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District-wise Geospatial Distribution of Fluoride in Groundwater of Uttar Pradesh, India: A Narrative Review based on Secondary Data Synthesis

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ABSTRACT

Globally, fluoride contamination in groundwater is a major environmental and public health concern. Current district-level fluoride mapping is inadequate in Uttar Pradesh, India, as data available from the early 2000s no longer accurately reflects present-day groundwater fluoride contamination. The present study synthesised secondary data to analyse the distribution of fluoride levels, particularly where concentrations exceed the permissible limit of 1.5 mg/L, and to understand environmental influences on fluoride distribution. A comprehensive search was conducted using MEDLINE (PubMed), Google Scholar, Embase, reports from governmental and institutional agencies, and public health databases related to fluoride contamination, its health implications, and district-level fluoride mapping studies published between 2000 and 2024. The findings of present review emphasise substantial variation in fluoride contamination across different districts of Uttar Pradesh, with some regions showing very high concentrations. Reported fluoride levels ranged from marginal exceedances to extreme hotspots exceeding 20–30 mg/L, highlighting the need for a multidisciplinary approach integrating environmental management, public health strategies, and sustainable water resource planning.

Keywords: Drinking water surveliance, Fluoride concentration, Fluoride contamination, Fluoride mapping, Fluorosis

INTRODUCTION

Globally, more than 260 million people are exposed to high-fluoride groundwater [1]. Elevated fluoride concentration is a significant public health issue within the geographic "fluoride belt," which extends from Turkey to China and Japan through the Middle East and Asia [2]. Worldwide, the most severely affected countries are India, Pakistan, and Jordan [3].

In India, high fluoride concentration was first reported in 1937 from the Nellore (Prakasam) district in Andhra Pradesh. Currently, high fluoride contamination in groundwater has affected 223 districts across 22 Indian states [3]. Rajasthan, Telangana, and Andhra Pradesh are the most severely affected states [4]. Moderate fluoride contamination is observed in Uttar Pradesh (UP), Madhya Pradesh, Gujarat, Jharkhand, Chhattisgarh, West Bengal, Bihar, Maharashtra, Karnataka, Tamil Nadu, Kerala, and Odisha, while Jammu and Kashmir, Punjab, and Manipur are among the least affected [5].

An estimated 62 million people in India are affected by dental, skeletal, and non skeletal fluorosis, including 6 million children under the age of 14 [6]. Uttar Pradesh, the largest state in India, has 10 districts significantly impacted by high fluoride concentrations in groundwater [3]. This issue is attributed to the presence of fluoride-bearing minerals within the aquifer system [7]. Approximately 50% of the population in UP shows evidence of fluorosis, either in the form of tooth mottling or skeletal deformities [3].

The National Oral Health Survey (NOHS) and fluoride mapping conducted by the Dental Council of India (DCI) in 2002–2003 reported that 38.6% of the population in Uttar Pradesh consumed water with high fluoride levels (≥1.5 mg/L), 16.9% consumed water with moderate levels (1.01-1.50 mg/L), and 44.6% used water with low fluoride levels (≤1 mg/L) [8].

Despite significant progress in Uttar Pradesh, several challenges persist. These include inadequate strategies to reduce fluoride intake from alternative sources, limited availability of safe drinking water options in severely affected areas, the need for improved maintenance and expansion of defluoridation units, and more effective management and rehabilitation of fluorosis cases in districts where intervention programmes are being implemented.

Recent district-wise fluoride mapping is lacking, as data from the early 2000s no longer reflect the current status of groundwater fluoride contamination across the 75 districts of Uttar Pradesh, India. This secondary data review will facilitate the rapid synthesis of dispersed research, identify emerging hotspots, and guide public health policymakers in evidence-based prioritisation of mitigation measures, thereby strengthening national initiatives.

MATERIALS AND METHODS

The study adopted a narrative review approach aimed at synthesising evidence from existing scientific and grey literature on fluoride contamination, its health effects, and district-level distribution in Uttar Pradesh, India.

Data sources and search strategy: A comprehensive literature search was undertaken across three major databases—MEDLINE (via PubMed), Embase, and Google Scholar—between August and November 2024. The review focused on studies published from 2000 to 2024 that investigated fluoride concentrations in groundwater, their spatial distribution, and associated public health implications in Uttar Pradesh. Search strategies combined relevant keywords and controlled vocabulary, including "fluoride contamination," "fluorosis," "groundwater," "water quality," and "Uttar Pradesh." Boolean operators (AND, OR) were applied to refine results, with search strings tailored to the indexing systems of individual databases.

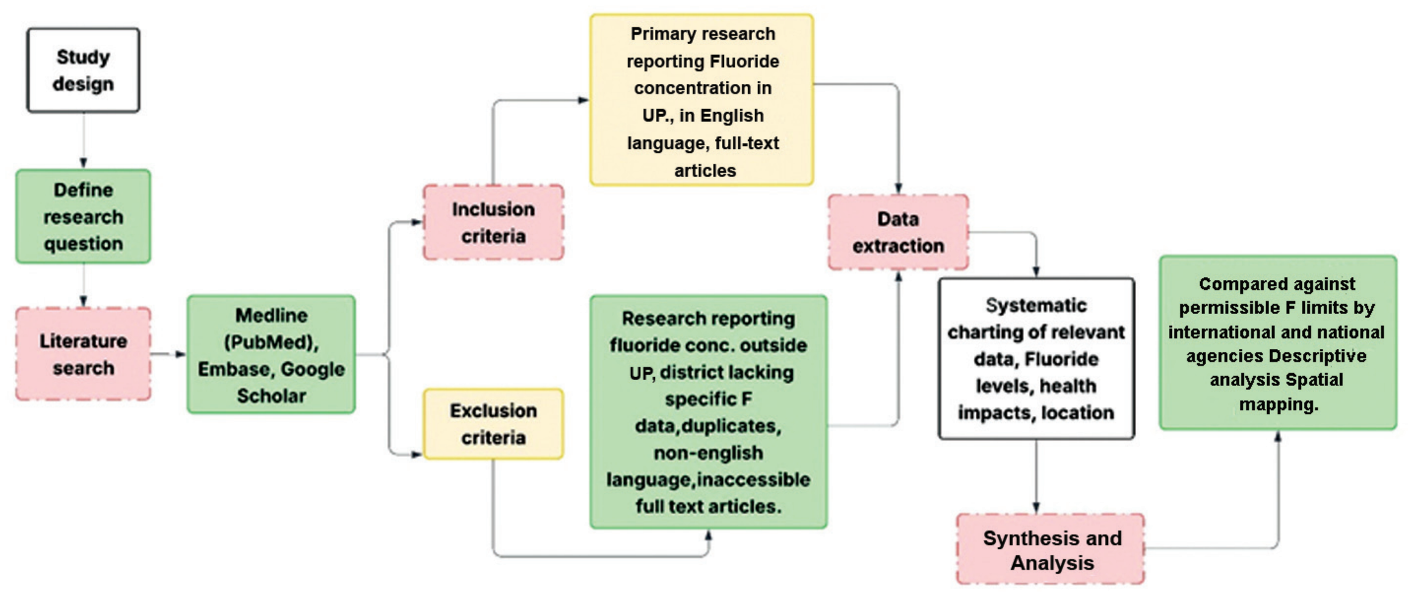
To ensure comprehensive coverage, grey literature was also reviewed through Institutional repositories, national thesis databases, and government publications, particularly reports from the Central

Ground Water Board (CGWB) and state health departments. Additionally, the reference lists of included studies were manually screened to identify further relevant sources.

Inclusion and Exclusion criteria: Eligible studies comprised primary research reporting measured fluoride concentrations in drinking water or groundwater sources within Uttar Pradesh, presenting district-level data, published in English during the defined search period, and available in full text. Studies were excluded if, they were conducted outside Uttar Pradesh, lacked district-specific fluoride data or fluoride measurements, were classified as reviews or opinion pieces, identified as duplicates, published in non English languages, inaccessible in full text, or presented unclear methods or insufficient data for extraction [Table/Fig-1].

elevated concentrations due to naturally occurring fluoride-bearing minerals, extended water-rock interaction, and semi-arid climatic conditions. States such as Karnataka, Rajasthan, and Uttar Pradesh consistently report levels surpassing permissible limits, influenced by both geogenic formations and human-induced factors. Variability in seasonal recharge, industrial effluents, and aquifer depth further compounds regional differences, contributing to widespread fluoride exposure and associated health burdens [Table/Fig-2] [9].

A comprehensive regional analysis of fluoride concentrations across districts of Uttar Pradesh, systematically compiled from diverse secondary sources has been depicted in [Table/Fig-3]. [10-72]. This tabulation consolidates previously scattered data into a unified format, enabling clearer geographic comparisons and facilitating



[Table/Fig-1]: Flowchart of study methodology.
This flowchart depicts the sequential methodology of the narrative review, illustrating each stage from literature identification and screening through eligibility assessment, inclusion, data extraction, and descriptive synthesis

Study Procedure

Data extraction and synthesis: Data extraction was carried out independently by two reviewers and organised into thematic categories, including fluoride concentration ranges, affected districts, population exposure, and associated health outcomes, to enable spatial comparisons. Any discrepancies were resolved through consensus. Adopting a narrative synthesis approach, the findings were descriptively analysed to emphasise emerging patterns, regional disparities, and existing research gaps, rather than statistically pooled.

Data analysis: The collected data were compared against permissible fluoride limits set by international and national agencies (World Health Organisation (WHO): <1.5 mg/L) [3]. Descriptive analysis was used to identify districts exceeding these thresholds. Spatial mapping tools and graphical illustrations (e.g., district-wise heatmaps) were utilised to display fluoride distribution trends and support risk assessment.

Ethical considerations: As present study is based entirely on secondary data from publicly accessible sources, no ethical approval was required.

RESULTS

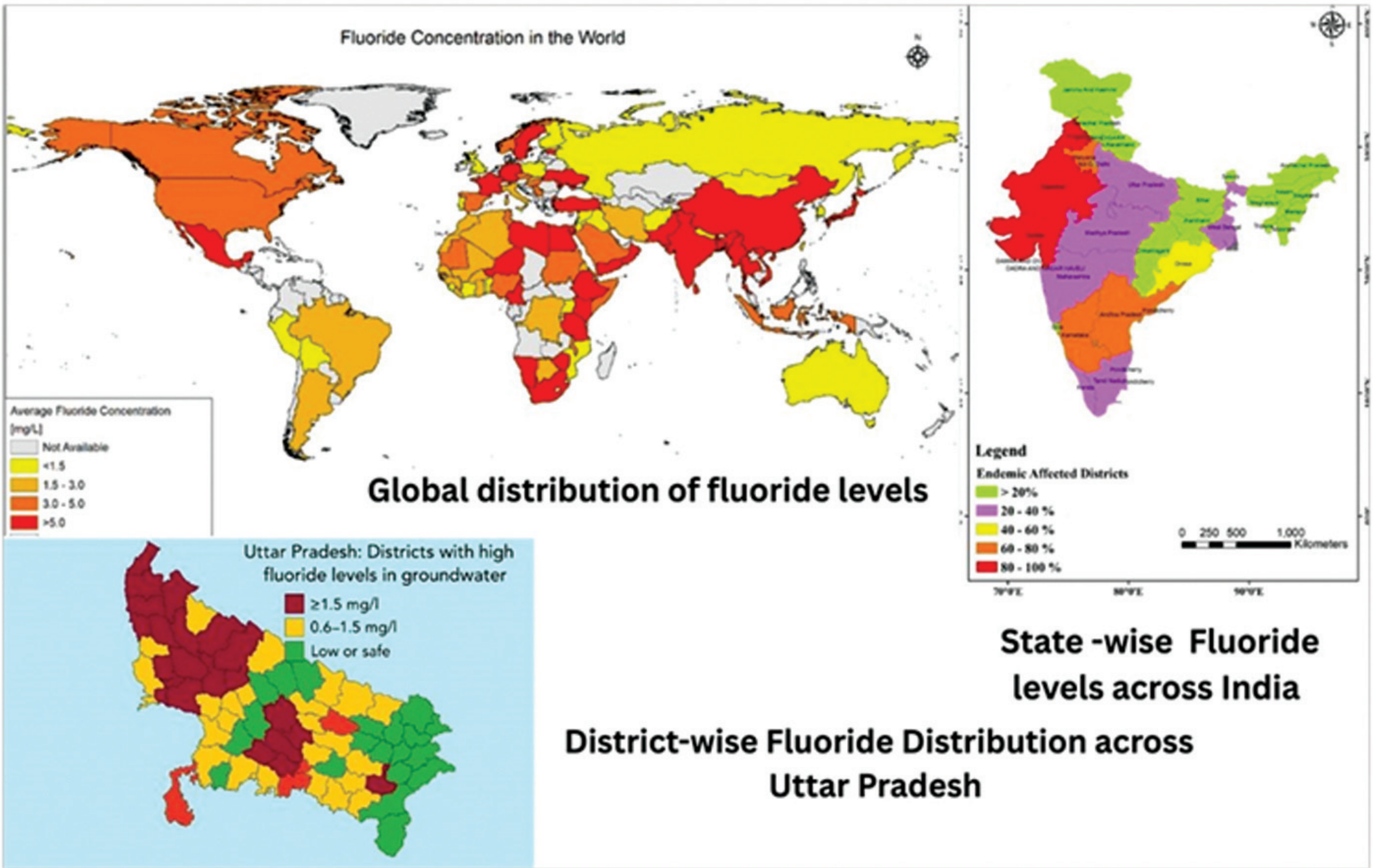
Shaji E et al., (2024) reported that more than 100 countries are affected by fluoride contamination in groundwater beyond the WHO maximum permissible limit of 1.5 mg/L, with the highest number of affected countries in Africa (38), followed by Asia (28), Europe (24), North America (3), South America (5), and Australia (2) [3]. Fluoride contamination in India's groundwater exhibits a broad geographic footprint, with the central, western, and southern regions showing

public health assessment. Districts are categorised by their location as Northern, Western, Central, Southern, and Eastern UP, with fluoride levels ranging from <0.1 mg/L to 30 mg/L. This highlights significant inter-district variability and enables clearer identification of high-risk zones for targeted public health intervention.

The districts across Uttar Pradesh identified as having elevated fluoride concentrations in groundwater has been depicted in [Table/Fig-4]. Blue teardrop markers denote locations with documented sensitivity to fluoride exposure, based on prior surveillance and published reports.

Analysis of fluoride concentration data across Uttar Pradesh revealed marked regional variation, with all three regions recording values that exceeded both the Bureau of Indian Standards (BIS) permissible limit of 1.0 mg/L and the WHO guideline value of 1.5 mg/L. In Northern and Western Uttar Pradesh, concentrations ranged from 0.02 to 14.80 mg/L, with several districts reporting levels far above the WHO threshold, indicating a substantial risk for both dental and skeletal fluorosis. Southern and Eastern Uttar Pradesh exhibited the widest range (0.004–30.00 mg/L), including the highest recorded fluoride concentration in the dataset (Balrampur, 30.00 mg/L), and encompassed multiple high-risk districts where values greatly exceeded safe limits. Central Uttar Pradesh recorded concentrations ranging from 0.00 to 13.90 mg/L, again surpassing WHO limits in several districts, demonstrating that excessive fluoride exposure is not confined to peripheral or isolated areas but is a concern throughout the state [Table/Fig-5].

The classification of districts in Uttar Pradesh based on fluoride concentrations in drinking water, providing a clear framework for assessing regional exposure risks have been depicted in [Table/Fig-6]. Districts with fluoride levels exceeding 1.5 mg/L are



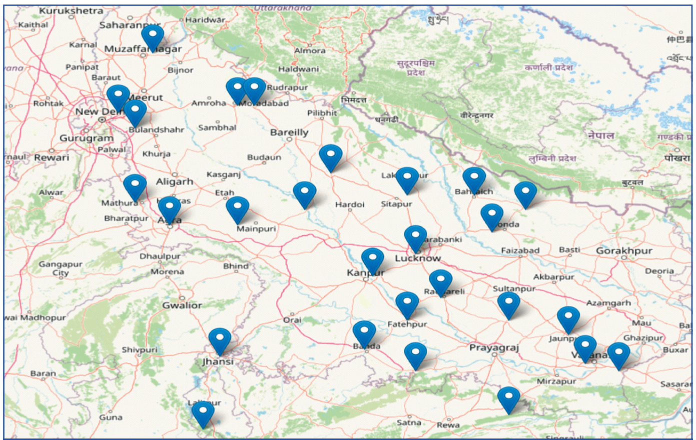
[Table/Fig-2]: Global [9], National (India) [9], and State-wise (Uttar Pradesh) distribution of fluoride.
Global and National map was prepared based on published scientific reports [9]. District-wise distribution of fluoride concentrations in groundwater across Uttar Pradesh, India. The map is self prepared with the assistance of Microsoft Copilot. Districts are color coded according to fluoride concentration levels in milligrams per liter (mg/L): High (≥ 1.5 mg/L, dark red), Moderate (0.6-1.5 mg/L, yellow), and Low or safe (≤0.5 mg/L, green)

Districts of Northern and Western Uttar Pradesh		Range of Fluoride Concentration (mg/L)	Districts of Southern and Eastern Uttar Pradesh		Range of Fluoride Concentration (mg/L)
1.	Agra [10]	0.1-14.80	27.	Varanasi [33]	0.28 - 2.01
2.	Mathura [11,12]	0.6-2.5/0.21-1.71	28.	Pratapgarh [34]	0.2-6.4
3.	Gautam buddha nagar [13]	1.5-4.3	29.	Sonbhadra [35]	0.483-6.7
4	Firozabad [14]	21.-2.3	30.	Balrampur [36]	8.0-30.0
5.	Rampur [15]	0.88 - 4.75	31.	Jaunpur [14,37]	1.5-1.8/0.27-4.81
6.	Shahjahanpur [16]	0.68 -2.87	32.	Fatehpur [14]	3.7– 4.0
7.	Muzaffarnagar [17]	0.23 -2.26	33.	Banda [38]	0.32-3.5
8.	Lakhimpur Kheeri [18]	0.5 -4.3	34.	Jhansi [22]	2.8
9.	Ghaziabad [14]	2.7-2.9	35.	Chitrakoot [39]	1.3-3.9
10.	Mainpuri [19].	>1.5	36.	Ghazipur [40]	0.8±0.132
11.	Moradabad [20]	0.10-1.92	37.	Bahraich [41]	0.18-0.95
12.	Bagpat [21]	1.85	38.	Shravasti [21]	0-10.0
13.	Saharanpur [21]	0.02-1.16	39.	Gonda [42]	No history
14.	Etah [22]	3.0	40.	Mau [21]	>2
15.	Meerut [23]	1.132 -1.532	41.	Kaushambi [21]	0.4-2.6
16.	Shamli [24]	0.3 - 0.9	42.	Ballia [43]	0-2.6
17.	Aligarh [25]	0.02-0.80	43.	Lalitpur [44]	<1 - >1.5
18.	Hathras [26]	0.08-1.17	44.	Kushinagar [45]	>1.5
19.	Bareilly [27]	0.4-0.44	45.	Gorakhpur [46]	0.004 - 1.42
20.	Pilibhit [21]	0.17 - 0.33	46.	Deoria [47]	0.4-0.59
21.	Khurja [28]	0.52.0.69	47.	Maharajganj [42]	No history
22.	Hapur [29]	0.46-0.97	48.	Mahoba [48]	0.11-3.91
23.	Bijnor [21]	0.03-0.54	49.	Sant Ravidas nagar (Bhadohi) [49]	0.38-1.20
24.	Sambhal [30]	0.09-0.36	50.	Sant Kabir nagar [50]	1.54±0.09
25.	Kasganj [31]	0.34-1.36	51.	Siddharthnagar [51]	0.3-1.2
26.	Amroha [32]	0.03-0.68	52.	Basti [52]	0.6-0.60

53.	Mirzapur [53]	0.049 -0.543
54.	Sultanpur [54,55]	0.86 -1.15/0.76-0.92
55.	Faizabad/Ayodhaya [56]	0.4-0.75
56.	Azamgarh [57]	0.173 -0.592
57.	Jalaun [42]	1.0-1.5
58.	Hamirpur [58]	0.4-0.13
59.	Allahabad/Prayagraj [59]	0.17-0.65
60.	Chandauli [60]	0.2-6.0

Districts of Central Uttar Pradesh		Fluoride concentration (mg/L)	Districts of Central Uttar Pradesh		Fluoride concentration (mg/L)
61.	Unnao [61,62]	0.8 - 13.9	69.	Kanpur Nagar [68]	0.3-1.25
62.	Kannauj [14]	3.5-4.0	70.	Hardoi [69]	0.52
63.	Bundelkhand [63]	0.01–4.10	71.	Barabanki [21]	0.5-0.93
64.	Farukkhabad [64]	0.16-2.26	72.	Amethi [70]	0.3-0.5
65.	Etawah [65]	0-4	73.	Kanpur Dehat [71]	0.2-4.76
66.	Raebareli [66]	1.3-2.74	74.	Ambedkarnagar [72]	0.27-0.73
67.	Lucknow [5,67]	0.42–6.85/0.15 - 1.15	75.	Sitapur	No information available
68.	Auraiya [14]	1.5-2.0			

[Table/Fig-3]: Fluoride concentration across districts of Uttar Pradesh: A regional analysis [10-72].
The table is categorised based on Uttar Pradesh's geographical regions: Northern, Western, Southern, Eastern, and Central, Fluoride Concentration Units: All concentrations are measured in milligrams per liter (mg/L),"No information available" indicates missing data for specific districts, Certain districts report multiple ranges or averaged values (e.g., Mathura, Lucknow), indicating variability across different areas. No history of fluoride has been reported from Gonda and Maharajganj districts



[Table/Fig-4]: Geomapping showing locations in Uttar Pradesh (UP) with elevated fluoride levels.
The identified regions may require targeted interventions, such as water treatment solutions, alternative water sources, and public health awareness campaigns to mitigate fluoride-related health effects

categorised as high-risk zones, where prolonged consumption may lead to serious health outcomes such as dental and skeletal fluorosis. Districts with concentrations ranging from 0.5 to 1.5 mg/L are considered moderate-risk, indicating potential health concerns with sustained exposure, particularly among vulnerable populations. Districts reporting fluoride levels below 0.5 mg/L are classified as low-risk or safe, suggesting minimal likelihood of adverse effects. Additionally, a subset of districts lacks sufficient data, underscoring the need for expanded water quality surveillance and targeted public health interventions.

The spatial distribution of fluoride concentrations across districts in Uttar Pradesh reveals marked regional disparities. As shown in [Table/Fig-7], while Balrampur exhibits the highest recorded fluoride level at 30.00 mg/L, districts such as Agra (14.00 mg/L), Unnao (7.30 mg/L), and Fatehpur (7.15 mg/L) also report significantly elevated concentrations, indicating a high-risk profile for fluoride-related health outcomes. Several urban and peri-urban districts, including Lucknow, Sonbhadra, and Pratapgarh, fall within the 5-7 mg/L range, reinforcing the need for targeted mitigation strategies. In contrast, districts such as Sultanpur (1.10 mg/L) remain within acceptable limits, though continued surveillance is warranted. The colour gradient in the figure, ranging from blue (low concentration) to red (high concentration), visually emphasises the severity of

Region	District	Fluoride concentration Min-Max (mg/L)
Northern and Western Uttar Pradesh	Agra, Mathura, Gautam Buddha Nagar, Firozabad, Rampur, Shahjahanpur, Muzaffarnagar, Lakhimpur Kheri, Ghaziabad, Mainpuri, Moradabad, Bagpat, Saharanpur, Etah, Meerut, Shamli, Aligarh, Hathras, Bareilly, Pilibhit, Khurja, Hapur, Bijnor, Sambhal, Kasganj, Amroha	0.02 - 14.80
Southern and Eastern Uttar Pradesh	Varanasi, Pratapgarh, Sonbhadra, Balrampur, Jaunpur, Fatehpur, Banda, Jhansi, Chitrakoot, Ghazipur, Bahraich, Shravasti, Mau, Kaushambi, Ballia, Lalitpur, Kushinagar, Gorakhpur, Deoria,Mahoba, Sant Ravidas Nagar (Bhadohi), Sant Kabir Nagar, Siddharthnagar,Basti, Mirzapur, Sultanpur, Faizabad/Ayodhya, Azamgarh, Jalaun, Hamirpur, Allahabad/ Prayagraj, Chandauli	0.004 - 30.00
Central Uttar Pradesh	Unnao, Kannauj, Bundelkhand, Farrukhabad, Etawah, Raebareli, Lucknow, Auraiya, Kanpur Nagar, Hardoi, Barabanki, Amethi, Kanpur Dehat, Ambedkarnagar, Sitapur	0.00 - 13.90

[Table/Fig-5]: Region-wise distribution of districts in Uttar Pradesh with minimum–maximum fluoride concentrations in drinking water.
Fluoride concentration values represent the lowest and highest reported measurements for each district within the specified region, based on compiled survey and literature data. "No history" or "No information" entries were excluded from calculations. Values expressed as ">" or "<" were included using their numeric component for range estimation. Regional min–max values reflect the extreme limits observed among all districts in that region and do not indicate uniform distribution across the area

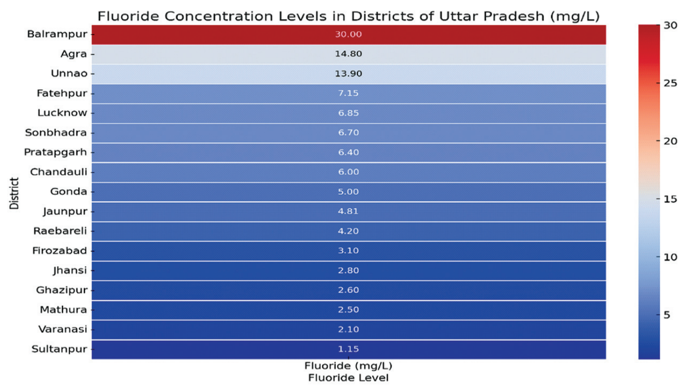
contamination and aids in rapid risk identification. These findings align with the tabulated classification in [Table/Fig-3], reinforcing the urgency of region-specific interventions and the importance of strengthening water quality monitoring systems.

DISCUSSION

The present analysis of groundwater fluoride concentrations across various districts of Uttar Pradesh highlights significant regional variability. This variability can be attributed to geological differences, alkaline pH conditions that enhance fluoride dissolution from minerals, and semi-arid climatic conditions with high evaporation rates that concentrate dissolved fluoride in groundwater. The findings confirm that elevated fluoride concentrations in drinking water remain a

Risk category	Fluoride level (mg/L)	Districts	Colour code
High	>1.5	Agra, Mathura, Gautam Buddha Nagar, Firozabad, Rampur, Shahjahanpur, Lakhimpur Kheeri, Ghaziabad, Mainpuri, Bagpat, Etah, Mau, Kaushambi, Kushinagar, Chitrakoot, Jhansi, Sonbhadra, Pratapgarh, Fatehpur, Balrampur, Jaunpur, Banda, Mahoba, Chandauli, Raebareli, Unnao, Kannauj, Etawah, Kanpur Dehat, Auraiya, Lucknow.	Red
Moderate	0.5-1.5	Meerut, Moradabad, Saharanpur, Hathras, Kasganj, Sultanpur, Jalaun, Farukkhabad, Barabanki, Ghazipur, Sant Kabir Nagar, Siddharthnagar, Basti, Amroha, Hardoi, Kanpur Nagar.	Yellow
Low/Safe	<0.5	Aligarh, Bareilly, Pilibhit, Khurja, Hapur, Bijnor, Sambhal, Shamli, Bahraich, Ballia, Gorakhpur, Deoria, Mirzapur, Faizabad/Ayodhya, Azamgarh, Hamirpur, Allahabad/ Prayagraj, Amethi, Ambedkarnagar.	Green
No Data	------	Gonda, Maharajganj, Sitapur	White

[Table/Fig-6]: District-wise classification of fluoride risk levels in Uttar Pradesh.
Concentrations above 1.5 mg/L are classified as High Risk (Red), Levels between 0.5-1.5 mg/L fall under the Moderate Risk category (Yellow), Fluoride concentrations below 0.5 mg/L are deemed Low Risk or Safe (Green), Districts lacking reliable data are marked as No Information Available (White), indicating the need for expanded monitoring and surveillance



[Table/Fig-7]: The heatmap visualising fluoride concentration levels across districts in Uttar Pradesh.
The colour scale represents different fluoride levels, helping identify regions with high or low contamination. Darker or more intense colours indicate higher fluoride concentrations, while lighter colours represent lower levels

widespread concern across the state, with 36 districts exceeding the permissible fluoride limits set by the WHO (<1.5 mg/L).

Elevated fluoride levels in drinking water (0.1-30 mg/L) were found in districts across western, central, southern, and eastern Uttar Pradesh, posing potential health risks. Extreme hotspots include Balrampur (8-30 mg/L), Agra (0.1-14.8 mg/L), Unnao (0.8-13.9 mg/L), and Fatehpur (3.5-3.7 mg/L). These findings are consistent with Gupta VK et al., (2024) and Shaji E et al., (2024), who reported high groundwater fluoride levels in India linked to dental and skeletal fluorosis [2,3].

Excessive fluoride exposure may initially manifest as burning sensations in the hands and feet, joint stiffness, muscle weakness, loss of appetite, digestive problems, and weight loss. A study conducted in Sonbhadra district, Uttar Pradesh, revealed groundwater fluoride levels ranging from 0.483 to 6.7 mg/L [Table/Fig-3] [21]. Higher levels of fluoride in drinking water can damage the pineal gland, affect the reproductive system, and cause significant deficits in Intelligence Quotient (IQ), as reported by Nakamoto T and Rawls HR (2018) and Khan SA et al., (2015) in Unnao, Uttar Pradesh [73,74].

In 2009, India initiated the National Programme for Prevention and Control of Fluorosis (NPPCF). Since then, the programme has expanded to nearly 200 districts in 17 states, intensifying diagnostic measures, delivering treatment, and supporting rehabilitation efforts at both district and village levels [75]. In Uttar Pradesh, the programme promotes nutrition initiatives encouraging calcium- and vitamin-rich diets, ensures access to safe drinking water, and conducts community-level fluorosis surveillance. Currently, districts such as Unnao, Sonbhadra, Varanasi, Raebareli, Agra, Mathura, Pratapgarh, Firozabad, Jhansi, and Ghazipur are covered; however, several other high-fluoride districts remain outside the programme and require inclusion under NPPCF [75]. While reducing fluoride intake from other potential sources (e.g., certain foods, beverages, and consumer products) may be beneficial, the immediate priority in this context is mitigating groundwater contamination in affected areas.

The persistence of high-fluoride pockets despite decades of awareness highlights the need for sustained mitigation strategies, including source substitution, defluoridation technologies, and targeted health education to prevent long-term morbidity in vulnerable populations. Establishing well-equipped district-level laboratories would support systematic monitoring of fluoride concentrations in drinking water and enable diagnostic assessments such as urine, blood, and serum analyses, alongside radiological evaluations. Regular surveillance of fluoride biomarkers is essential for detecting both excessive and deficient intake, thereby facilitating timely interventions and effective management of fluorosis-related health risks.

The present review has several limitations that should be acknowledged. Firstly, the data synthesised are based on secondary sources, and variability in reported analytical techniques and standards across studies may introduce bias in inter-district comparisons. Additionally, some districts lack recent data, and temporal trends could not be fully assessed. Future research should incorporate standardised water testing protocols, seasonal monitoring, and geospatial modelling to improve accuracy and comparability.

Despite these limitations, present review provides valuable insights into the fluoride contamination landscape in Uttar Pradesh, emphasising the need for policy-driven interventions and robust monitoring mechanisms to safeguard public health.

CONCLUSION(S)

The findings of present review emphasise the substantial variation in fluoride contamination across different districts of Uttar Pradesh. The results highlight the need for targeted fluoride mapping, uniform water testing protocols, deployment of low-cost community-level defluoridation units, improved water quality surveillance, and community-driven mitigation strategies. Establishing district-level testing facilities and ensuring widespread access to safe drinking water are crucial steps in reducing fluoride-related health risks. Public awareness campaigns and implementation of evidence-based policies should be prioritised to minimise exposure and prevent fluorosis. Future research should focus on detailed geospatial fluoride assessments and comprehensive health studies to support effective intervention strategies.

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