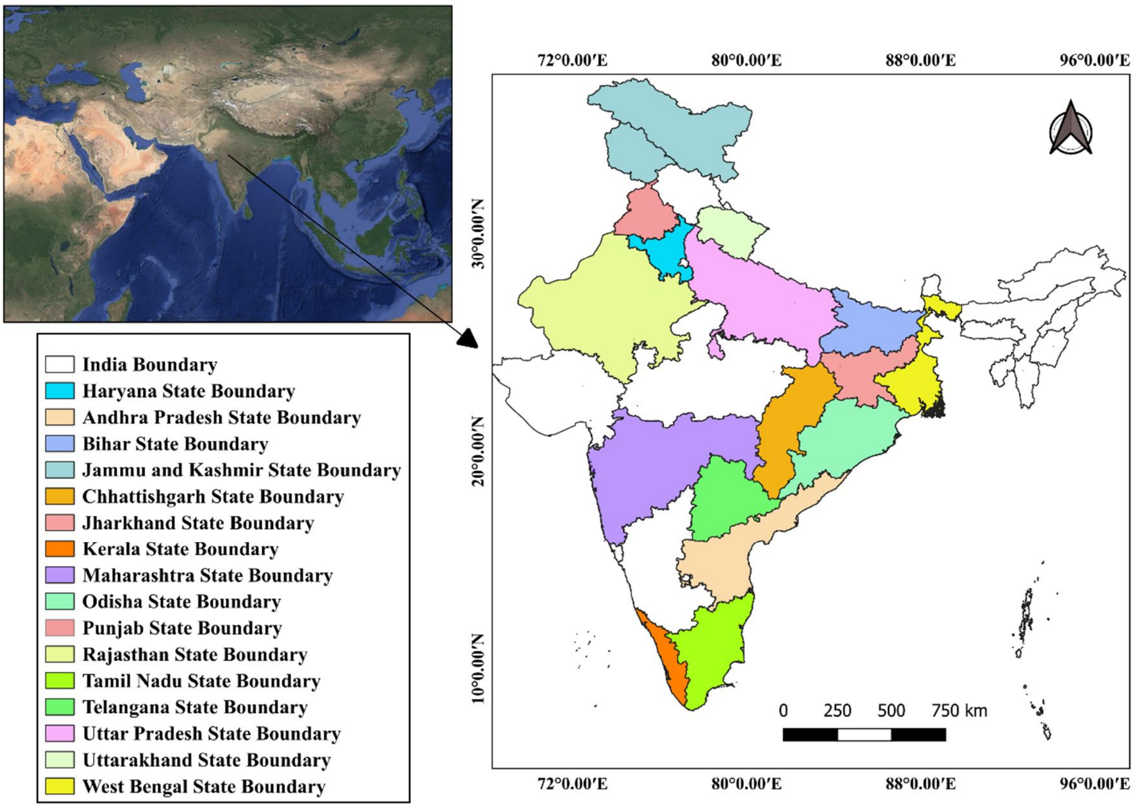


Fig. 1 The study area showing different states of India included in the study

2.2. Search strategy

A systematic review was performed following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Moher et al. 2010) (Figure 2). We searched peer-reviewed literature to find studies that reported potential health risk assessments for nitrate contamination in different water resources in India. We systematically searched the following databases: ScienceDirect, Google Scholar, and PubMed from 1 January 2014 to 1 January 2024. Several keywords were used: “Nitrate contamination”, AND “groundwater”, AND “drinking water”, AND “surface water”, “Nitrate pollution” AND “India” AND (“Jammu and Kashmir” OR “Andhra Pradesh” OR “Rajasthan” OR “Haryana” OR “Punjab” OR “Telangana” OR “Tamil Nadu” OR “West Bengal” OR “Kerala” OR “Bihar” OR “Chhattisgarh” OR “Jharkhand” OR “Uttar Pradesh” OR “Uttarakhand” OR “Odisha” OR “Maharashtra”). This was done for each Indian state. The search strategy was meticulously crafted in ScienceDirect, employing the same search terms and making the necessary modifications to integrate seamlessly with other databases.

2.3. Inclusion and exclusion criteria

The inclusion criteria used for selecting research papers were as follows: 1) text papers in the English language, 2) articles that included the average or mean value of nitrate, and 3) articles that included nitrate concentrations in groundwater and surface water in India. 4) At least three studies from each state were included. We excluded books, theses, case reports, papers not published in English, papers that did not have nitrate concentrations and DOI numbers, papers older than the time period (2014-2024), and states with fewer than three studies.

2.4. Data extraction and synthesis

Descriptive studies that included nitrate concentrations in groundwater or surface water from different states in India were selected for data extraction. The following data were extracted from these studies: nitrate concentration in different types of water bodies, first author's name, year of publication, state, average concentration, and exposure assessment.

In the identification stage of the PRISMA model, 345 research articles were identified, as shown in Figure 2. Among the 345 articles, approximately 145 were duplicates. During screening, the titles and abstracts of 200 articles were reviewed, and 110 articles were excluded. Ninety research articles were accessed to determine eligibility for review. After the complete texts were read, ninety research articles were included on the basis of various inclusion criteria. The highest number of studies was from Telangana, 16 from Tamil Nadu, eight from Maharashtra, six each from Rajasthan and Uttar Pradesh, four each from Andhra Pradesh, Haryana and West Bengal, three each from Bihar, Chhattisgarh, Jammu and Kashmir, Jharkhand, Kerala, Odisha, Uttarakhand, and Punjab (Table S1; Figure 3). All recently published studies from 2014-2024 were included.

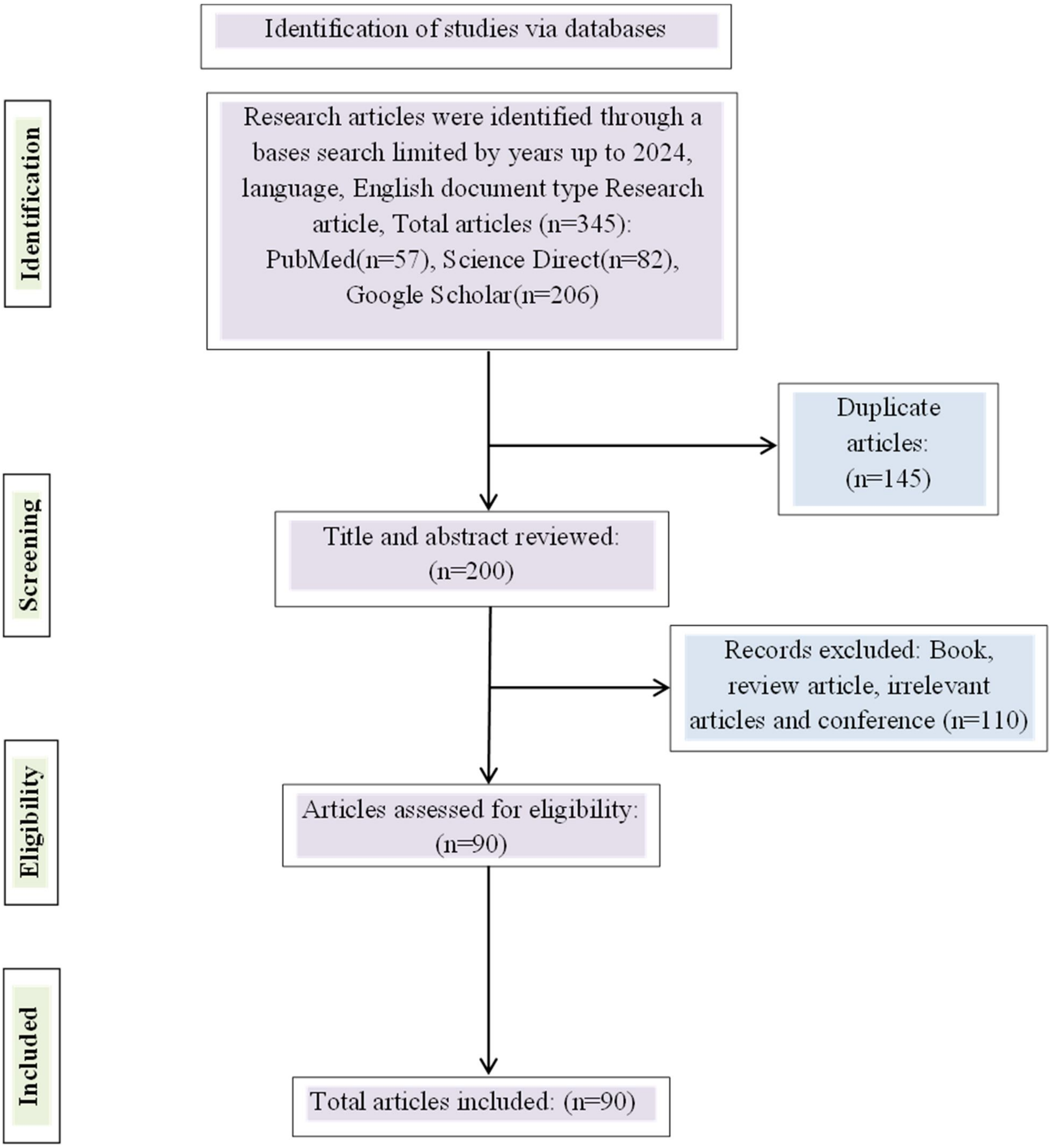


Fig. 2 Stages of the PRISMA methodology used to identify articles for review (Moher et al. 2010)

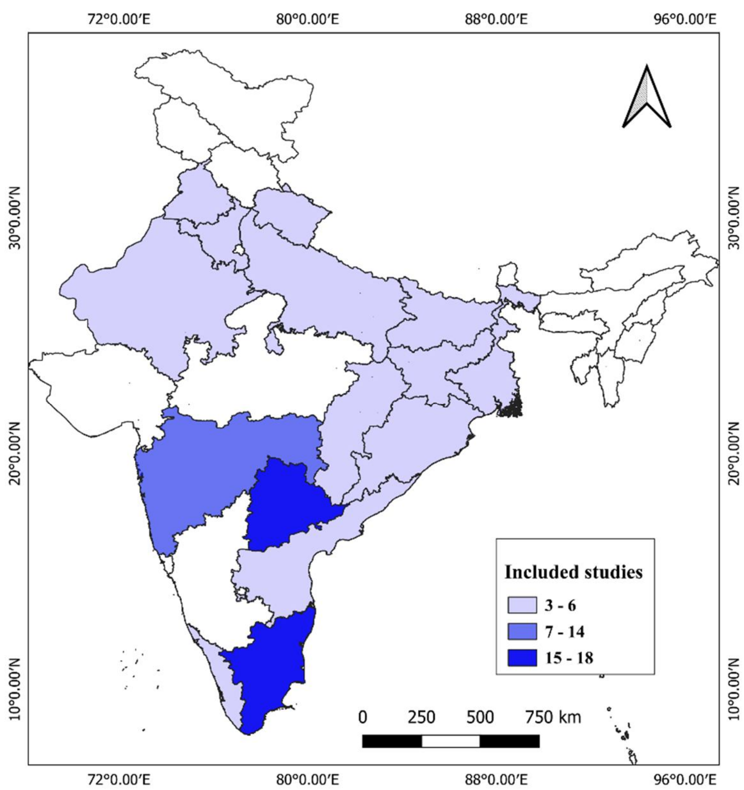


Fig. 3 Distribution of included published studies related to nitrate contamination in Indian water resources

2.5. Health risk assessment

Exposure to nitrate-contaminated water can pose various risks to human health. Humans can contact this contamination in two ways: the oral route (through drinking water consumption) and the dermal route (through skin exposure). The noncarcinogenic human health risk assessment (HHR) model developed by the United States Environmental Protection Agency (USEPA 1989) incorporates these two exposure pathways. The noncarcinogenic nitrate risk was calculated via the human health risk assessment model (Table 2). HHR was conducted for three population groups: adults, children, and infants. The HHR due to nitrate was estimated via the addition of hazard quotient (HQ) values for both the oral and dermal pathways (Adimalla et al. 2021; Mukherjee and Singh 2021; USEPA 1989) via the following equations (1) and (2):

$$\mathbf{CDI} = \frac{\mathbf{C \times IR \times ED \times EF}}{\mathbf{BW \times AT}} \qquad \mathbf{\ldots\ldots\ldots\ldots\ldots (1)}$$

where CDI is chronic daily intake (in mg/kg/day), which indicates the ingested quantity of nitrate; C is the concentration of nitrate (in mg L^{-1}); IR is the ingestion rate (in litres per day); EF is the exposure frequency (in days/year); ED is the exposure duration (in years); BW is the average body weight (in kg); and AT is the average time (in days).

2.5.1. Oral hazard quotient (OHQ)

The oral hazard quotient index (USEPA 1989, 2001) is calculated via equation (2):

$$\mathbf{OHQ} = \frac{\mathbf{CDI}}{\mathbf{RfD1}} \qquad \mathbf{\ldots\ldots\ldots\ldots\ldots (2)}$$

where OHQ is the oral hazard quotient, CDI is chronic daily intake (in mg/kg/day), and RfD1 is the oral reference dose of nitrate (in mg/kg/day) (Table 2).

2.5.2. Dermal hazard quotient (DHQ)

The chemical substances absorbed through the skin are expressed by calculating the dermally absorbed dose (DAD). It is calculated via the following equations (3) and (4):

$$\mathbf{DAD} = \frac{\mathbf{C \times Ki \times SA \times ED \times EF \times EV \times CF}}{\mathbf{BW \times AT}} \qquad \mathbf{\ldots\ldots\ldots\ldots\ldots (3)}$$

where C is the concentration of nitrate, Ki is the dermal absorption parameter (in cm/h), SSA is the skin surface area (in sq. cm), ED is the exposure duration (in years), EF is the exposure frequency (in days/year), EV is the bathing frequency (in baths/day), CF is the unit conversion factor, BW is the average body weight (in kg), and AT is the average exposure time (in days) (Table 2).

$$\mathbf{DHQ} = \frac{\mathbf{DAD}}{\mathbf{RfD2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(4)}$$

DHQ is the dermal hazard quotient, DAD is the dermally absorbed dose, and RfD2 is the dermal reference dose of nitrate.

2.5.3. Total hazard quotient (THQ)

The sum of HQ1 and HQ2 is used to calculate the THQ. The total hazard quotient reflects the collective health risk to a population. To calculate the THQ, equation (5) was used:

$$\mathbf{THQ = HQ1 + HQ2} \quad \ldots\ldots\ldots\ldots\ldots \mathbf{(5)}$$

If the THQ is less than one, it indicates that it is safe for the population; however, if the THQ is greater than one, it indicates adverse health risks (USEPA 1991, 2001).

2.6. Statistical analysis

The descriptive statistics, including the maximum, minimum, mean, and standard error of the mean (SEM), were calculated via IBM SPSS software. Analysis of variance (ANOVA), along with post hoc tests (Tukey and Duncan tests), was performed to identify significant differences ($p<0.05$) in the mean nitrate concentration across various Indian states.

Table 2 Parameters used to calculate the risk assessment of nitrate. Adapted from (Wagh et al. 2020).

Parameters	Description	Adults	Children	Infants	Unit	References
EF	Exposure frequency	365	-	-	Day	(USEPA 1989, 1991)
ED	Exposure duration	30	6	0.5		(Wagh et al. 2020)
IR	Ingestion rate	3000	1500	250	mL day^{-1}	(Vetrimurugan et al. 2017)
AT	Average exposure time	10,950	2190	182.5	Day	(Wagh et al. 2020)
BW	Average body weight	57.5	18.7	6.9	kg	(Wagh et al. 2020)
BH	Average body height	161.2	122.07	62.43	cm	(Wagh et al. 2020)
SA	Skin surface area	15683.8	8007.1	3419	cm^2	(Zhai et al. 2017)
EV	Bathing frequency	1	-	-	Time/day	(Yang et al. 2012)
CF	Unit conversion factor	0.002	-	-	L cm^{-3}	(Wagh et al. 2020)
Ki	Dermal absorption	0.001	-	-	cm h^{-1}	(Wagh et al. 2020)
RfD1	Oral reference dose for nitrate	1.6	-	-	mg kg^{-1} day^{-1}	IRIS (2012)
RfD2	Dermal reference dose for nitrate	0.8	-	-	mg kg^{-1} day^{-1}	(Yang et al. 2012)
C	Nitrate concentration in groundwater samples	-	-	-	mg L^{-1}	
HQ1	Oral hazard quotient	-	-	-	-	(USEPA 1991)
HQ2	Dermal hazard quotient	-	-	-	-	
THQ	Total hazard quotient	-	-	-	-	

3. Results and discussion

3.1. Nitrate contamination in different water sources

Approximately 90 research articles were included after the full texts were read on the basis of various inclusion criteria. The highest number of studies was from Telangana, followed by sixteen articles from Tamil Nadu, eight from Maharashtra, six each from Rajasthan and Uttar Pradesh, four each from Andhra Pradesh, Haryana and West Bengal, three each from Bihar, Chhattisgarh, Jammu and Kashmir, Jharkhand, Kerala, Odisha, Uttarakhand, and Punjab. All the studies included were recent, from 2014 to 2024. According to the WHO (World Health Organization), the permissible limit of nitrate in drinking water is 10 mg L^{-1} (WHO 2017). According to the Bureau of Indian Standards, the acceptable limit of nitrate in drinking water is 45 mg L^{-1} (BIS 2012). The descriptive analysis revealed significant variations in nitrate concentrations across different regions of India. The mean nitrate levels, along with the standard error of the mean (SEM), minimum, and maximum concentrations, are presented in Table 3.

In all the studies, water sources in thirteen out of the fifteen states were highly contaminated with nitrate, particularly with respect to both the WHO and BIS acceptable values (Table 3). Among these studies, the surface water of Rajasthan was reported to be highly contaminated with nitrate. The mean concentration was 80.43 mg $L^{-1,}$ with minimum and maximum values ranging from 37.2 mg L^{-1} and 181.19 mg L^{-1}, respectively. These values were above the acceptable values concerning BIS regulatory standards. In most studies of Rajasthan, the primary reason for this nitrate pollution was anthropogenic activities. Anthropogenic activities, such as agricultural fertilizer leaching, inappropriate sewage disposal, and industrial and domestic waste, may increase the nitrate concentration in water sources (Jandu et al. 2021). However, in Uttar Pradesh, the mean nitrate concentration was reported to be 68.90 mg L^{-1}, with a peak value of 196.96 mg L^{-1}. These values far surpassed the BIS standards. A study from the Gautam Budh Nagar district of Uttar Pradesh reported a high mean value (196.96 mg L^{-1}) of nitrate in groundwater attributed to poor sanitation conditions and improper disposal of animal and human excreta (Ahamad et al. 2018). In Telangana, the results revealed a mean nitrate concentration of 62.68 mg L^{-1}, which was above the acceptable BIS limit.

Moreover, the minimum and maximum concentrations were reported as 0.58 mg L^{-1} and 155.93 mg L^{-1}, respectively. Among all eighteen studies from Telangana, the high nitrate concentration was strongly attributed to the excess load of fertilizers into the water sources (Sulthana et al. 2022). Moreover, the low nitrate concentration might be due to the utilization of nitrate through eutrophication (Srinivas and Aruna 2018). In Punjab, the mean nitrate concentration was reported to be 57.32 mg L^{-1}, with maximum and minimum concentrations of 118.23 mg L^{-1} and 26.4 mg L^{-1}, respectively. These nitrate levels were found to be above the permissible limits of the BIS. This increased nitrate concentration could be due to the excessive use of synthetic fertilizers to increase crop yield (Ahada and Suthar 2018).

Moreover, the mean nitrate concentration in Andhra Pradesh was 56.26 mg L^{-1}, which was above the BIS guideline a value. The maximum and minimum values were 86.13 mg L^{-1} and 23.2 mg L^{-1}, respectively. A study conducted in the Yerraguntla region in the Kadapa district reported a peak mean value (86.13 mg L^{-1}) of nitrate (Suvarna et al. 2020), whereas the hard rock area of the Y.S.R. District of Andhra Pradesh presented a low mean value (23.2 mg L^{-1}) (Sunitha et al. 2022). The increased nitrate concentration in this region might be associated with the utilization of chemical fertilizers and manure, septic tanks, and improper industrial waste disposal leaching (C. K. V. C. Reddy et al. 2022; M. B. Reddy and Sunitha 2020; Sunitha et al. 2022). The mean nitrate concentration in Maharashtra was 54.91 mg L^{-1}, exceeding the BIS acceptable limits. The maximum and minimum values were 93 mg L^{-1} and 0.95 mg L^{-1}, respectively. Many studies have reported high mean values of nitrate in water due to anthropogenic activities such as excessive use of chemical fertilizers, animal waste, and domestic sewage discharge (Bartakke et al. 2024; Nawale et al. 2021; Patil et al. 2024).

Jharkhand reported a mean concentration of 47.03 mg L^{-1}, ranging from 18.06 mg L^{-1} to 76 mg L^{-1}. These concentrations exceeded the BIS permissible limit only, indicating potential contamination. This could be due to poor water management practices and agricultural runoff (Giri et al. 2021; Thapa et al. 2019). Haryana reported a mean nitrate concentration of 49.19 mg L^{-1}, ranging from 17 mg L^{-1} to 80 mg L^{-1}. The mean value exceeded the BIS limit, indicating significant contamination. Agricultural practices, particularly the overuse of nitrogen fertilizers, may contribute to high nitrate levels (Laxmi et al. 2022; Raheja et al. 2024). A study from Haryana, in the Shahbad region of the district Kurukshetra, revealed high nitrate contamination in surface water and groundwater due to excessive use of nitrogenous fertilizers in crop fields (Wats et al. 2019). Odisha reported a mean concentration of 38.73 mg L^{-1}, with a minimum and maximum range of 3.46 mg L^{-1} to 73 mg L^{-1}. Although the mean value was below the WHO and BIS limits, certain regions presented high nitrate levels, posing localized risks. The contributing factors include improper sewage effluent, septic tank spills, agricultural runoff, and agrochemical fertilizers (Das et al. 2023; Madhav et al. 2020; Naik et al. 2022).

The nitrate concentration in Chhattisgarh had a mean value of 19.71 mg L^{-1}, ranging from 1.08 mg L^{-1} to 29.64 mg L^{-1}. Although these levels were within the BIS limit, they surpassed the WHO guidelines, highlighting the need for continuous water quality monitoring in this region. Anthropogenic activities (*e.g.*, urbanization and industrial activities) and agricultural practices (*e.g.*, extensive use of chemical fertilizers and pesticides) both contribute to nitrate contamination in this region (Jhariya 2019; Panigraphi and Das 2022). Similarly, Bihar presented a mean concentration of 19.25 mg L^{-1}, with minimum and maximum values of 11.43 mg L^{-1} and 26.43 mg L^{-1}, respectively. While the mean value remained below the BIS limit, it exceeded the WHO standards, suggesting that moderate nitrate contamination may pose health risks over long-term exposure. The variations in nitrate contamination in the Bihar region might be due to increased agricultural runoff and sewage contamination (K Sharma et al. 2020; Kumar et al. 2019). The nitrate concentrations in Kerala ranged from 1.7 mg L^{-1} to 25.3 mg L^{-1}, with a mean value of 12.58 mg L^{-1}. While the values remained below the BIS limit, they exceeded the WHO guidelines, necessitating regular water quality assessments to prevent long-term health risks. Conversely, states such as Jammu & Kashmir, West Bengal, and Uttarakhand reported significantly lower nitrate levels, with mean concentrations of 8.08, 8.37, and 2.21 mg L^{-1}, respectively. These values were well within the WHO and BIS permissible limits, indicating a minimal risk of nitrate contamination in these regions.

Among these studies, anthropogenic activities were the primary cause of contamination. In rural areas, agricultural activities and excessive use of fertilizers have been reported as significant causes of nitrate contamination (Verma et al. 2023). In urban areas, sewage water, leakage from septic tanks and effluent from industrial areas are the primary sources of nitrate contamination (Verma et al. 2023). Since the 1960s, the application of fertilizers has steadily increased in India (Verma et al. 2023). If this increase in fertilizer application continues in India, it may severely impact the health of humans. Therefore, the findings of this study underscore the urgent need for region-specific strategies to mitigate nitrate contamination in drinking water.

Table 3 Descriptive analysis results showing the minimum and maximum values along with the mean and standard error mean (SEM) concentrations of nitrate in water (mg L^{-1}) across different regions of India

Locations	Mean±SEM	Minimum	Maximum	WHO[a]	BIS[b]
Andhra Pradesh	56.26±13.52	23.2	86.13	10	45
Bihar	19.25±4.34	11.43	26.43	10	45
Chhattisgarh	19.71±9.32	1.08	29.64	10	45
Haryana	40.69±13.47	12.8	74.12	10	45
Jammu & Kashmir	8.08±3.41	4	14.85	10	45
Jharkhand	47.03±18.06	14.99	77.5	10	45
Kerala	12.58±6.87	1.7	25.3	10	45
Maharashtra	54.91±10.40	0.95	93	10	45
Odisha	38.73±4.16	34.16	47.03	10	45
Punjab	57.32±30.46	26.4	118.23	10	45
Rajasthan	80.43±21.90	37.2	181.19	10	45
Tamil Nadu	51.79±6.55	12.23	89	10	45
Telangana	62.68±8.32	0.58	155.93	10	45
Uttar Pradesh	68.90±27.98	16.005	196.96	10	45
Uttarakhand	2.21±1.27	0.54	4.7	10	45
West Bengal	8.37±2.84	1.86	15.23	10	45

SEM: Standard error mean; Superscript[a]: World Health Organization standard permissible value of nitrate for drinking water in mg L^{-1}; Superscript[b]: Bureau of Indian Standards acceptable value of nitrate for drinking water in mg L^{-1}

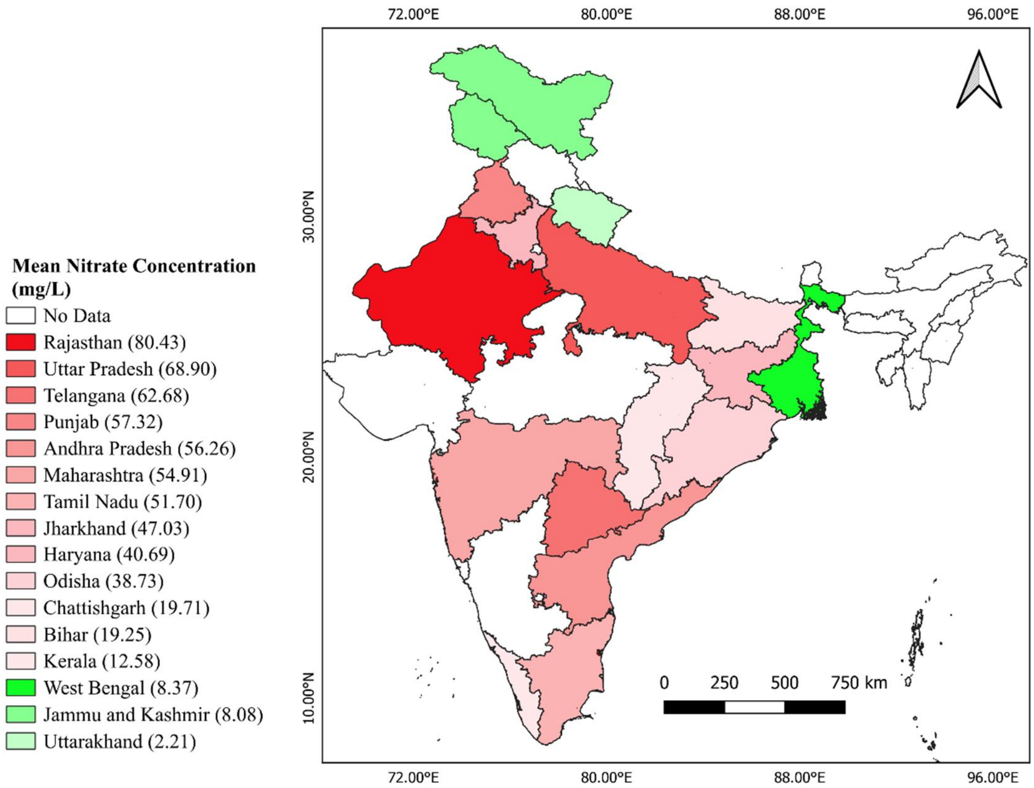


Fig. 4 Mean concentration of total nitrate contamination in water sources of different Indian states based on the included studies. This figure shows variations in the mean nitrate concentrations, with all other states, except West Bengal, Jammu and Kashmir, and Uttarakhand, falling above the WHO (10 mg L^{-1}) and BIS (45 mg L^{-1}) permissible limits.

3.2. Noncarcinogenic health risk assessment of nitrate contamination

The prolonged presence of nitrate-contaminated groundwater and surface water can negatively affect human health. In most of the regions, groundwater is heavily polluted with nitrate. This study appraises the noncarcinogenic health risks associated with nitrate concentrations in different water sources. Health risk assessment was conducted for infants, children and adults as per the standard guidelines of the United States Environmental Protection

Agency (USEPA) (USEPA 1989). According to the USEPA health risk guidelines, if the total hazard quotient is less than one, then it is considered safe. A potential health risk is considered if it is more than one. The health risk was calculated for different age groups, *i.e.*, infants (0–6 months), children (7 months–17 years), and adults (>18 years). The HQ values were calculated for each age group.

3.2.1. Chronic daily intake (CDI)

Chronic daily intake (CDI) was calculated for infants, children and adults in different states of India. The CDI values for nitrate varied across age groups and regions (Table 4). The CDI ranged from 115.48 to 4196.52 for adults, with the highest value observed in Rajasthan (4196.52) and the lowest in Uttarakhand (115.48). The state-wide values included 2935.17 in Andhra Pradesh, 1004.52 in Bihar, 1028.35 in Chhattisgarh, 2122.70 in Haryana, 421.57 in Jammu and Kashmir, 421.57 in Jharkhand, 656.52 in Kerala, 2864.67 in Maharashtra, 2020.70 in Odisha, 2990.43 in Punjab, 2701.99 in Tamil Nadu, 3270.12 in Telangana, 3594.65 in Uttar Pradesh, and 436.77 in West Bengal. For children, the CDI ranged from 177.54 - 6451.87, with the maximum value in Rajasthan (6451.87) and the minimum in Uttarakhand (177.54). The CDI values were 4512.63 in Andhra Pradesh, 1544.39 in Bihar, 1581.02 in Chhattisgarh, 3263.50 in Haryana, 648.13 in Jammu and Kashmir, 3772.46 in Jharkhand, 1009.36 in Kerala, 4404.24 in Maharashtra, 3106.68 in Odisha, 4597.59 in Punjab, 4154.13 in Tamil Nadu, 5027.58 in Telangana, 5526.54 in Uttar Pradesh, and 671.51 in West Bengal. The CDI ranged from 80.19 to 2914.25 for infants, with the highest value observed in Rajasthan (2914.25) and the lowest in Uttarakhand (80.19). The state-wide values were 2038.32 in Andhra Pradesh, 697.58 in Bihar, 714.13 in Chhattisgarh, 1474.09 in Haryana, 292.75 in Jammu and Kashmir, 1703.99 in Jharkhand, 455.92 in Kerala, 1989.36 in Maharashtra, 1403.26 in Odisha, 2076.69 in Punjab, 1876.38 in Tamil Nadu, 2270.91 in Telangana, 2496.29 in Uttar Pradesh, and 303.32 in West Bengal. Across all the age groups, Rajasthan presented the highest CDI values, whereas Uttarakhand presented the lowest. Among the age groups, the highest CDI values were observed in children, and the lowest were observed in infants. Significant differences were observed only between the CDI values of Rajasthan and Uttarakhand and not for the other cities.

3.2.2. Oral hazard quotient (OHQ)

The oral hazard quotient (OHQ) was calculated for infants, children, and adults across different states in India (Figure 5). The OHQ values for adults were as follows: 1834.48 in Andhra Pradesh, 627.83 in Bihar, 642.72 in Chhattisgarh, 1326.68 in Haryana, 263.48 in Jammu and Kashmir, 1533.59 in Jharkhand, 410.33 in Kerala, 1790.42 in Maharashtra, 1262.93 in Odisha, 1869.02 in Punjab, 2622.83 in Rajasthan, 1688.74 in Tamil Nadu, 2043.82 in Telangana, 2043.82 in Uttar Pradesh, 72.17 in Uttarakhand, and 272.98 in West Bengal. The highest OHQ value was observed in Rajasthan, whereas the lowest was in Uttarakhand (Table 4; Figure 5A). For children, the OHQ values were 2820.40 in Andhra Pradesh, 965.24 in Bihar, 988.14 in Chhattisgarh, 2039.69 in Haryana, 405.08 in Jammu and Kashmir, 2357.79 in Jharkhand, 630.85 in Kerala, 2752.65 in Maharashtra, 1941.68 in Odisha, 2873.50 in Punjab, 4032.42 in Rajasthan, 2596.33 in Tamil Nadu, 3142.24 in Telangana, 3454.09 in Uttar Pradesh, 110.96 in Uttarakhand, and 419.69 in West Bengal. Like adults, Rajasthan presented the highest OHQ value, whereas Uttarakhand presented the lowest value (Figure 5B). For infants, the OHQ values were 1273.95 in Andhra Pradesh, 435.99 in Bihar, 446.33 in Chhattisgarh, 921.31 in Haryana, 182.97 in Jammu and Kashmir, 1064.99 in Jharkhand, 284.95 in Kerala, 1243.35 in Maharashtra, 877.04 in Odisha, 1297.93 in Punjab, 1821.41 in Rajasthan, 1172.74 in Tamil Nadu, 1419.32 in Telangana, 1560.18 in Uttar Pradesh, 50.12 in Uttarakhand, and 189.57 in West Bengal. The highest OHQ value was observed in Rajasthan, and the lowest was observed in Uttarakhand (Figure 5C). Across all the age groups, Rajasthan consistently presented the highest OHQ values, whereas Uttarakhand presented the lowest. Among all age groups, the highest OHQ values were reported in children, followed by adults and, finally, infants. On average, all the OHQ values exceeded the critical value (>1), indicating a high noncarcinogenic risk due to nitrate exposure. Similar results were reported in a study conducted in groundwater in rural areas of Yantai, China (Yu et al. 2020). The findings revealed that all oral HQ values exceeded 1 for all age groups (Yu et al. 2020). Another study revealed children as the most vulnerable group, with HQ values more significant than the acceptable limit (>1) in all age groups (Alizadeh et al. 2024). The high risk in children might be attributed to their high water ingestion rate (1500 mL day^{-1}) and low average body weight (Pazhuparambil Jayarajan and Kuriachan 2020; Vetrimurugan et al. 2017). Similar results were reported in a study where noncarcinogenic risks were greater in children and infants than in adults (Sailaukhanuly et al. 2023). This was also linked to their low body weight and enzyme metabolism (Sailaukhanuly et al. 2023). Another study reported that infants, children, and adults had the highest hazard quotients (Moeini and Azhdarpoor 2021). The analysis demonstrated significant differences in the mean OHQ values between Rajasthan and Uttarakhand across all age groups, whereas the other states showed no significant variation.

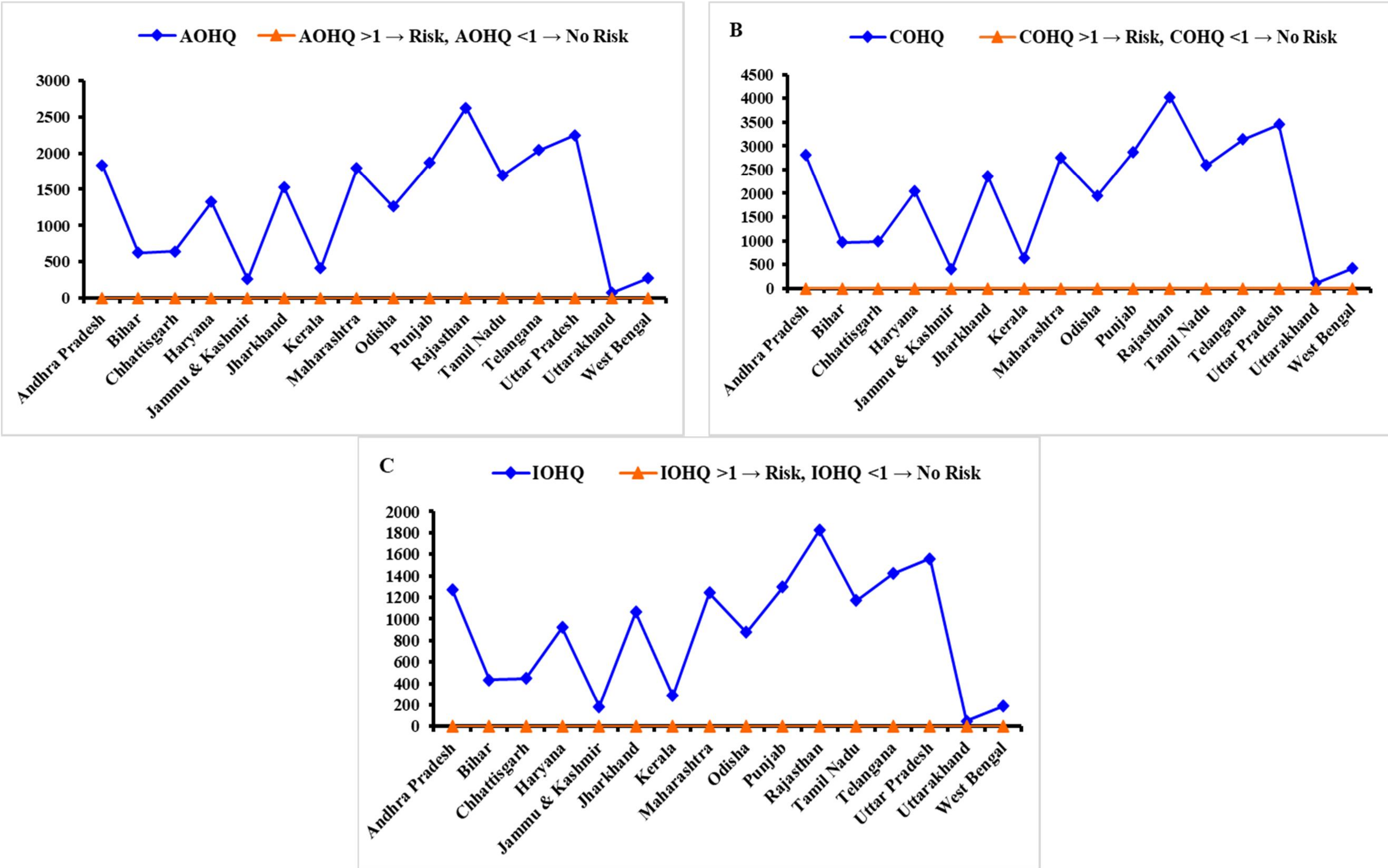


Fig. 5 Statewise OHQ (oral hazard quotient) in (A) adults, (B) children and (C) infants in India. The graphs show that the OHQ values were found to exceed the permissible limit (>1) in all age groups.

3.2.3. Dermally absorbed dose (DAD)

The dermally absorbed dose was calculated for adults, children, and infants. Dermally absorbed dose values for adults (DADs) were calculated as 0.031 in Andhra Pradesh, 0.011 in Bihar, 0.011 in Chhattisgarh, 0.022 in Haryana, 0.004 in Jammu and Kashmir, 0.026 in Jharkhand, 0.007 in Kerala, 0.030 in Maharashtra, 0.021 in Odisha, 0.031 in Punjab, 0.044 in Rajasthan, 0.028 in Tamil Nadu, 0.034 in Telangana, 0.038 in Uttar Pradesh, 0.001 in Uttarakhand, and 0.005 in West Bengal (Table 4). The DAD values for children were 0.05 in Andhra Pradesh, 0.02 in Bihar, 0.02 in Chhattisgarh, 0.03 in Haryana, 0.01 in Jammu and Kashmir, 0.04 in Jharkhand, 0.01 in Kerala, 0.05 in Maharashtra, 0.03 in Odisha, 0.05 in Punjab, 0.07 in Rajasthan, 0.05 in Tamil Nadu, 0.05 in Telangana, 0.06 in Uttar Pradesh, 0.002 in Uttarakhand, and 0.01 in West Bengal. The DAD values observed for infants were 0.06 in Andhra Pradesh, 0.02 in Bihar, 0.02 in Chhattisgarh, 0.04 in Haryana, 0.01 in Jammu and Kashmir, 0.05 in Jharkhand, 0.01 in Kerala, 0.05 in Maharashtra, 0.04 in Odisha, 0.05 in Punjab, 0.08 in Rajasthan, 0.05 in Tamil Nadu, 0.06 in Telangana, 0.07 in Uttar Pradesh, 0.002 in Uttarakhand, and 0.01 in West Bengal. The highest DAD value was reported in Rajasthan across all age groups, whereas the lowest was reported in Uttarakhand. The statistical analysis revealed significant differences in the mean DAD values between Rajasthan and Uttarakhand across all the age groups, whereas no significant differences were found among the other states.

3.2.4. Dermal hazard quotient (DHQ)

The dermal hazard quotient (DHQ) was calculated for adults, children, and infants. For adults, the DHQ values were 0.038 in Andhra Pradesh, 0.013 in Bihar, 0.013 in Chhattisgarh, 0.028 in Haryana, 0.006 in Jammu and Kashmir, 0.032 in Jharkhand, 0.009 in Kerala, 0.009 in Maharashtra, 0.026 in Odisha, 0.039 in Punjab, 0.055 in Rajasthan, 0.035 in Tamil Nadu, 0.043

in Telangana, 0.047 in Uttar Pradesh, 0.002 in Uttarakhand, and 0.006 in West Bengal (Table 4). The highest DHQ for adults was observed in Rajasthan, whereas the lowest was observed in Uttarakhand (Figure 6A). For children, the DHQ values were calculated as 0.06 in Andhra Pradesh, 0.02 in Bihar, 0.02 in Chhattisgarh, 0.04 in Haryana, 0.01 in Jammu and Kashmir, 0.05 in Jharkhand, 0.01 in Kerala, 0.06 in Maharashtra, 0.04 in Odisha, 0.06 in Punjab, 0.09 in Rajasthan, 0.06 in Tamil Nadu, 0.07 in Telangana, 0.07 in Uttar Pradesh, 0.002 in Uttarakhand, and 0.01 in West Bengal. The highest DHQ for children was reported in Rajasthan, whereas the lowest was reported in Uttarakhand (Figure 6B). For infants, the DHQ values were 0.07 for Andhra Pradesh, 0.02 for Bihar, 0.02 for Chhattisgarh, 0.05 for Haryana, 0.01 for Jammu and Kashmir, 0.06 for Jharkhand, 0.02 for Kerala, 0.07 for Maharashtra, 0.05 for Odisha, 0.07 for Punjab, 0.10 for Rajasthan, 0.06 for Tamil Nadu, 0.08 for Telangana, 0.09 for Uttar Pradesh, 0.003 for Uttarakhand, and 0.01 for West Bengal. The highest DHQ score for infants was reported in Rajasthan, whereas the lowest was reported in Uttarakhand (Figure 6C). Across all the age groups, the DHQ values were less than 1, indicating that there was no significant dermal risk for adults, children, or infants in any of the studied states (Figure 6). Many studies reported similar results, with dermal HQ levels less than 1 for all age groups, *i.e.*, infants, children, and adults, indicating low risk through the dermal pathway (Egbueri et al. 2024; Shalyari et al. 2019; Yu et al. 2020). The analysis revealed significant differences in the mean DHQ values between Rajasthan and Uttarakhand across all age groups, whereas no significant differences were observed among the other states.

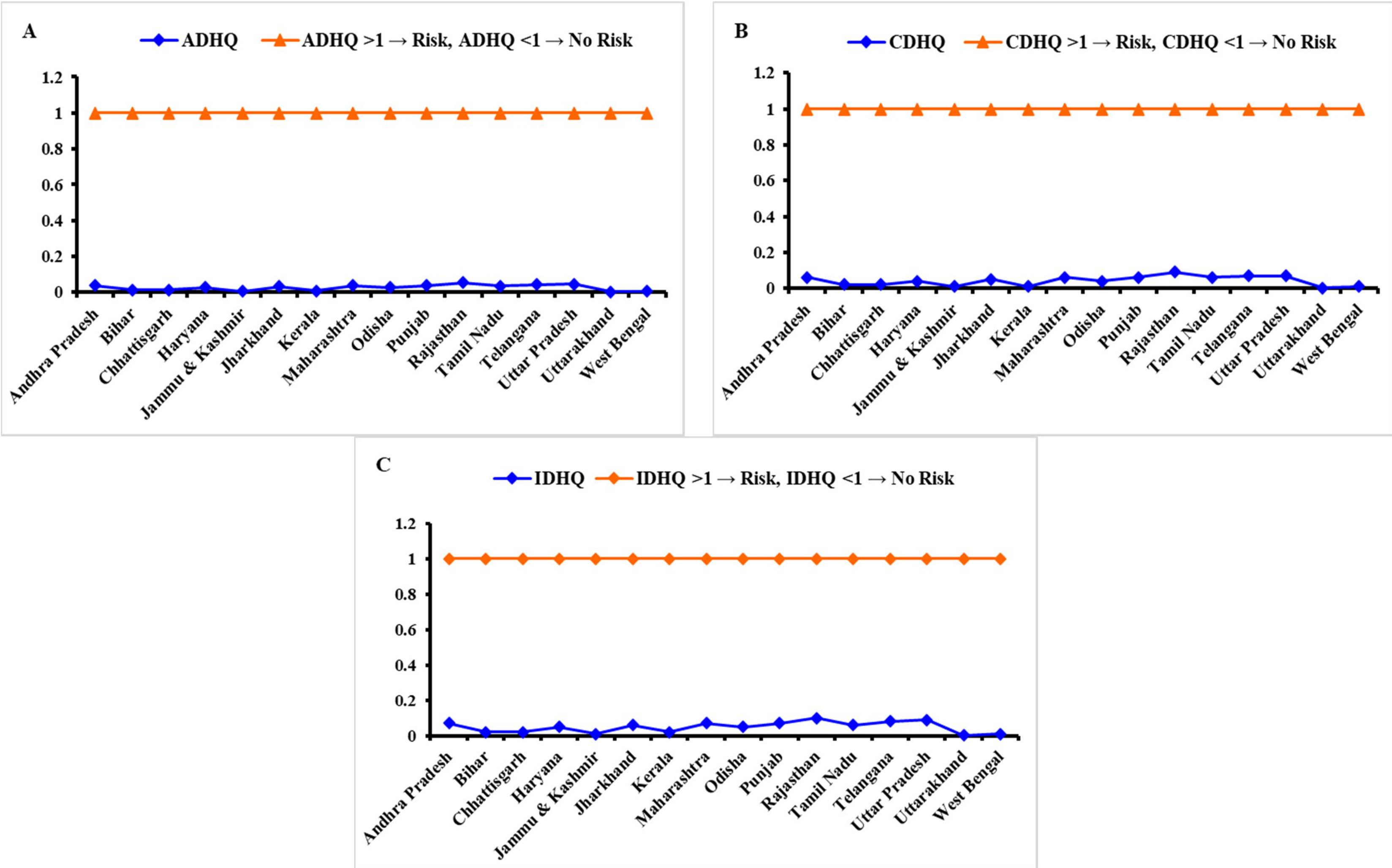


Fig. 6 Statewise DHQ (dermal hazard quotient) in (A) adults, (B) children and (C) infants in India. The graphs show that the DHQ values were below the acceptable limit (<1) in all age groups.

3.2.5. Total hazard quotient (THQ)

The THQ was calculated for adults, children, and infants across various states. For adults, the THQ was highest in Rajasthan at 2622.88 and lowest in Uttarakhand at 72.18 (Table 4; Figure 7A). The values for other states ranged as follows: Andhra Pradesh (1834.52), Bihar (627.84), Chhattisgarh (642.73), Haryana (1326.71), Jammu and Kashmir (263.48), Jharkhand (1533.62), Kerala (410.33), Maharashtra (1790.46), Odisha (1262.96), Punjab (1869.06), Tamil Nadu (1688.78), Telangana (2043.87), Uttar Pradesh (2246.70), and West Bengal (272.99). The THQ was highest in Rajasthan at 4032.47 for children and lowest in Uttarakhand at 110.96 (Figure 7B). The values for other states were as follows: Andhra Pradesh (2820.43), Bihar (965.25), Chhattisgarh (988.15), Haryana (2039.72), Jammu and Kashmir (405.09), Jharkhand (2357.82), Kerala (630.86), Maharashtra (2752.69), Odisha (1941.70), Punjab (2873.54), Tamil Nadu (2596.37), Telangana (3142.28), Uttar Pradesh (3454.13), and West Bengal (419.70). The THQ was highest in Rajasthan at 1821.46 for infants and lowest in Uttarakhand at 50.12 (Figure 7C). Other state values were as follows: Andhra Pradesh (1273.99), Bihar (436.00), Chhattisgarh (446.34), Haryana (921.34), Jammu and Kashmir (182.98), Jharkhand (1065.02), Kerala (284.96), Maharashtra (1243.39), Odisha (877.06), Punjab (1297.97), Tamil Nadu (1172.77), Telangana (1419.36), Uttar Pradesh (1560.23), and West Bengal (189.58). According to the USEPA (1991, 2001), a THQ greater than one indicates potential health risks, whereas a value less than one is considered safe (USEPA 1991, 2001). Although all the states presented THQ values that were more significant than one, indicating a greater risk to human health, the highest THQ values were observed in children in Rajasthan, indicating a higher risk of nitrate contamination due to their lower body weight, followed by adults and infants. Studies have shown that total HI values are greater in children than in adults, making children the most susceptible group at high risk of nitrate contamination (Adimalla 2020; Wang et al. 2021). The statistical analysis revealed significant differences in the mean THQ values of Rajasthan and Uttarakhand across all the age groups. Moreover, no significant difference was observed in the remaining states.

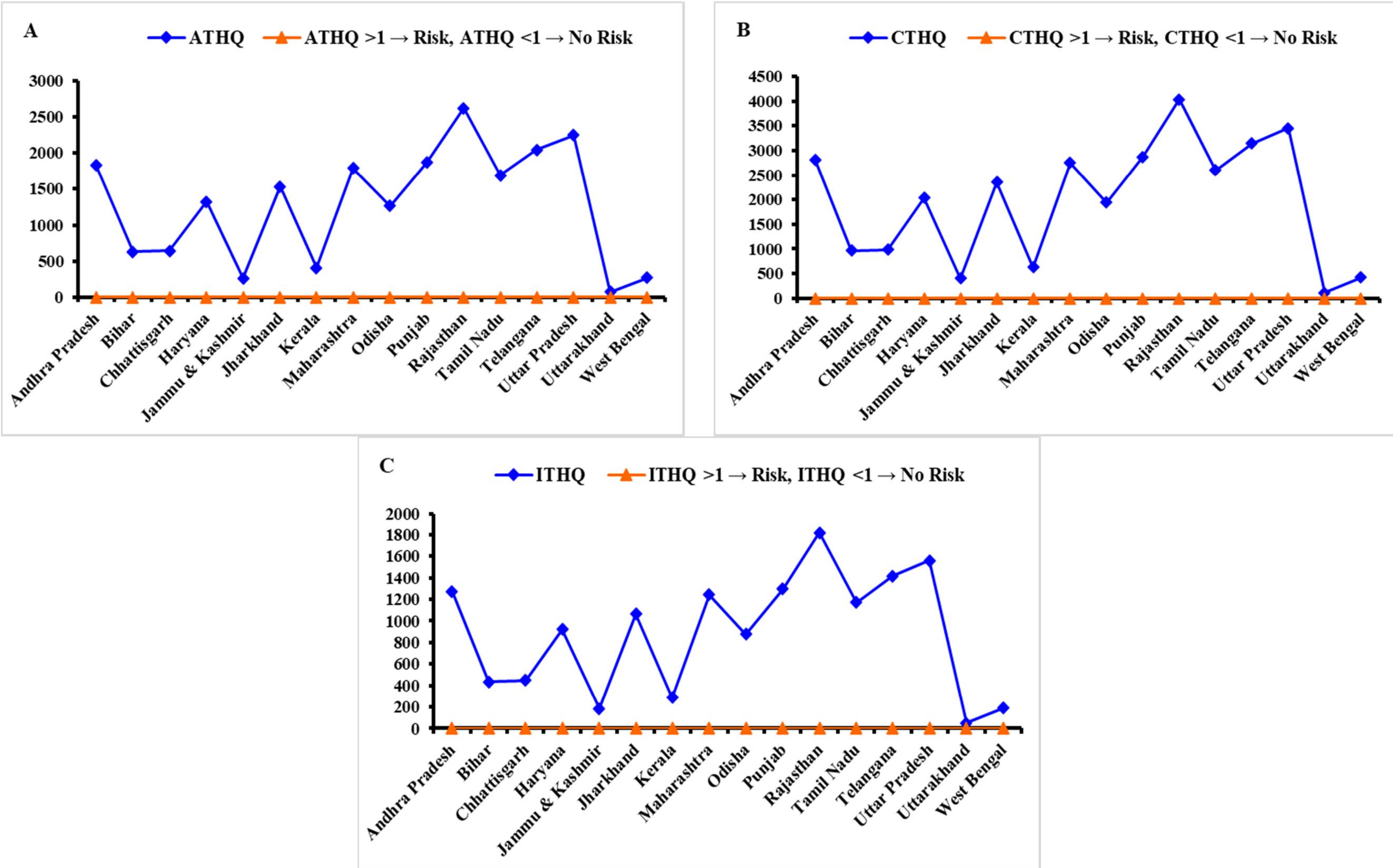


Fig. 7 Statewise THQ (total hazard quotient) in (A) adults, (B) children and (C) infants in India. The graphs show that the THQ values were above the threshold limit (>1) in all age groups.

Table 4 Estimated noncarcinogenic risk assessment (mean±SEM) of nitrate in different states of India

Locations	Adult					Child					Infant				
	CDI	OHQ	DAD	DHQ	THQ	CDI	OHQ	DAD	DHQ	THQ	CDI	OHQ	DAD	DHQ	THQ
Andhra Pradesh	$2935.17^{abcd}\pm705.19$	$1834.48^{abcd}\pm440.74$	$0.031^{abcd}\pm0.007$	$0.038^{abcd}\pm0.009$	$1834.52^{abcd}\pm440.75$	$4512.63^{abcd}\pm1084.18$	$2820.40^{abcd}\pm677.62$	$0.05^{abcd}\pm0.01$	$0.06^{abcd}\pm0.01$	$2820.43^{abcd}\pm677.62$	$2038.32^{abcd}\pm489.72$	$1273.95^{abcd}\pm306.07$	$0.06^{abcd}\pm0.01$	$0.07^{abcd}\pm0.02$	$1273.99^{abcd}\pm306.08$
Bihar	$1004.52^{abc}\pm226.55$	$627.83^{abc}\pm141.59$	$0.011^{abc}\pm0.002$	$0.013^{abc}\pm0.003$	$627.84^{abc}\pm141.6$	$1544.39^{abc}\pm348.3$	$965.24^{abc}\pm217.69$	$0.02^{abc}\pm0.004$	$0.02^{abc}\pm0.005$	$965.25^{abc}\pm217.69$	$697.58^{abc}\pm157.33$	$435.99^{abc}\pm98.33$	$0.02^{abc}\pm0.004$	$0.02^{abc}\pm0.01$	$436.00^{abc}\pm98.33$
Chhattisgarh	$1028.35^{abc}\pm486.35$	$642.72^{abc}\pm303.97$	$0.011^{abc}\pm0.005$	$0.013^{abc}\pm0.006$	$642.73^{abc}\pm303.98$	$1581.02^{abc}\pm747.74$	$988.14^{abc}\pm467.33$	$0.02^{abc}\pm0.01$	$0.02^{abc}\pm0.01$	$988.15^{abc}\pm467.34$	$714.13^{abc}\pm337.75$	$446.33^{abc}\pm211.09$	$0.02^{abc}\pm0.01$	$0.02^{abc}\pm0.01$	$446.34^{abc}\pm211.1$
Haryana	$2122.70^{abcd}\pm702.62$	$1326.68^{abcd}\pm439.14$	$0.022^{abcd}\pm0.007$	$0.028^{abcd}\pm0.009$	$1326.71^{abcd}\pm439.15$	$3263.50^{abcd}\pm1080.23$	$2039.69^{abcd}\pm675.15$	$0.03^{abcd}\pm0.01$	$0.04^{abcd}\pm0.01$	$2039.72^{abcd}\pm675.16$	$1474.09^{abcd}\pm487.93$	$921.31^{abcd}\pm304.96$	$0.04^{abcd}\pm0.01$	$0.05^{abcd}\pm0.02$	$921.34^{abcd}\pm304.97$
Jammu & Kashmir	$421.57^{ab}\pm177.85$	$263.48^{ab}\pm111.15$	$0.004^{ab}\pm0.002$	$0.006^{ab}\pm0.002$	$263.48^{ab}\pm111.16$	$648.13^{ab}\pm273.43$	$405.08^{ab}\pm170.89$	$0.01^{ab}\pm0.003$	$0.01^{ab}\pm0.004$	$405.09^{ab}\pm170.89$	$292.75^{ab}\pm123.5$	$182.97^{ab}\pm77.19$	$0.01^{ab}\pm0.003$	$0.01^{ab}\pm0.004$	$182.98^{ab}\pm77.19$
Jharkhand	$2453.74^{abcd}\pm942.37$	$1533.59^{abcd}\pm588.98$	$0.026^{abcd}\pm0.01$	$0.032^{abcd}\pm0.012$	$1533.62^{abcd}\pm589$	$3772.46^{abcd}\pm1448.84$	$2357.79^{abcd}\pm905.52$	$0.04^{abcd}\pm0.02$	$0.05^{abcd}\pm0.02$	$2357.^{82abc}\,^{d}\pm905.53$	$1703.99^{abcd}\pm654.43$	$1064.99^{abcd}\pm409.02$	$0.05^{abcd}\pm0.02$	$0.06^{abcd}\pm0.02$	$1065.02^{abcd}\pm409.03$
Kerala	$656.52^{abc}\pm358.65$	$410.33^{abc}\pm224.16$	$0.007^{abc}\pm0.004$	$0.009^{abc}\pm0.005$	$410.33^{abc}\pm224.16$	$1009.36^{abc}\pm551.4$	$630.85^{abc}\pm344.63$	$0.01^{abc}\pm0.01$	$0.01^{abc}\pm0.01$	$630.^{86abc}\pm344.63$	$455.^{92abc}\pm249.06$	$284.95^{abc}\pm155.66$	$0.01^{abc}\pm0.01$	$0.02^{abc}\pm0.01$	$284.96^{abc}\pm155.67$
Maharashtra	$2864.67^{abcd}\pm542.58$	$1790.42^{abcd}\pm339.11$	$0.030^{abcd}\pm0.006$	$0.037^{abcd}\pm0.007$	$1790.46^{abcd}\pm339.12$	$4404.24^{abcd}\pm834.18$	$2752.65^{abcd}\pm521.36$	$0.05^{abcd}\pm0.001$	$0.06^{abcd}\pm0.01$	$2752.69^{abcd}\pm521.37$	$1989.36^{abcd}\pm376.79$	$1243.35^{abcd}\pm235.5$	$0.05^{abcd}\pm0.01$	$0.07^{abcd}\pm0.01$	$1243.39^{abcd}\pm235.5$
Odisha	$2020.70^{abcd}\pm216.89$	$1262.93^{abcd}\pm135.56$	$0.021^{abcd}\pm0.002$	$0.026a^{bcd}\pm0.003$	$1262.96^{abcd}\pm135.56$	$3106.68^{abcd}\pm333.46$	$1941.68^{abcd}\pm208.41$	$0.03^{abcd}\pm0.004$	$0.04^{abcd}\pm0.004$	$1941.70^{abcd}\pm208.41$	$1403.26^{abcd}\pm150.62$	$877.04^{abcd}\pm94.14$	$0.04^{abcd}\pm0.004$	$0.05^{abcd}\pm0.01$	$877.06^{abcd}\pm94.14$
Punjab	$2990.43^{abcd}\pm1589.1$	$1869.02^{abcd}\pm993.19$	$0.031^{abcd}\pm0.017$	$0.039^{abcd}\pm0.021$	$1869.06^{abcd}\pm993.21$	$4597.59^{abcd}\pm2443.14$	$2873.50^{abcd}\pm1526.96$	$0.05^{abcd}\pm0.03$	$0.06^{abcd}\pm0.03$	$2873.54^{abcd}\pm1526.98$	$2076.69^{abcd}\pm1103.54$	$1297.93^{abcd}\pm689.72$	$0.06^{abcd}\pm0.03$	$0.07^{abcd}\pm0.04$	$1297.97^{abcd}\pm689.74$
Rajasthan	$4196.52^{d}\pm1142.57$	$2622.83^{d}\pm714.11$	$0.044^{d}\pm0.012$	$0.055^{d}\pm0.015$	$2622.88^{d}\pm714.12$	$6451.87^{d}\pm1756.63$	$4032.42^{d}\pm1097.89$	$0.07^{d}\pm0.02$	$0.09^{d}\pm0.02$	$4032.47^{d}\pm1097.91$	$2914.25^{d}\pm793.45$	$1821.41^{d}\pm495.91$	$0.08^{d}\pm0.02$	$0.10^{d}\pm0.03$	$1821.46^{d}\pm495.92$
Tamil Nadu	$2701.99^{abcd}\pm341.61$	$1688.74^{abcd}\pm213.5$	$0.028^{abcd}\pm0.004$	$0.035^{abcd}\pm0.004$	$1688.78^{abcd}\pm213.51$	$4154.13^{abcd}\pm525.19$	$2596.33^{abcd}\pm328.25$	$0.04^{abcd}\pm0.01$	$0.06^{abcd}\pm0.01$	$2596.37^{abcd}\pm328.25$	$1876.38^{abcd}\pm237.23$	$1172.74^{abcd}\pm148.27$	$0.05^{abcd}\pm0.01$	$0.06^{abcd}\pm0.01$	$1172.77^{abcd}\pm148.27$
Telangana	$3270.12^{bcd}\pm434.06$	$2043^{bcd}.82\pm271.29$	$0.034^{bcd}\pm0.005$	$0.043^{bcd}\pm0.006$	$2043.87^{bcd}\pm271.3$	$5027.58^{bcd}\pm667.35$	$3142.24^{bcd}\pm417.09$	$0.05^{bcd}\pm0.01$	$0.07^{bcd}\pm0.01$	$3142.28^{bcd}\pm417.1$	$2270.91^{bcd}\pm301.43$	$1419.32^{bcd}\pm188.4$	$0.06^{bcd}\pm0.01$	$0.08^{bcd}\pm0.01$	$1419.36^{bcd}\pm188.4$
Uttar Pradesh	$3594.65^{cd}\pm1460.05$	$2246.66^{cd}\pm912.53$	$0.038^{cd}\pm0.015$	$0.047^{cd}\pm0.019$	$2246.70^{cd}\pm912.55$	$5526.54^{cd}\pm2244.72$	$3454.09^{cd}\pm1402.95$	$0.06^{cd}\pm0.02$	$0.07^{cd}\pm0.03$	$3454.13^{cd}\pm1402.97$	$2496.29^{cd}\pm1013.92$	$1560.18^{cd}\pm633.7$	$0.07^{cd}\pm0.03$	$0.09^{cd}\pm0.03$	$1560.23^{cd}\pm633.72$
Uttarakhand	$115.48^{a}\pm$	$72.17^{a}\pm$	$0.001^{a}\pm0.$	$0.002^{a}\pm0.$	$72.18^{a}\pm4$	$177.54^{a}\pm101$	$110.96^{a}\pm$	$0.002^{a}\pm0.$	$0.002^{a}\pm0.$	$110.96^{a}\pm$	$80.19^{a}\pm4$	$50.12^{a}\pm$	$0.002^{a}\pm0.$	$0.003^{a}\pm0.$	$50.12^{a}\pm$

	66.15	41.34	001	001	1.34	.7	63.56	001	001	63.56	5.94	28.71	001	002	28.71
West Bengal	436.77^{ab} ±148.25	272.98^{ab} ±92.66	0.005^{ab}±0 .002	0.006^{ab}±0 .002	272.99^{ab} ±92.66	671.51^{ab}±22 7.92	419.69^{ab} ±142.45	0.01^{ab}±0. 002	0.01^{ab}±0. 003	419.70^{ab} ±142.46	303.32^{ab} ±102.95	189.57^{ab} ±64.34	0.01^{ab}±0. 003	0.01^{ab}±0. 004	189.58^{ab} ±64.35

CDI: Chronic daily intake; OHQ: Oral hazard quotient; DAD: Dermally absorbed dose; DHQ: Dermal hazard quotient; THQ: Total hazard quotient; SEM: Standard error means; Superscripts $^{a,\ ab,\ abc,\ abcd,\ bcd,\ cd}$ and ^{d} represent significant differences in the mean noncarcinogenic risk values among different Indian states of respective parameters (CDI, OHQ, DAD, DHQ, and THQ) in different age groups.

3.3. Health implications of nitrate contamination

Nitrate contamination poses significant health risks, particularly in areas with agricultural runoff or improper wastewater management. When consumed at high levels, nitrate is converted to nitrite in the body (Tiso and Schechter 2015), which can interfere with oxygen transport in the blood, leading to a condition known as methemoglobinemia (Figure 8) or blue baby syndrome (Rahman et al. 2021), especially in infants under six months of age (Coffman et al. 2021). Low levels of cytochrome b5 (MetHb) reductase, which converts MetHb back to hemoglobin, are believed to put fetuses at high risk of nitrate exposure (Coffman et al. 2021). Chronic exposure to increased nitrate levels is also associated with an increased risk of certain cancers, such as gastric and colorectal cancer (Figure 8), due to the formation of carcinogenic N-nitroso compounds (Picetti et al. 2022). These compounds can include N-nitrosamines, which are carcinogenic, particularly in the stomach and intestine (Carlström et al. 2020). Additionally, nitrate exposure can disrupt thyroid function by blocking iodide uptake into the thyroid (Mervish et al. 2015), leading to hypothyroidism, goiter (Street et al. 2024), and complications during pregnancy (Horton et al. 2015; Sherris et al. 2021). Emerging evidence suggests a link between nitrate consumption and reproductive issues, including preterm birth, low birth weight, and congenital disabilities (Clemmensen et al. 2023; Street et al. 2024). Long-term nitrate exposure may also contribute to cardiovascular conditions such as hypertension, cardiovascular hypertrophy, myocardial infarction, and even heart attack (Ramalingam et al. 2022). Furthermore, it can also cause metabolic disturbances such as type 1 diabetes (Ramalingam et al. 2022). These wide-ranging health impacts underscore the importance of regular water quality testing and implementing effective treatment strategies in nitrate-contaminated regions to safeguard public health.

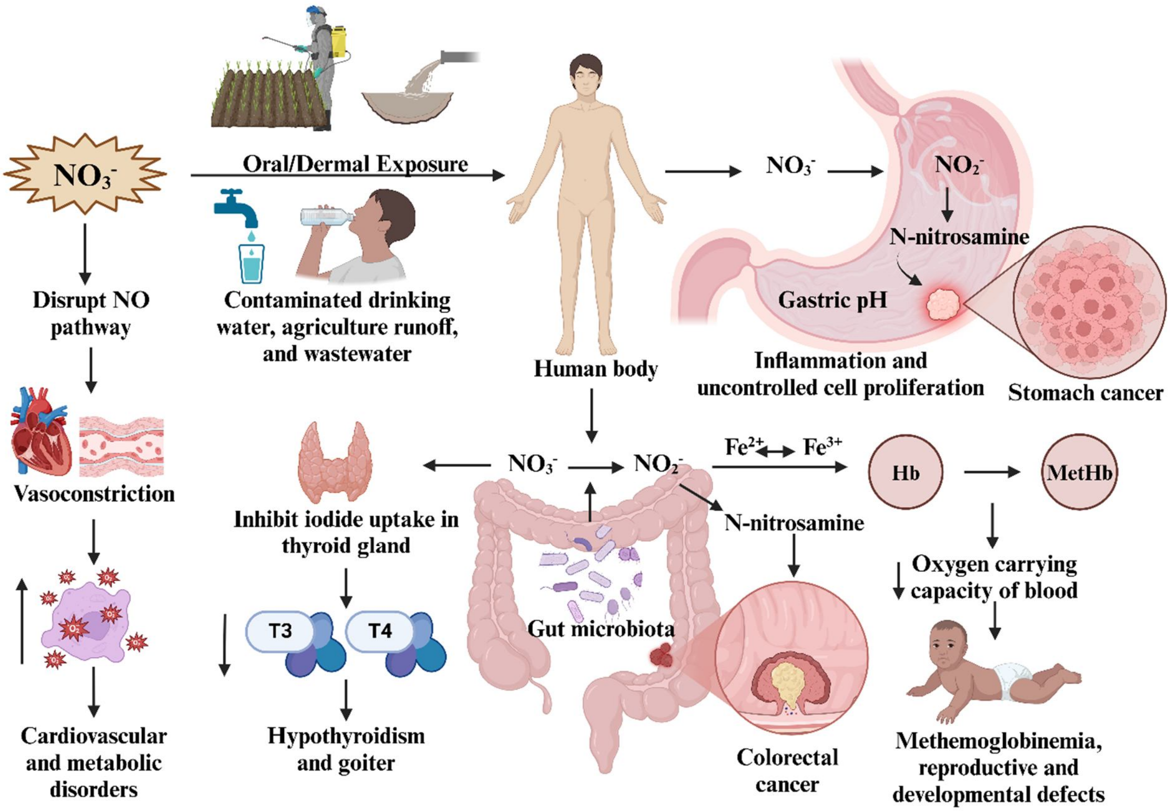


Fig. 8 Mechanistic pathways of nitrate contamination and possible health risks. Nitrate (NO_3^-) enters the body through oral or dermal exposure from sources such as contaminated drinking water, agricultural runoff, and wastewater. It disrupts the nitric oxide (NO) pathway, causing vasoconstriction and cardiovascular and metabolic disorders. In the stomach and intestine, NO_3^- is reduced to nitrite (NO_2^-), forming N-nitrosamines, which contribute to stomach and colorectal cancer through inflammation and uncontrolled cell proliferation. Nitrate also inhibits iodide uptake in the thyroid gland, resulting in hypothyroidism and goiter. In the blood, NO_2^- oxidizes Fe^{2+} in hemoglobin (Hb) to Fe^{3+}, forming methemoglobin (MetHb), reducing oxygen transport and causing methemoglobinemia, reproductive issues, and developmental defects.

3.4. Limitations and future perspectives of the study

This study on nitrate contamination in water resources across various Indian states provides valuable insights but has several limitations. This study only covers selected states, leaving gaps in understanding contamination in less-studied areas. Future research should address this limitation by expanding the geographical coverage to include all Indian states and union territories, ensuring a more comprehensive understanding of nitrate contamination patterns. Additionally, the temporal scope includes data from 2014 - 2024, potentially missing historical trends or changes in contamination patterns over extended periods. Incorporating historical data and conducting longitudinal studies can help identify long-term trends and evaluate the effectiveness of mitigation measures. This study's primary focus on noncarcinogenic health risks overlooks nitrate's potential carcinogenic effects and synergistic impacts with other contaminants. A holistic approach that examines the combined health risks of nitrate and other contaminants, such as fluoride or heavy metals, would provide a broader perspective on water quality issues.

Additionally, while the study identifies high-risk areas, it does not propose detailed, actionable strategies for mitigating nitrate contamination beyond general recommendations. Policy-focused research is also essential, emphasizing region specific, cost-effective strategies for nitrate mitigation. Collaboration with local communities to monitor water quality and implement interventions can enhance the sustainability of these efforts. Future studies should also assess the impacts of climate change on nitrate leaching, agricultural practices, and water quality, as these factors may exacerbate the issue in the coming decades. Addressing these aspects will provide a stronger evidence base for informed policymaking and sustainable water management.

4. Conclusion

This study provides critical insights into nitrate contamination in water resources across India, highlighting significant health risks, particularly for vulnerable populations such as children. The findings revealed significant regional variations in nitrate levels, with states such as Rajasthan, Punjab, Uttar Pradesh, and Telangana exhibiting contamination far exceeding the WHO and BIS permissible limits. This high nitrate contamination in these specific regions was primarily attributed to the excessive use of fertilizers. Moreover, states such as Jammu and Kashmir, Uttarakhand, and West Bengal presented low nitrate contamination. The noncarcinogenic health risk assessment revealed that children face the highest risks due to higher ingestion rates and lower body weights. In this case, the values of the oral hazard quotient (OHQ) and total hazard quotient (THQ) far exceeded the safety thresholds in high-contamination areas. However, the DHQ values were reported to be less than the acceptable limits in all age groups, indicating no dermal risk. These results underscore the urgent need for targeted interventions in high-risk regions to ensure safe drinking water and mitigate adverse health impacts. By identifying nitrate contamination regions and vulnerable populations, this study provides a foundation for region-specific mitigation strategies that align with global sustainable development goals (SDG-3 and SDG-6). Moreover, these findings emphasize the importance of sustainable agricultural practices, improved wastewater management, and regular water quality monitoring to reduce nitrate contamination. The work also highlights the need for advanced water purification technologies and community engagement to safeguard public health. This research can inform policymakers and stakeholders and serves as a valuable reference for future studies addressing water quality challenges and ensuring the long-term sustainability of water resources.

Author Contributions

Ritu Ritu: Data acquisition, Data analysis, Methodology, Manuscript drafting; **Ruby Ruby:** Data acquisition, Data analysis, Methodology, Manuscript drafting, Writing– review & editing; **Dimple Dimple:** Data acquisition, Data analysis, Methodology, Manuscript drafting, Writing– review & editing; **Nancy Nancy:** Data acquisition, Data analysis, Methodology, Manuscript drafting; **Arup Giri:** Study concept and design, Supervision, Critical revision, Final editing, Manuscript finalization

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Declaration of competing interest

None.

Data availability

Data will be available from the corresponding author on request basis.

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