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Groundwater Nitrate Contamination: Spatial Assessment and Land Use and Land Cover Analysis in Ajmer District, Rajasthan

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Abstract:
This study assesses groundwater nitrate contamination across eight administrative blocks of Ajmer District, Rajasthan, using 418 samples, statistical analysis, GIS-based spatial mapping, and LULC analysis. Nitrate concentrations ranged from 2–5 mg/L at the minimum to 884 mg/L in Srinagar and 840 mg/L in Kekri, far exceeding the BIS limit of 45 mg/L and WHO guideline of 50 mg/L (BIS, 2012; WHO, 2017). Kekri recorded the highest mean concentration (108.3 mg/L), followed by Masuda (81.4 mg/L), while high standard deviations in Kekri (150.6) and Srinagar (147.2) indicate strong local variability. Arain and Bhinay were comparatively less affected, although contamination remained locally significant. The spatial pattern indicates strong links with intensive agriculture, sanitation conditions, and hydrogeological vulnerability, highlighting the need for targeted fertilizer management, improved sanitation, monitoring, and safe drinking-water alternatives.

Keywords: Nitrate contamination, groundwater quality, Geographic Information Systems (GIS), land use/land cover, Ajmer District

1. Introduction

Groundwater nitrate contamination is an increasing environmental and public-health concern in arid and semi-arid regions because nitrate is highly soluble and readily moves through soil and the vadose zone into groundwater (Spalding and Exner, 1993; Zaresefat et al., 2023). Excess nitrate in drinking water is associated particularly with infant methemoglobinemia, while long-term exposure has been linked with thyroid dysfunction and other chronic health effects (Fewtrell, 2004; Ward et al., 2018; Chaudhary et al., 2025; Ritu et al., 2025).

The WHO guideline for nitrate is 50 mg/L, while BIS specifies 45 mg/L for drinking water (WHO, 2017; BIS, 2012). Exceedances are common in areas affected by intensive agriculture and inadequate sanitation. In India, Rajasthan and other states show substantial nitrate contamination, with national monitoring indicating a rise in post-monsoon exceedances from about 30.77% to 32.66% (CGWB, 2022; Lin et al., 2023; Verma et al., 2023).

In semi-arid Rajasthan, nitrate enrichment is mainly associated with fertilizer use, inefficient irrigation, septic systems, soak pits, unlined drains, open waste disposal, sewage, and livestock waste (Sharma et al., 2017; Singh et al., 2019; Chander et al., 2023; Gupta and Rao, 2016). Soil organic-matter mineralisation and atmospheric deposition are generally secondary sources. Limited recharge, shallow groundwater, and high evapotranspiration can further increase nitrate accumulation by reducing dilution (Verma et al., 2023; Zaresefat et al., 2023).

Ajmer is a semi-arid, hard-rock district where groundwater is central to domestic and irrigation needs. Limited seasonal rainfall, substantial cultivation of wheat, mustard, and vegetables, fertilizer use, rural dependence on on-site sanitation, and increasing urban sewage loads create conditions favourable for nitrate enrichment (Gantait et al., 2022). Heavy dependence on groundwater therefore increases risks to public health, agriculture, and sustainable water management (Ahamad et al., 2023; Lin et al., 2023; CGWB, 2022).

GIS helps relate groundwater quality to LULC, settlement density, soil characteristics, and agricultural intensity and can interpolate nitrate concentrations between sampling points (Zaresefat et al., 2023). Recent studies also support geostatistical approaches for mapping nitrate and associated spatial uncertainty (Liang et al., 2024; Gupta and Rao, 2016).

This study evaluates groundwater nitrate contamination in the southwestern sector of Ajmer District using hydrochemical measurements, GIS-based spatial mapping, and land-use analysis. The objectives are to quantify nitrate concentrations and their spatial distribution, examine their relationship with major land-use categories, and delineate vulnerable areas for prioritized mitigation. The results support groundwater protection, sustainable agricultural and land-use planning, and reduction of nitrate-related health risks.

1. Quantify nitrate concentrations in sampled wells and assess their spatial distribution;
2. Examine relationships between nitrate concentrations and major land-use categories, including agricultural, urban, and rural areas; and
3. Delineate vulnerable areas with elevated nitrate contamination to support prioritized mitigation measures.

2. Materials and Methods

2.1 Study Area

Ajmer District lies in central Rajasthan between 25°38′–26°58′N and 73°54′–75°22′E, covers about 8,481 km², and comprises eight administrative blocks. It has a semi-arid climate with 400–600 mm mean annual rainfall, mainly during the southwest monsoon, temperatures from about 10°C in winter to above 45°C in summer, and high evapotranspiration that affects water availability and recharge (IMD, 2020; CGWB, 2022) (Figure 1).

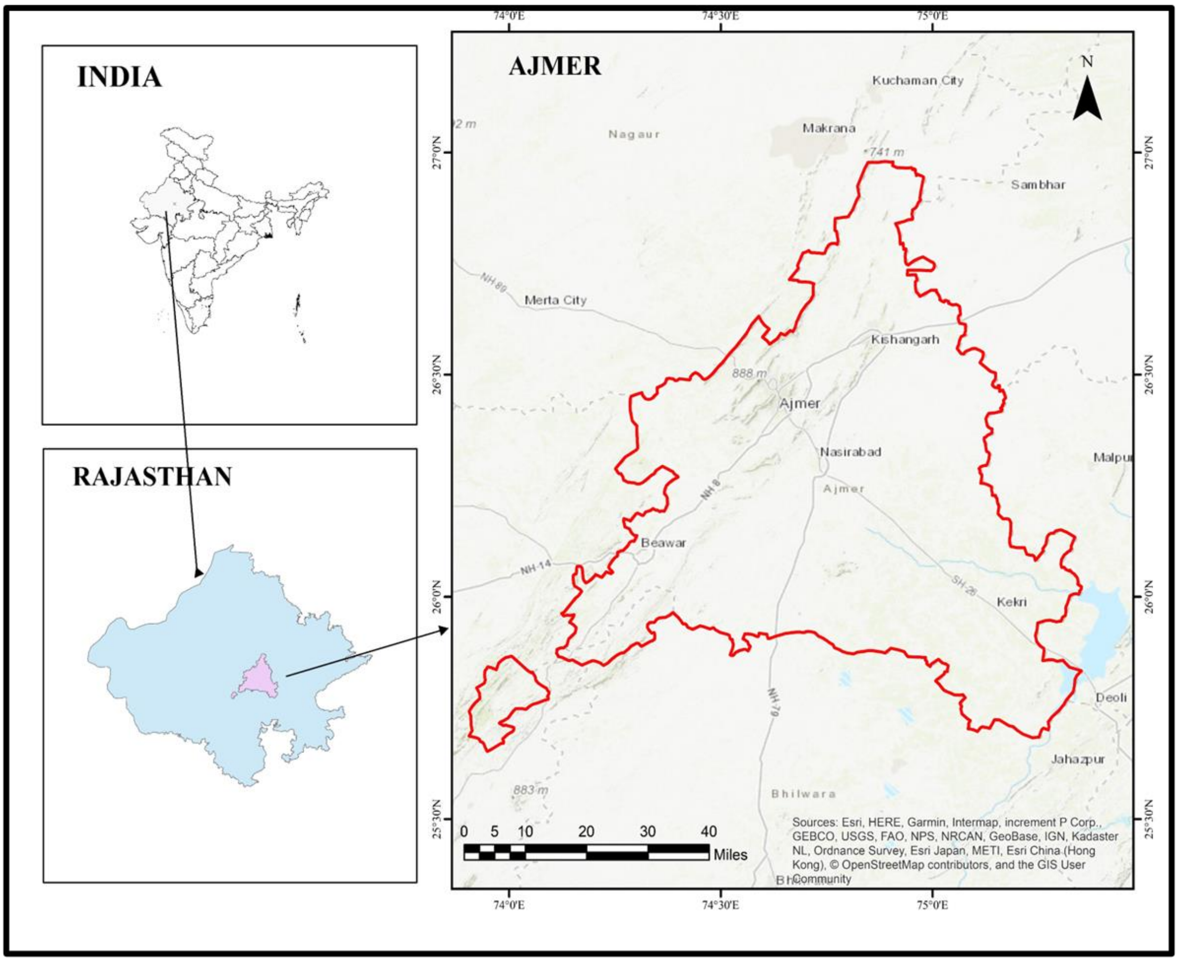

Figure 1: Study area location map

2.2 Geological Profile of Ajmer District

Ajmer, within the Aravalli Craton, is mainly underlain by Precambrian granite, schist, gneiss, quartzite, and phyllite, with minor amphibolites and intrusives (Heron, 1953; GSI, 2011; Biswas et al., 2021; Babu et al., 2023). Low primary porosity means groundwater occurrence and movement are controlled mainly by fractures, joints, faults, and weathered zones. NE–SW Aravalli hills form recharge/runoff zones, while valleys contain localized colluvial and alluvial deposits; weathered zones of about 5–20 m provide additional storage (CGWB, 2024a).

Groundwater occurs mainly under unconfined to semi-confined conditions, with typical yields of 1–5 L/s. Fractured quartzites and weathered granites generally yield more than massive gneisses and schists (Verma et al., 2023). Residual hills, pediments, and pediplains, together with shallow soils and high evapotranspiration, limit effective recharge. This heterogeneous setting creates variable aquifer potential and vulnerability to nitrate and fluoride deterioration under intensive abstraction and contaminant loading (Gupta, 2014; Chaudhary et al., 2025; CGWB, 2024b). The geological framework of the study area is shown in Figure 2.

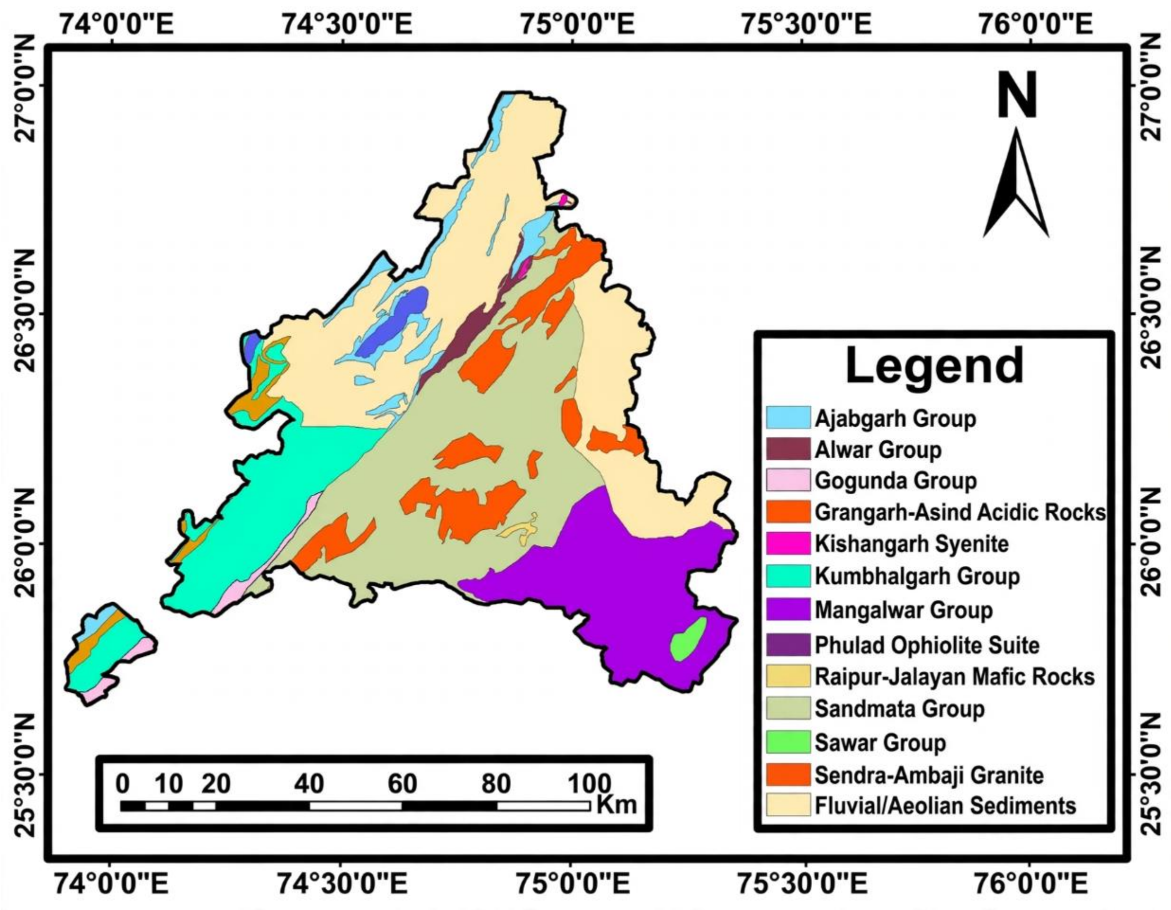

Figure 2: Geological map of the study area

2.3 Groundwater Sampling

A total of 418 groundwater samples were collected across rural, peri-urban, agricultural, and densely populated areas using stratified random sampling to represent different hydrogeological and land-use settings (Figure 3). Coordinates were recorded by handheld GPS and integrated into GIS. Samples were collected in pre-cleaned 500 mL HDPE bottles, rinsed three times with site groundwater, and analysed for in-situ pH, EC, and temperature using a calibrated Eutech multiparameter meter.

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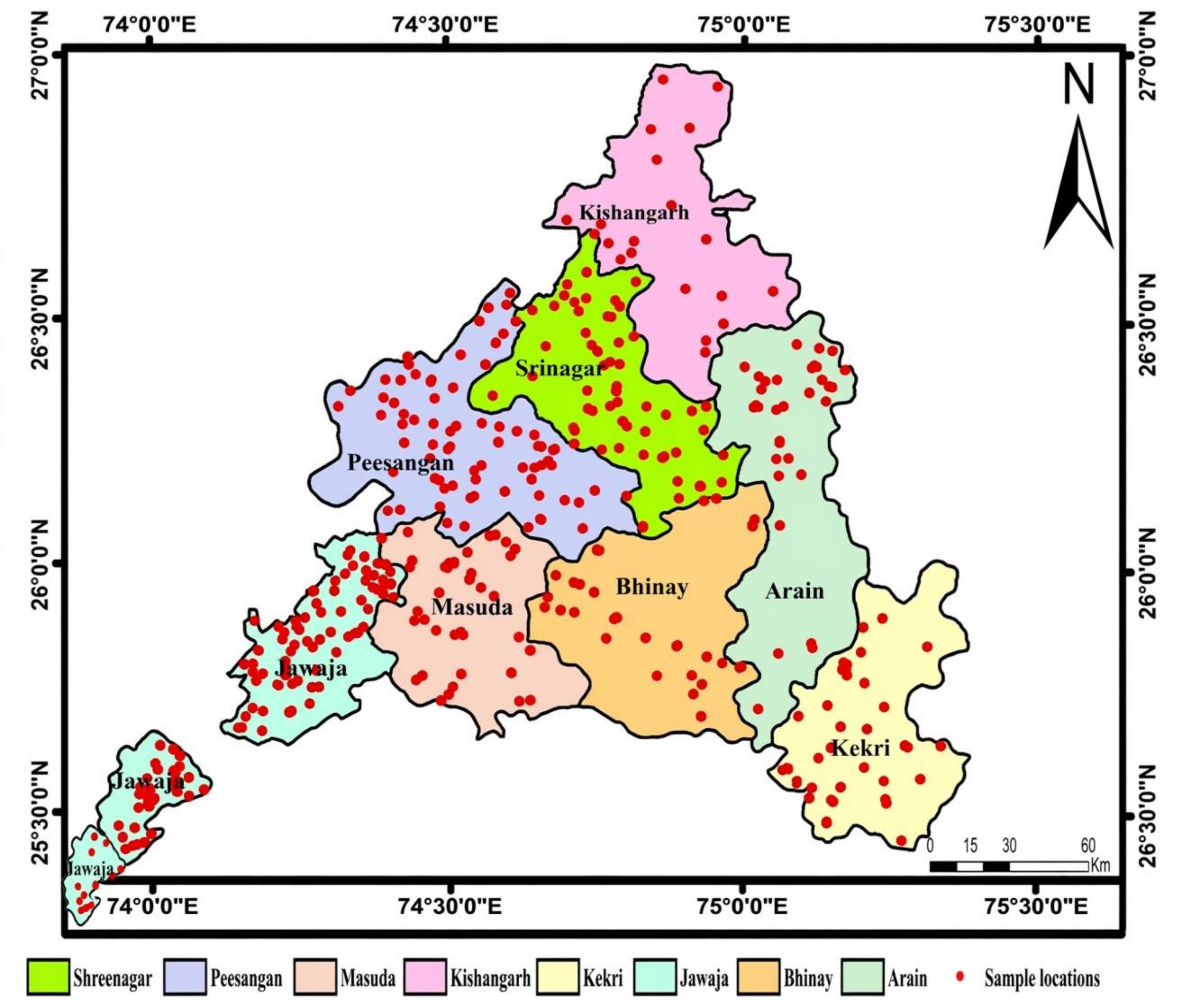

Figure 3: Sample location map

2.4 Analytical Method for Nitrate Determination

Nitrate (NO_3^-) was determined following APHA (2017) using UV spectrophotometry at 220 and 275 nm; the 275 nm reading corrected for dissolved-organic-matter interference. Samples were filtered through 0.45 µm membranes, stored at 4°C, and reported in mg/L. Analytical precision was checked using replicate measurements.

2.5 Criteria for Comparison

Nitrate concentrations were compared with BIS (IS 10500:2012) and WHO (2017) drinking-water guidelines (Table 1): 45 mg/L as NO_3^- for BIS and 50 mg/L as NO_3^- for WHO. These limits are intended to protect against nitrate-related health risks, particularly infant methemoglobinemia.

Table 1. Standard guidelines for nitrate concentration in drinking water

Standard	Guideline / Permissible Limit for Nitrate in Drinking Water	Reference
BIS (IS 10500:2012)	45 mg/L as NO_3^- (no relaxation beyond this limit)	BIS, 2012
WHO (2017)	50 mg/L as NO_3^-	WHO, 2017

2.6 GIS-Based Spatial Analysis of Nitrate Distribution

The 418 sampling locations were georeferenced and analysed in ArcGIS 10.3. Inverse Distance Weighting (IDW) was used to generate a continuous nitrate surface because the influence of each observation decreases with distance (Mohan et al., 2024). The resulting spatial pattern supports interpretation of nitrate sources, transport pathways, groundwater processes, and management priorities (Ohlert et al., 2023).

2.7 Preparation of Land Use and Land Cover (LULC) Map

The LULC map was prepared from ESRI Living Atlas vector data derived from multispectral imagery including Sentinel-2, Landsat 8, and MODIS, using the year corresponding to groundwater sampling. Data were processed in ArcGIS 10.3, projected to WGS 84 UTM Zone 43N, clipped to the Survey of India Ajmer boundary, and grouped into agriculture, scrubland/rangeland, barren/rocky and mining areas, urban/peri-urban settlements, forest, and water bodies.

The classification was checked using field ground-truth points and high-resolution Google Earth imagery; inconsistencies, especially at agricultural–scrubland boundaries, were manually corrected.

3. Results and Discussion

3.1 Groundwater Nitrate Concentration

Nitrate concentrations were assessed against the BIS limit of 45 mg/L; samples above this value were considered unsafe for drinking. The eight blocks showed marked spatial variability (Table 2). Minimum concentrations were 2–5 mg/L, while maxima reached 884 mg/L in Srinagar, 840 mg/L in Kekri, and 720 mg/L in Pisangan, about 16–20 times the BIS limit.

Kekri had the highest mean concentration (108.3 mg/L), followed by Masuda (81.4 mg/L); Jawaja (60.3 mg/L) and Bhinay (61.8 mg/L) were moderately high, while Arain (45.6 mg/L) was closest to the permissible limit. Standard deviations were highest in Kekri (150.6), Srinagar (147.2), and Pisangan (112.6), showing strong local contrasts between contaminated and less affected sites. Jawaja (71.6) and Arain (66.8) showed lower variability.

Table 2: Statistical summary of nitrate levels across the eight blocks of Ajmer district

Statistical Nitrate value (mg/L) across eight Blocks of Ajmer District				
Block	Minimum	Maximum	Average	Standard Deviation
Arain	2	330	45.6	66.8
Bhinay	2	360	61.8	94.3
Jawaja	2	312	60.3	71.6
Kekri	2	840	108.3	150.6

Kishangarh	5	390	66.9	93.5
Peesangan	2	720	62.8	112.6
Masuda	3	400	81.4	93.7
Srinagar	2	884	67.2	147.2

3.2 Average Nitrate Concentration Across Blocks of Ajmer District

Mean nitrate concentrations varied considerably among blocks (Figure 4; Table 3). Arain had the lowest mean (45 mg/L), approximately equal to the BIS limit and below the WHO guideline, whereas all other blocks exceeded both standards: Jawaja 60, Bhinay 62, Pisangan 63, Kishangarh 67, Srinagar 67, Masuda 81, and Kekri 108 mg/L. Kekri therefore represents the most widespread block-level enrichment rather than an isolated hotspot.

Based on mean nitrate concentration, contamination increases in the order Arain < Jawaja < Bhinay < Pisangan < Kishangarh < Srinagar < Masuda < Kekri. The consistently elevated means support spatially targeted monitoring and management.

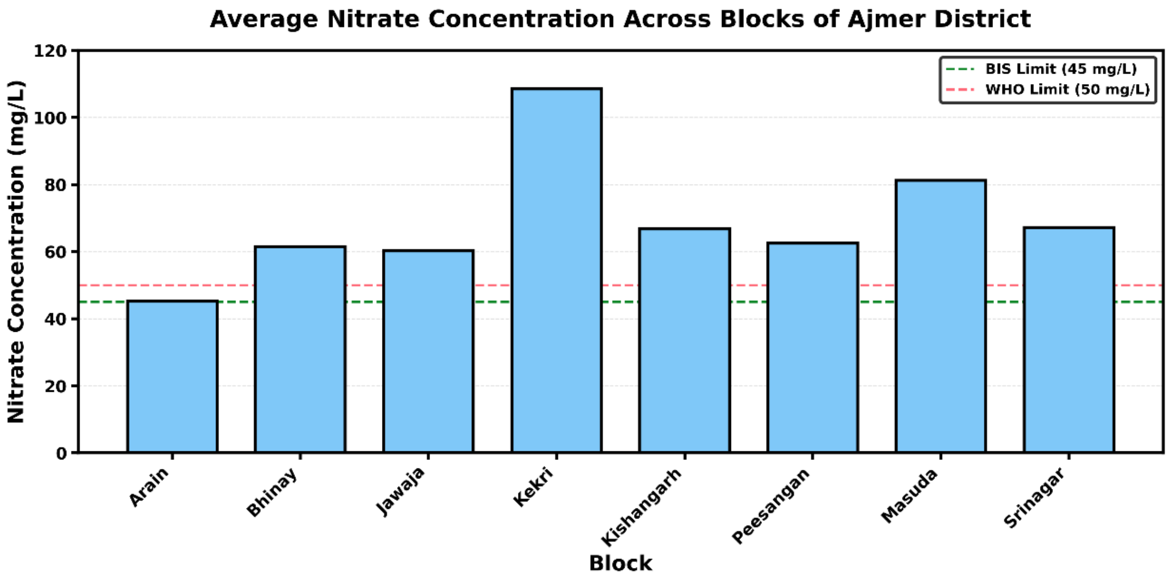

Figure 4: Bar chart showing average nitrate concentrations across blocks of Ajmer District.

Table 3: A comparative summary table of average nitrate concentrations across blocks of Ajmer District in accordance with BIS/WHO drinking water standards.

Block	Average Nitrate (mg/L)	Status (Acoording to BIS & WHO standards)
Arain	45	Safe
Bhinay	62	Unsafe
Jawaja	60	Unsafe
Kekri	108	Unsafe
Kishangarh	67	Unsafe
Masuda	81	Unsafe

Pisangan	63	Unsafe
Srinagar	67	Unsafe

3.3 Spatial Distribution of Nitrate Contamination in Groundwater

The nitrate map (Figure 5) shows a marked spatial gradient from relatively low concentrations in the north and northeast to higher concentrations in the central, southern, and southwestern parts of Ajmer. Areas below 45 mg/L represent relatively better groundwater; 45–100 mg/L indicates moderate contamination but exceeds the BIS limit; 100–200 mg/L represents high contamination linked potentially to agriculture, fertilizer use, and wastewater/sewage infiltration; and >200 mg/L represents very high contamination unsuitable for direct drinking without treatment.

- Low nitrate concentrations (<45 mg/L) occur mainly in northern and northeastern areas and remain within the BIS limit.
- Moderate concentrations (45–100 mg/L) occur mainly in central and northern areas and require continued monitoring because they exceed the BIS limit.
- High concentrations (100–200 mg/L) are more common in central and southwestern areas and may reflect agricultural inputs, fertilizer use, and wastewater or sewage infiltration.
- Very high concentrations (>200 mg/L) are concentrated mainly in southern, southwestern, and central areas, indicating severe contamination and the need for treatment before drinking.

The spatial pattern identifies vulnerable areas for targeted monitoring and groundwater-quality management.

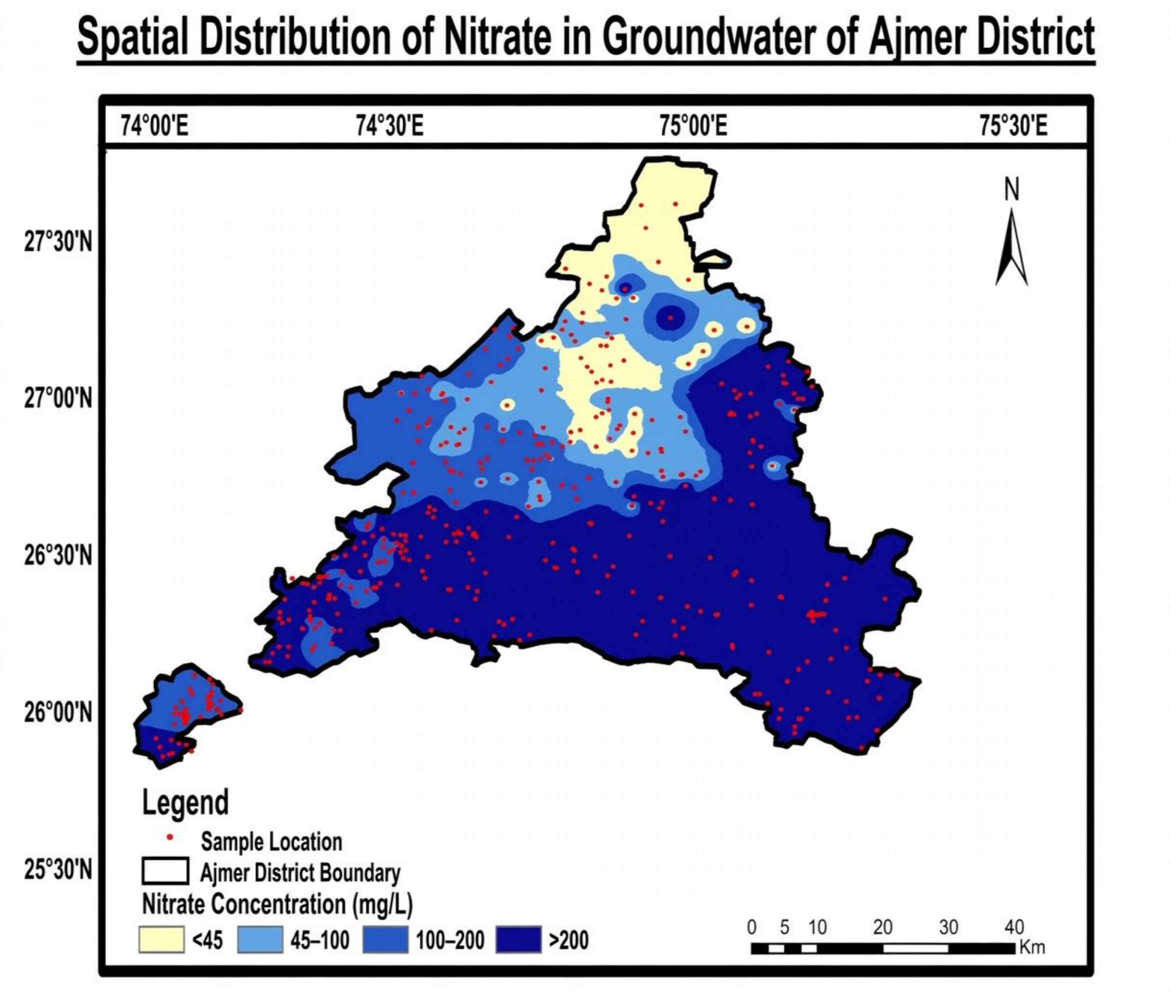

Figure 5: Spatial distribution map of Ajmer district showing nitrate contamination of groundwater

3.4 Spatial Extent of Nitrate Contamination

Only 971.8 km², representing 11.5% of Ajmer District's total area of 8,481 km², has nitrate concentrations below the safe limit of 45 mg/L.Moderate-risk areas (45–100 mg/L) cover 1,183.1 km² (14.0%), high-risk areas (100–200 mg/L) 1,639.4 km² (19.4%), and very-high-risk areas (>200 mg/L) 4,648.05 km² (55.1%). Thus, 88.5% of the district exceeds the BIS limit, with high and very-high zones indicating strong influences from fertilizer use, sanitation/wastewater inputs, and hydrogeological vulnerability (Table 4; Figure 6). The dominance of high and very-high contamination zones emphasizes the need for targeted monitoring, groundwater-quality management, and safe drinking-water provision.

Table 4: Area wise Distribution of Nitrate Concentration Classes in Groundwater of Ajmer District

Nitrate Concentration Class (mg/L)	**BIS/WHO Category**	**Area (km²)**	**% of District Area**
< 45	Safe	971.8	11.5
45 – 100	Moderate Risk	1183.1	14
100 – 200	High Risk	1639.4	19.4
> 200	Very High Risk	4648.05	55.1
Total	–	8,481	100%

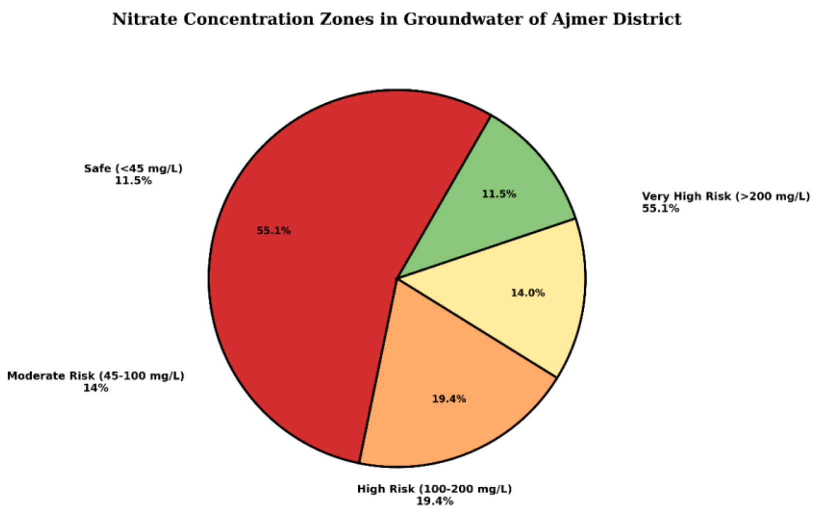

Figure 6 Percentage risk assessment of nitrate concentration in groundwater of Ajmer district

The chart shows that only 11.5% of the district is within the safe limit, while 88.5% exceeds the BIS standard; 55.1% falls in the very-high-risk class (>200 mg/L) (Figure 6).

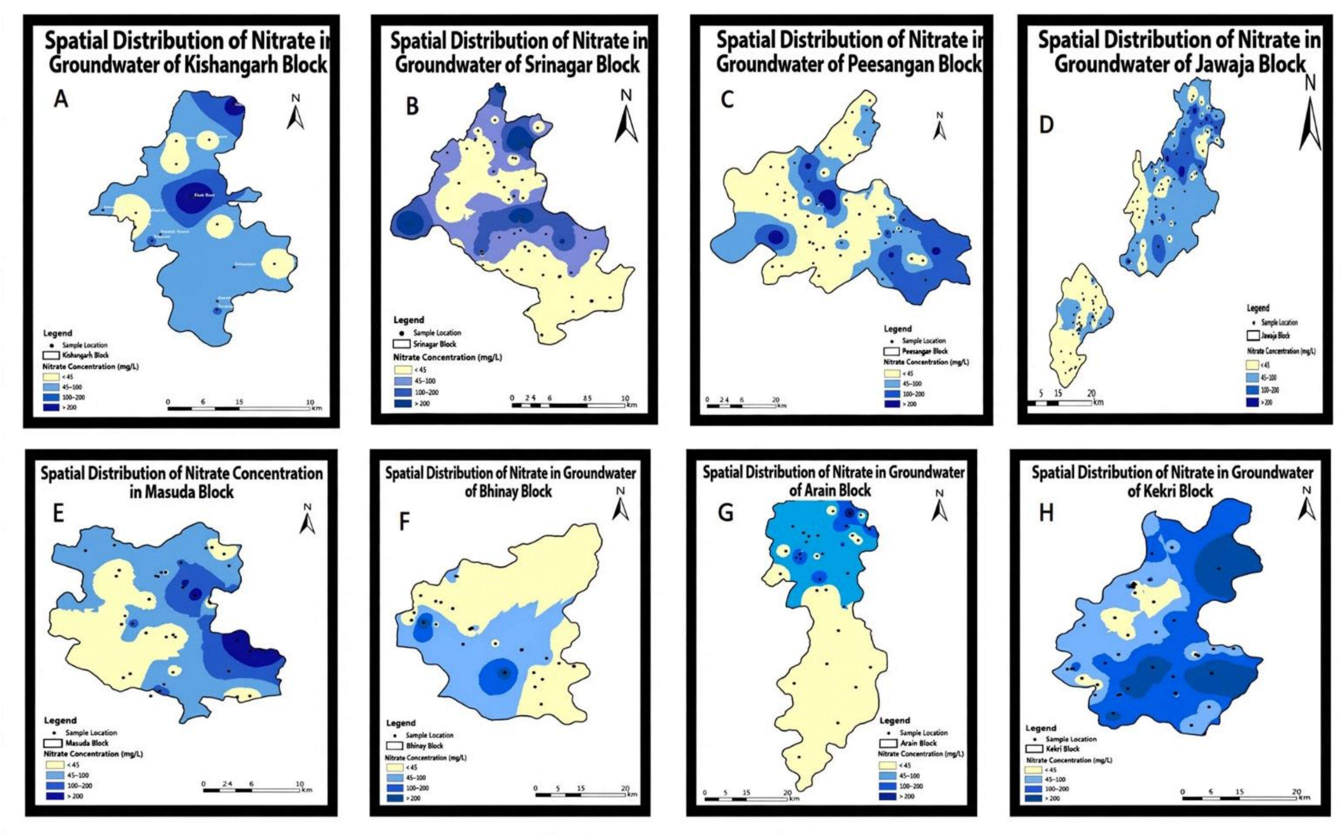

Figure 7: Block wise Spatial distribution map of study area; (Fig 7 A) Kishangarh Block (Fig 7 B) Srinagar Block (Fig 7 C) Peesangan Block (Fig 7 D) Jawaja Block (Fig 7 E) Masuda Block (Fig 7 F) Bhinay Block (Fig 7 G) Arain Block (Fig 7 H) Kekri Block

3.6 Block-wise Spatial Analysis

Block-wise samples were grouped into safe (<45 mg/L), moderate (45–100 mg/L), high (100–200 mg/L), and very high (>200 mg/L) classes (Figure 7; Table 5). Kishangarh had about 56% safe samples, 18.8% moderate, and nearly 19% above 100 mg/L, with very high values around Chak Beer, Cheeta Khera, and Brijpura. Pisangan had about 52% safe samples and nearly 20% above 100 mg/L, including >200 mg/L hotspots. Srinagar had about 66% safe, 20% moderate, and nearly 14% above 100 mg/L, mainly in northwestern and central areas.

Jawaja had 37% of samples above the safe limit, including about 7% above 200 mg/L. Masuda had 54% safe samples and nearly 25% above 100 mg/L. Bhinay had 65.2% safe samples; none were in the 100–200 mg/L class, but 13% exceeded 200 mg/L. Arain had 65.5% safe samples, with 17% moderate and another 17% high to very high. Kekri had only 47.3% safe samples and 16.4% above 200 mg/L.

Moderate contamination was highest in Kishangarh (25%) and Srinagar (20.3%); high concentrations were most common in Kekri (18.2%), Jawaja (13.9%), and Masuda (13.5%); and very high concentrations occurred notably in Kekri (16.4%), Masuda (10.8%), Pisangan (10.6%), and Srinagar (10.2%). Kekri and Masuda were the most affected blocks, while Arain and Bhinay were comparatively safer. The pattern is consistent with differences in agriculture, wastewater infiltration, and hydrogeological conditions (Figure 8).

Table 5. Block-wise distribution of groundwater samples in Ajmer District according to nitrate concentration categories.

Block	Arain	Bhinay	Jawaja	Kekri	Kishangarh	Masuda	Pisangan	Srinagar
Total Samples	34	27	113	61	18	38	69	58
< 45 mg/L (%)	65.5	65.2	62.6	47.3	56.3	54.1	66.7	66.1
45-100 mg/L (%)	17.2	21.7	16.5	18.2	25	21.6	12.1	20.3
100-200 mg/L (%)	13.8	0	13.9	18.2	12.5	13.5	10.6	3.4
> 200 mg/L (%)	3.4	13	7	16.4	6.3	10.8	10.6	10.2

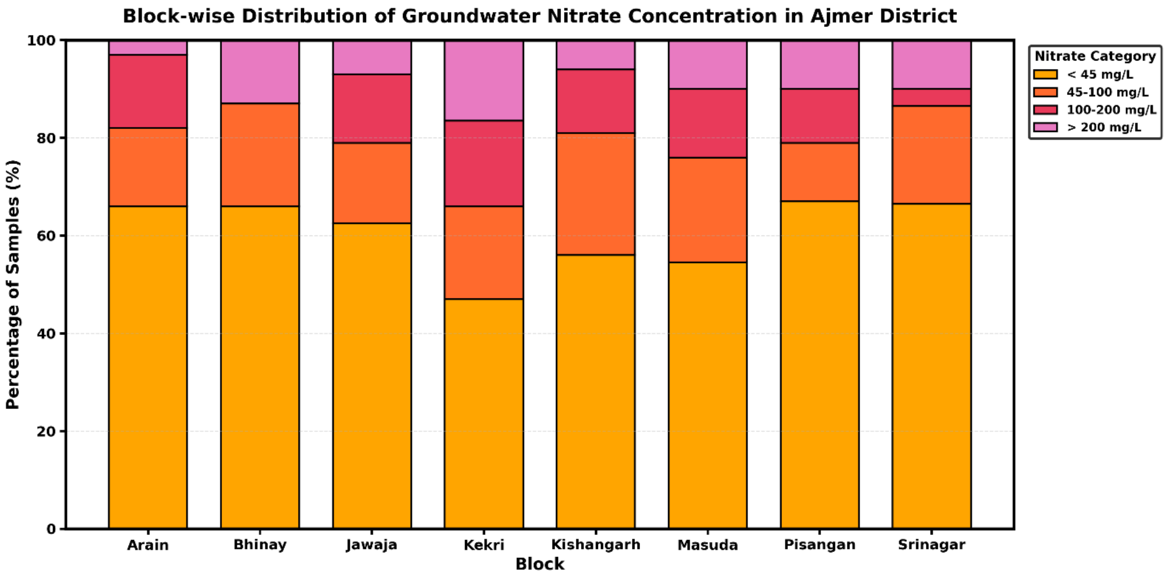

Figure 8: Bar chart showing the block-wise distribution of groundwater nitrate concentrations in Ajmer District.

3.7 Land Use/Land Cover

The LULC map was used to relate nitrate distribution to agricultural activity, settlement growth, and wasteland conditions (ICAR, 2015).

Agriculture covers 4,950 km² (58.3%) and is the main land-use setting associated with nitrate vulnerability because of fertilizer use, irrigation return flow, and leaching. Built-up areas (760 km²; 8.9%) may contribute through septic tanks, sewage infiltration, and unlined drains. Grass/grazing land, wasteland/barren areas, forest/tree cover, and water bodies cover 9.6%, 13.2%, 6.8%, and 2.9%, respectively; fallow areas may retain residual nitrate, barren areas can transport contaminants by runoff, forest areas generally receive fewer anthropogenic inputs, and water bodies may receive nitrate-rich runoff and require eutrophication monitoring (Figure 9; Table 6).

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Table 6: Land Use / Land Cover (LULC) Statistics of Ajmer District (Bhuvan, 2022)

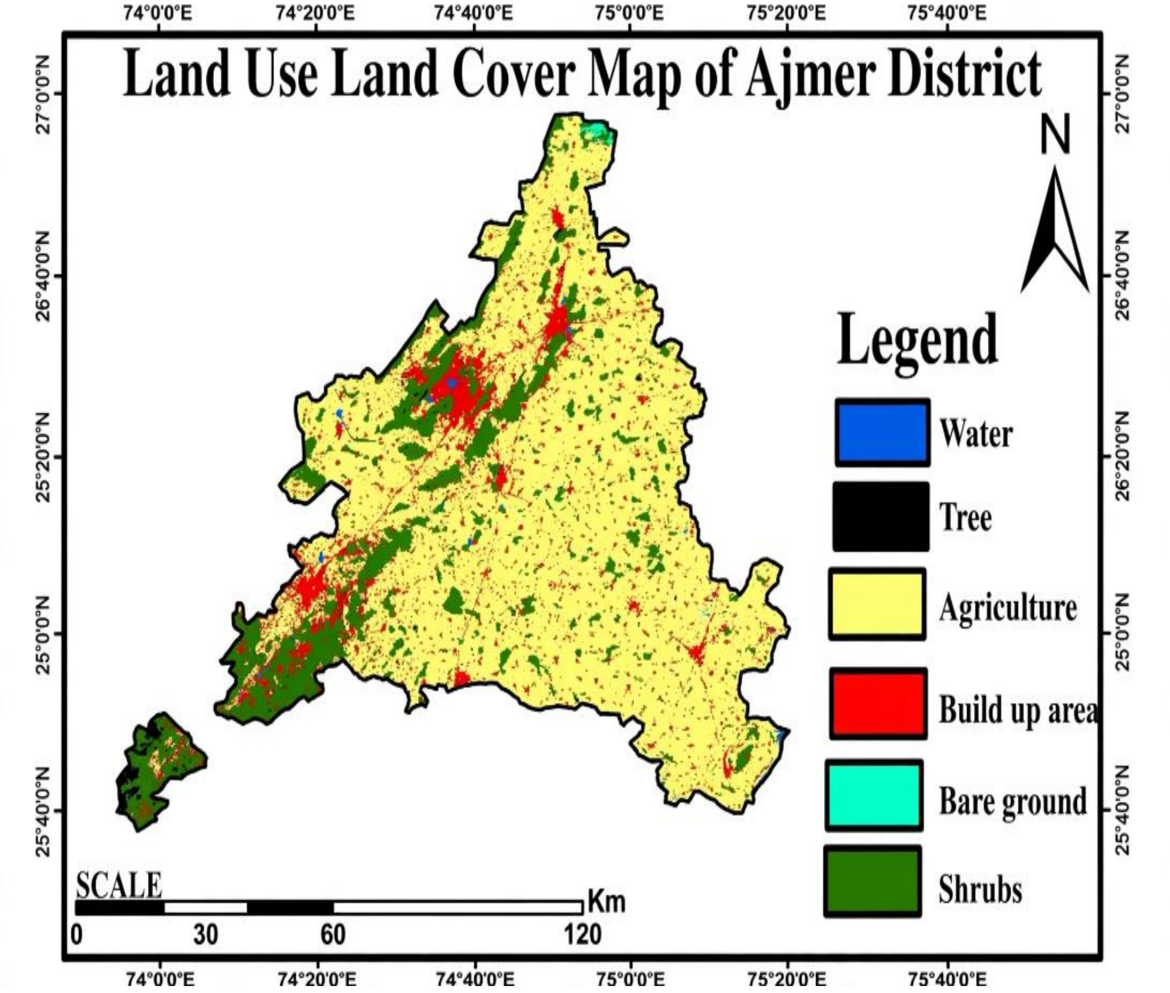

Figure 9: Land use/Landcover map of Ajmer district (2023)

LULC Category	Area (km²)	Percentage of District Area (%)	Key Characteristics
Agriculture Land	4,950	58.3	Predominantly rainfed croplands; irrigated in canal command and groundwater-fed zones
Grass/Grazing	820	9.6	Temporarily uncultivated fields, post-monsoon fallows
Built-up Area	760	8.9	Urban centres (Ajmer city, Kishangarh) and rural settlements
Wasteland / Barren	1,120	13.2	Rocky outcrops, degraded soils, scrubland, and Aravalli slopes
Forest & Tree Cover	580	6.8	Scattered forest patches, plantations, and hill vegetation
Water Bodies	251	2.9	Lakes (Ana Sagar, Pushkar), reservoirs, and tanks
Total	8,481	100	District area

3.8 Integration of Nitrate Distribution with Land Use/Land Cover (LULC)

High and very high nitrate concentrations (>100 mg/L) are concentrated mainly in the central, southern, and southwestern parts of Ajmer, where intensive wheat, mustard, and vegetable cultivation, groundwater irrigation, and nitrogenous fertilizer use may promote nitrate leaching into shallow aquifers (Singh et al., 2019).

Low concentrations (<45 mg/L) are more common in the north and northeast, where scrubland, forest, and rocky terrain have lower anthropogenic inputs. Urban and peri-urban areas, including Ajmer, Beawar, and Kishangarh, contain localized 100–200 mg/L hotspots potentially associated with wastewater infiltration, septic tanks, soak pits, and unlined drainage. Forest and barren rocky areas generally show lower concentrations than agricultural and built-up zones.

The IDW–LULC overlay therefore identifies agricultural and built-up areas as the main settings associated with higher nitrate contamination, while forest and scrubland are comparatively less affected. The results support improved fertilizer and irrigation management in agricultural areas and better wastewater and sanitation practices in urban and peri-urban zones (Table 7).

Table 7: Nitrate Contamination Risk Assessment Based on LULC Classes in Ajmer District

LULC Category	Nitrate Contamination Risk	Justification
Agriculture Land	High	Intensive fertilizer use, irrigation return flow, and soil leaching increase nitrate loading to aquifers.
Built-up Area	High	Septic tanks, sewage leakage, and unlined drains contribute to nitrate infiltration.
Waste Land	Moderate	Residual fertilizer from past cultivation can leach during rainfall or irrigation events.

Wasteland / Barren	Moderate	Limited direct inputs, but runoff from surrounding areas accelerates contaminant migration to low-lying aquifers.
Forest & Tree Cover	Low	Minimal anthropogenic inputs; vegetation enhances infiltration and natural attenuation.
Water Bodies	Moderate to High	Vulnerable to eutrophication from nitrate-rich runoff and groundwater inflows from adjacent agriculture/built-up zones.

4. Conclusions and Recommendations

Nitrate contamination in Ajmer is widespread but spatially variable. Although safe groundwater (<45 mg/L) occurs in parts of Arain, Pisangan, and Bhinay, several areas of Kekri, Srinagar, Masuda, and Kishangarh exceed the BIS limit of 45 mg/L. Concentrations >200 mg/L, particularly in Kekri and Srinagar, indicate serious drinking-water concerns and potential health risks, especially infant methemoglobinemia (BIS, 2012).

GIS analysis shows that nitrate hotspots coincide with intensive agriculture, inadequately serviced built-up areas, and vulnerable hydrogeological settings. The distribution is consistent with anthropogenic inputs from excessive fertilizer use, wastewater seepage, and livestock activities, with local hydrogeology influencing contaminant movement and accumulation.

Management should prioritize balanced fertilizer application, efficient irrigation, improved sanitation and wastewater management, artificial recharge where hydrogeologically suitable, and safe alternative drinking-water sources in highly contaminated areas. Agricultural and peri-urban hotspots identified by GIS should receive priority, supported by regular groundwater-quality monitoring and periodic reassessment of contamination zones.

Conflict of Interest: The authors declare that there is no conflict of interest associated with this study. The research was conducted independently, and no external sponsor, organization, or individual influenced the study design, data analysis, interpretation of results, or conclusions.

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