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Nitrate Toxicity of Ground Water: Preventive & Mitigation Strategies

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ABSTRACT

The issue of nitrate pollution of the Indian groundwater and surface waters is a complex socio-ecological crisis that is due to the intense use of fertilisers, wastewater discharge, and dramatic geo-heterogeneity. It is a critical review in the sense that it questions the provenance of nitrate, the hydrogeochemical regulation of its occurrences, the routes of its redox-based changes, and the spatiotemporal changes that take place under the condition of hydrology dominated by monsoons. Special focus is made on those dangers to human health linked to exposure to nitrates, including methemoglobinemia and endocrine disturbance, and the ecological implications, including eutrophication and loss of biodiversity. Forming a synthesis of the existing literature compares the existing monitoring networks, analytical methods, and modelling paradigms, thus identifying gaps in long-term datasets, understanding gaps in processes and an absence of integrated view of groundwater and surface-water regimes. The review completely searches mitigation measures on various scales, such as field-level measures and watershed-level interventions, and includes precision of nutrient control, high-quality treatment of wastewater, selective remediation of groundwater, and nature-based remedies. To conclude, the review indicates the main knowledge gaps and research requirements in the future and then provides the need to employ interdisciplinary, watershed-based structures and attain policy unity in order to achieve sustainable management of nitrogen and closing water resources across India

Introduction

Nitrate (NO_3^-) pollution is one of the most widespread and the most persistent forms of anthropogenic contamination in the water body, especially in the regions where groundwater-based water supplies prevail. Groundwater supplies more than 60 per cent of the global population and more than 85 per cent of households in rural areas in India with potable water (Ali *et al*., 2024; Murthy *et al*., 2024). Due to its extreme solubility, insignificant retardation in most aquifer matrices and stability in oxic environments, nitrate attains a concentration very easily along groundwater flow paths and is frequently retained long after surface contributions are discontinued. Massive groundwater evaluations of semi-arid, alluvial, coastal, hard-rock aquifers all continuously report groundwater levels of nitrate which are above drinking-water quality in a significant proportion of the sampled wells. On-site research shows that the percentage of groundwater samples in highly cultivated areas exceeding the Bureau of Indian Standards standard (45 mg L^{-1} NO_3^-) is between 30 and 50, with the characteristics of exceedance up to 40% in semi-arid and coastal areas (Sanjupriya *et al*., 2025; Pal *et al*., 2024; Jodhani *et al*., 2025). Health-risk analyses also reveal that children and infants are the most exposed to non-carcinogenic hazard quotients, and this fact supports the importance of the nitrate problem in rural India as a health-threatening factor (Raheja *et al*., 2024; Ratandeep *et al*., 2024).

1.1 Background and Analytical Context

On a national level, the issue of nitrate contamination is closely connected to a fast-developing process of the nitrogen cycle in India. Detailed reconstructions of nitrogen budgets in the districts between 1966 and 2017 show that the amount of agricultural nitrogen surplus has increased significantly, but the mode values are now much higher than they used to be in the 1960s (Goyal *et al*., 2024). This excess (nitrogen that is not captured in biomass that is collected) forms one of the major sources of nitrate leaching to groundwater and nutrient loss to surface waters. Notably, the distribution of nitrogen surplus in space significantly coincides with known locations of hotspots of nitrate, which proves a strong relationship between the land-based inputs of nitrogen and the water quality of the subsurface.

The comparative analyses indicate that a number of Indian regions have acquired the levels of nitrate contamination that are as severe as the time-established hotspots in Europe and North America but under the circumstances of less stringent regulatory implementation and scant treatment facilities (Goyal *et al*., 2024). The acute rise in nitrates is frequently accompanied by a high level of salinity and fluoride in the aquifers of India with the outcome of fertiliser use, sewage incursion, evaporation and the interplay of water and rocks (Ratandeep *et al*., 2024; Rajan *et al*., 2025). Co-pollution raises the risks to health as well as restricting the mitigation possibilities, particularly in semi-arid and coastal climates.

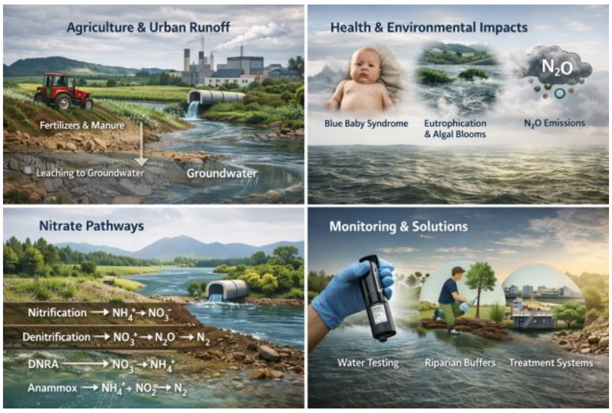

Image 1: Conceptual overview of nitrate impurity sources, transformation pathways, impacts, and mitigation in aquatic systems

1.2 Environmental Chemistry Framework

On the basis of environmental chemistry, the presence of nitrates in Indian groundwater is indicative of the overprinting of anthropogenic nitrogen loading on a geochemically regulated basis water structure. The natural hydrochemical structure is characterised by rock-water interaction, mineral dissolution-evaporation, and ion exchange and is largely exhibited by nitrate in oxic aquifers with a low denitrification capacity (Ali *et al*., 2024; Murthy *et al*., 2024). Multivariate statistical analysis and hydrochemical facilities patterns are always consistent regarding the control of nitrate distributions by the intensity of land use, the state of recharge, and the lithology of the aquifer (Pareta, 2024; Pal *et al*., 2024).

The studies in critical-zone and numerical transport further illustrate how nitrogen that is deposited at the surface of land can for instance, require years to decades to be deposited in the groundwater, leading to significant legacy effects. According to the modelling outcomes of the Indian river basins, the high levels of nitrates may not disappear regardless of low surface loads, which dictates the path-dependent character of the nitrate pollution issue and constrained efficacy of short-term remediation actions (Goyal *et al*., 2024; Pareta, 2024).

1.3 Scope and Contribution

This review convenes literature that exists on the subject of the distribution and trends of nitrate in the Indian hydrology, with the use of an integrative chemical approach. It connects the geochemical trends of groundwater nitrates that are observed to long-term indicators of nitrogen overload in the agricultural setting, thus placing Indian data in the larger worldwide framework of nitrogen regulation and management. The analysis puts nitrate contamination in the water-food-health nexus, which entails integrating the hydrochemical, spatial and health-risk evidence which, in combination, supports the environmental sustainability in India.

2.0 Biogeochemistry of Nitrate in Aquatic Systems: From Molecular Stability to Microbial Control

2.1 Molecular Chemistry and Redox stability

Natural waters contain the nitrate anion (NO_3^-), a delocalised, resonance-stabilised oxyanion in three equivalent N-O oxybonds, where p-bonding is delocalised. The solubility of this electronic structure in aqueous is high, the sorption to a mineral surface is poor and the complexation is weaker than in most cases by other anions. Consequently, nitrate continues to exist as a major dissociated ion in solution and becomes important in having electrostatic interactions with major cations (Ca^{2+}, Na^+, and Mg^{2+}) only in high-ionic-strength groundwater systems (Antony *et al*., 2025).

Nitrate, located at the extreme oxidised state of nitrogen in the pE-pH diagram, is thermodynamically most likely to be found in the oxic and high-redox state of the well-aerated rivers and shallow aquifers. Reduced nitrogen species, e.g., nitrite, ammonium, and dinitrogen, can only be favoured energetically when the redox potential is still suboxic or anoxic. Nevertheless, the groundwater system may have persistent high level of nitrate which is not necessarily explained by thermodynamic principles but rather limited by a slow rate of those phase reductions and blocked access to the donors of electrons, i.e., dissolved carbon or reduced iron and sulphur phases (Ratandeep *et al*., 2024). Thus, it is the interplay between redox thermodynamics, advective dispersion transport, and reaction kinetics that govern the behaviour of nitrates and not equilibrium.

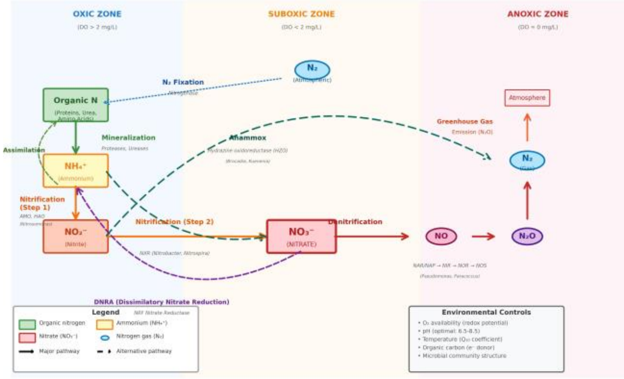

Figure 2: Nitrogen cycle in aquatic systems with emphasis on nitrate transformations

2.2 Nitrogen transformations by Microorganisms

Microbial metabolism is the dominating regulatory influence on the creation and alleviation of nitrates in the water bodies. Nitrification in aerobic conditions takes place by oxidation, oxidising, and nitrite-to-nitrate oxidation (Ghatak *et al*., 2025). Nitrification can thrive in neutral pH or slightly low pH, moderate temperatures, and sufficient dissolved oxygen but is not good in high salinity, organic overload, and trace-metal toxicity, as may be found in eutrophic Indian lakes and wetlands (Dashora *et al*., 2025).

The leading routes are the nitrate reduction ones where oxygen is limiting. Denitrification is indicated in the sequential reactions of the enzymes that transform nitrate into a dinitrogen gas in Indian rivers, aquifers, and coastal sediments, which indicate a general genetic capability to denitrify fully (Mootapally *et al*., 2025). It has been found that in most Indian aquifers, the heterotrophic denitrification is hampered by the absence of labile dissolved organic carbon. Autotrophic denitrification in cooperation with the sulphur oxidation process occurs in this instance, particularly in nitrogen-contaminated sulphate environments and artificial nitrogen purification wetlands (Soti *et al*., 2024). Another pathway is dissimilatory nitrate reduction to ammonium (DNRA) that is favoured in excessively reducing conditions that are abundant in carbon, and nitrogen is retained in the system as bioavailable ammonium. This examination of lakes and coastlines hypertrophy has likewise demonstrated a variety of potential in DNRA, making the in-house reuse of nitrogen important over its removal (Dashora *et al*., 2025). Incomplete denitrification and DNRA can initiate nitrogen oxide accumulation at the locations with low levels of nitrous oxide reductase activity, and this significantly affects the greenhouse gas emissions. Another route used in the elimination of nitrogen in low-organic-carbon, anoxic environments that is directly coupled with both ammonium and nitrite oxidised to dinitrogen is called nitrogen ammonium oxidation (anammox). Although the proportion of anammox to total nitrogen metabolism is typically a minor fraction, anammox bacteria have been identified in deep sediments and effective working treatment systems that have been designed in India, where anammox bacteria have their own important share in the overall performance of nitrogen removal (Soti *et al*., 2024).

2.3 Controls of Hydrogeochemical and Transport

Zonation is an extreme redox phenomenon that is common in water bodies horizontally and vertically. The surface waters and shallow recharge areas are typically oxic, and that is preferential to nitrates, but deeper, hydraulically isolated recharge areas transition to suboxic and anoxic, in which case, the reduction of nitrates can occur at the cost of the availability of the appropriate electron donors (Islam *et al*., 2025). Geothermal indicators used to show hydrogeochemical dynamics, including dissolved oxygen, redox potential, Fe2+/Mn2+, sulphate-sulphide, alkalinity, and carbonate saturation indices, are cumulative indicators of redox changes, mineral weathering, and ion changes, and all were used to determine nitrate behaviour (Ali *et al.*, 2024).

Nitrate reduction processes produce alkalinity, associating the alterations of nitrogen with the buffering of carbonates and the stabilisation of pH in Ca-Mg-HCO_3-dominated facies of groundwater found throughout India. It has been demonstrated by using reactive-transport models that advection and hydrodynamic dispersion play key roles in the controlling of nitrate movement, with biogeochemical reactions being the rate-limiting sinks. The bilateral-domain transit and polycrystalline diffusion within fractured and hard-rock aquifers accumulate the nitrate and low-nitrogen varieties in the regions with low permeability, thus giving its place to the response period of the system to source reduction significantly (Ratandeep *et al.*, 2024).

Redox State	Indicative Conditions	Dominant N Species	Nitrate Behavior	References
Oxic	DO > 2 mg L^{-1}; positive ORP	NO_3^-	Conservative transport; accumulation	Antony *et al.* (2025)
Suboxic	DO declining; Fe/Mn mobilization	NO_3^-, NO_2^-	Partial reduction begins	Islam *et al.* (2025)
Anoxic (denitrifying)	DO ≈ 0; negative ORP	N_2	Effective nitrate removal	Mootapally *et al.* (2025)
Strongly reducing (DNRA)	High DOC; very low ORP	NH_4^+	N retained in system	Dashora *et al.* (2025)
Sulfidic / methanogenic	SO_4^{2-} depleted; HS^-/CH_4	NH_4^+, N_2	Nitrate absent	Ratandeep *et al.* (2024)

Table 1: Hydrogeochemical states and redox zonation

2.4 Isotopic Constraints of Sources and Processes

The isotopic label of the nitrate ($\delta^{15}N–NO_3^-$ and $\delta^{18}O–NO_3^-$) puts strict restrictions on both sources and mechanisms of transformation of nitrates. The differentiation between synthetic fertilisers, soil nitrogen, sewage effluents and atmospheric inputs can be differentiated using distinct isotopic ranges, and characteristic enrichment patterns are used to diagnose the denitrification and processes of DNRA. Isotopic evidence is becoming an increasingly important part of recent Indian studies to determine contributions to sources and zones of active nitrate attenuation of the aquifers and river systems (Islam *et al.*, 2025; Thakur and Gauba, 2024).

3.0 Provenance and Measures of Nitrogen loading in Aquatic Systems

3.1 Agricultural Nitrogen Inputs: Mass-Balance view

With the mass-balance models of the distribution of nitrogen (N) loading at a district scale, as illustrated in the case of General and around the district scale, agriculture has remained the largest source of load of nitrogen (N) in the Indian aquatic environments, with the nearest contributions to the load by synthetic fertiliser, organic manure, biological nitrogen fixation (BNF) and atmospheric deposition and the offsets of the load by crop harvest, leaching, runoff and gaseous emissions (Goyal *et al.*, 2024). Due to the Green Revolution, fertiliser usage currently increased substantially; intensive rice-wheat systems in the Punjab-Haryana axis have reached and exceeded 150-200 kg N $ha^{-1}yr^{-1}$, and low rainfed peninsular regions had a slow homogeneity pattern in the past (Desai *et al.*, 2024). National fertiliser use is above 17.3 million tonnes of N per year, yet crop recovery gives up to 50-60 per cent, which results in a notable amount of unutilised matter to be lost to nature easily (Goyal *et al.*, 2024).

This discrepancy between the inputs and the total crop N removal has escalated among most of the districts and has established rather than intense hotspots throughout the Indo-Gangetic Plain and western and southern India (Goyal *et al.*, 2024). In analysing flood plots of rice systems, it has been demonstrated that, in conducive environments, the combined losses due to ammonia volatilisation, emittance of nitrous oxide and nitric oxide, as well as draining of nitrates present in the soil, may be estimated to be approximately 0.510 per cent of applied N (Chatterjee *et al.*, 2024). Presence of evidence Site-specific nutrient management indicates that it is able to decrease excessive use of nitrogen by around 20 per cent and hike nitrogen-use efficiency (NUE) by 20 per cent without yield diminishment (Nayak *et al.*, 2024; Bhagwan *et al.*, 2025). The organic amendments that induce a parallel N pathway, slower rate, and regulation by C:N ratios and microbe turnover include farmyard manure (FYM), press mud, composts, and enriched formulations of the organic form in which the speed of release was enhanced by adding organic acids and sulfonamides (which is the densest amendment), respectively (Kumari *et al.*, 2024; Sheoran *et al.*, 2025). Long-term FYM-fertiliser incorporations enlarge stocks of organised nitrogenatic organic matter and microbial biomass of the soil, consequently raising the seasonal buffer of N provision and can lessen or prevent nitrate jump in case of coordination between application per cent and consumption per cent (Sheoran *et al.*, 2024). The results of experiments with municipal composts, vermicompost, and biomass obtained following the lakes allow concluding that the highest percentage of the mineral N replacement in rice systems does not result in a decline of yield, but the N leached away in the mineral stores has been adequately reduced in the organic stores (Devi *et al.*, 2025).

Legume crops and rice-legume rotations have tens of kilograms of N/hectare/year, which has been quantified with the assistance of both tracer of 15N and budgeting (Pandey *et al.*, 2024). Even though these inputs enhance soil fertility and system-level NUE, it is a fact that there still may be a leakage of nitrates because of delayed mineralisation during fallow periods or low-uptake periods and hence the theme of the necessity of enacting coordinated fertiliser reductions in legume-based systems is becoming a reality (Dashora *et al.*, 2025).

3.2 Industrial Point Sources

The industrial point sources which include the fertiliser manufacturing units, chemical processing units and food-processing units, are what cause the concentrated nitrogen load into the surface waters especially around the urban and industrial corridors. The multivariate plot of urban lakes within the western region of India shows that high dissolved inorganic nitrogen (DIN), organic matter, and industrial estate and wastewater inflow proximities had a strong relationship (Bharadwaj *et al.*, 2025). Although national totals of N loads by industry remain loosely regulated, at the local level, effluent-based N loads could provide competition to diffuse agricultural contributions to particular situations, in this case, monsoon flushing events (Krishna *et al.*, 2025).

3.3 Municipal and Domestic Wastewater

The wastewater of cities is a promising N source with generation of approximately 3-5 kg N/person/year, which matches the urban loads of 3-5 kg/m^2. The incomplete sewerage systems and inefficient sewage-treatment plants lead to biased removal of nutrients and deluge releases that in turn contribute to the nutrition of the peri-urban rivers and lakes (Soti *et al.*, 2024). Nitrate pollution of shallow aquifers are also contributed by decentralised sanitation systems, and irrigation with wastewater contributes to N turn back to crop fields, which increases short-term soil and groundwater fertility but boosts long-term nitrate deflation in the soils and groundwater (Bharadwaj *et al.*, 2025).

3.4 Atmospheric Deposition

Atmospheric deposition takes several maintenance rates of above or below 20 kg N $ha^{-1}yr^{-1}$ to Indian landscapes, especially over the Indo-Gangetic plain, caused by transport and industrial emission of NOx and agricultural volatilisation of NH3 (Goyal *et al.*, 2024). Although the magnitude of deposition is lower than that of the inputs of fertiliser, it corresponds to, or is larger than that of BNF in non-legume systems and therefore is not a negligible component in watershed-scale N budgets.

3.5 Natural Background Contributions

In undisturbed aquifers, the levels of nitrates of geogenic and natural backgrounds are usually low, and this is evidence of equilibrium between mineralisation and plant uptake in forested or least impacted systems (Pandey *et al.*, 2024). As population growth (agriculture or settlements) increases, anthropogenic sources quickly surpass this, so to speak, base. The distinction of the natural and anthropogenic nitrate is based on the principles of concentrations, the land-use situation, and, in some cases, the isotope evidence of fertiliser and sewage sources (Krishna *et al*., 2025).

3.6 Integrated Nitrogen Budget Framework

The budgets of ICW watershed N incorporate all the major inputs and outflows and surpluses to a model of possible environmental loading and risk of nitrate (Goyal *et al*., 2024). Uncertainty in manure production, fields of crop N content and deposition have specifically been transported with manure production data at the recent district scale enabling scenario analysis and mitigation strategies have been given priority. Relentless lapses in data, particularly those of the industrial effluents, leakage of the septic system and riverine N export is incessant but also signify regions of concern in regard to monitoring and remediation. There is a solid basis for a combination of these budgets with isotopic, hydrochemical and modelling to guide fertiliser regulation, wastewater management and land-use planning towards the reduction of contamination by nitrates and eutrophication.

4.0 Nitrate and Hydrogeological Control in Indian Aquatic Systems

4.1 Groundwater Nitrate: Hydrogeochemical Controls and Regional Contrasts

4.1.1 Indo-Gangetic alluvial aquifers Alluvial Plain

Investigations at the district level throughout the Indo-Gangetic Plain (IGP) indicate that exceedances of nitrates of 45-50 mg L^{-1} are most commonly found in semi-shallow, unconfined formations (30-40 m depth). The predominantly recorded exceedance frequencies are quite high in the region of intensive cultivation, consisting of belts of Punjab, Haryana, and the western parts of Uttar Pradesh, between 30-50% (Ahmad *et al*., 2025; Mondal *et al*., 2025). The fact that there is in this case what seems to be vertical stratification here is not random but is in fact because the recharge pathways and the nitrogen contributions are closely coupled. Higher recharge rates due to monsoon recharge and canal seepage provide rapid movement of nitrate using advection because of oxic sandy horizons, hence decreasing the time available for denitrification.

Facies changes in hydrochemistry (between $Ca-HCO_3$ in shallow and $Ca-Mg-Cl-SO_4$ in deeper history) are inversely correlated with NO_3 001-values and also progressively enhance residence-time-indicating factors (Ahmad *et al*., 2025). Tracer-based investigations have shown that waters reauthorised in the recent decades have disproportionately high anthropogenic loads of nitrate, whereas more deeply (>5080 mm nitrate) have substantially pre-intensive fertiliser utilisation loads, hence have low nitrate concentrations but high salinity and geogenic solutes. Such observations indicate that the depth-dependent attenuation of nitrates is not controlled only by the in-situ removal processes but mainly by hydrologic isolation and redox evolution.

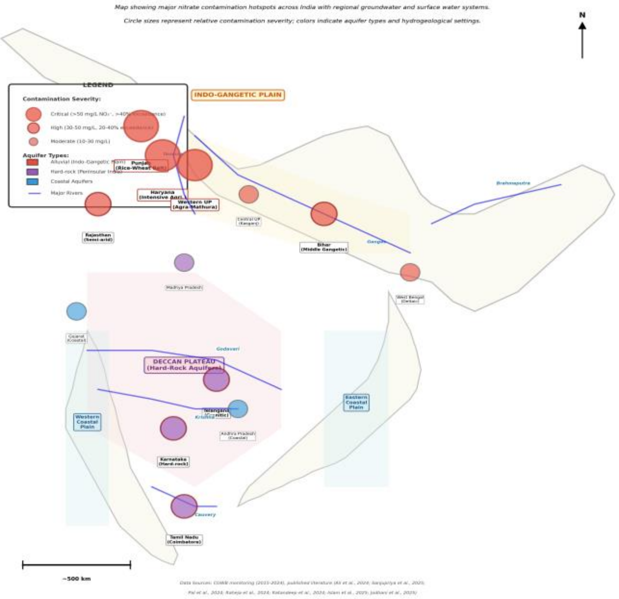

Figure 3: Spatial-Temporal Distribution and Hydrogeological Controls

4.1.2 Hard-Rock Aquifers of the Peninsular India

In crystalline aquifers, the pattern of the distribution of the nitrates depends on what is referred to as spatial concatenation between the inputs of nitrogen and the historically active areas. Whether they are fracture systems of weathered mantles (550 cm thick) or shallow fractures that touch agricultural and peri-urban lands, they always record higher levels of nitrate than the deeper fracture systems with rates of up to 40-50 per cent recorded in parts of the Kaveri basin (Subramaniyan, 2024). The situation is characterised by lateral heterogeneity instead of vertical gradients in contrast to alluvial systems where there is fracture-based flow and suppression of diffusion in the matrix. Lack of the presence of continuously deposited fine grains inhibits the effects of natural attenuation, and thus nitrate may remain in oxic fractures over extensive travel distances. Depending on the depth, where low nitrate levels are found, these probably result from hydraulic isolation rather than active denitrification, which has been concluded through the reported dearth of dissolved organic carbon within these systems.

4.1.3 Coastal Aquifer Systems

Seawater aquifers contain two types of nitrate on one hand: Anthropogenic loading and hydrochemical evolution: salinity. It has been found through the spatial studies at Nagapattinam coast that there exists some kind of disconnection between nitrate and salinity with high NO_3^- in the waters between the farming recharge region and the salty intrusion frontier and high NaCl-low nitrate-dragging along the coastlands (Dhakate, 2024). The mixing and factor analysis techniques can confirm that nitrate is an independent anthropogenic tracer dominating salinisation and not a conservative part of seawater intrusion.

The isotopic findings of the Godavari delta and mass balance also indicate that significant percentage of the nitrogen produced by fertilisers is confined or transformed in the groundwater in the coastal areas and not flushed into the surface waters in a moment, which indicates that groundwater is a reservoir and a latent source of nitrate to the estuaries (Krishna *et al*., 2025).

4.2 Surface Water Nitrate: Catchment Dynamics Storage of Catchment Inputs

The interaction of signals of catchment with the discharge is the cumulative outcome of nitrate in major Indian rivers. The Ganga-Yamuna system analysis has shown that the analysis of nitrate, electrical conductivity, TDS, and agricultural land fraction positively correlate in baseflow, which implies that the groundwater and diffuse contributions prevail. On the contrary, concentrations are diluted by monsoon flows even though the total of the nitrogen fluxes increases (Tiwari *et al*., 2025). This seasonal hysteria shows that hysteresis of concentration-based assessments underestimates nitrate loading at times of high flow.

Time-varying contributions to trend (statistical and good) but weak (monotonic) seasonal variation have been observed once more in such sub-basins as the Betwa (through examining the time variation in trends and water quality) and Chambal (through examining the time variation in nitrogen trends and water quality). Such results amplify the importance of the idea that riverine trends of nitrate are not an adequate measure of nitrogen pressure in areas where groundwater storage prevails (Akiner *et al*., 2024; Singh & Saxena, 2025).

The internal regulation is greater in the lentic systems. The growth of surface-water nitrate increases in high externally loaded lakes and decreases in sediment anoxic lakes, and seasonal denitrification and DNRA substitute permanent opacification in high export lakes (Mondal *et al*., 2025). The urban lakes have urban inputs of nitrates that are in full adherence to the sewage input that reaffirms little scale hegemony of local scales (Bharadwaj *et al*., 2025). In contrast, built and natural wetlands and the biogeochemical processes always have high efficiencies of eliminating the nitrates in terms of combined biogeochemical processes, which validate the designation of the artificial attenuation areas (Singh & Vaishya, 2025).

4.3 Temporal variability of risks, spatial modelling and Zonation

In alluvial, hard-rock, and coastal aquifers, the geostatistical findings show that the spatial autocorrelation of nitrate is moderate to high at kilometre scales; hence, well-defined development of hot spots can be achieved through the use of kriging (Dhakate, 2024; Ahmad *et al*., 2025). Along with the land-use and salinity predictors, combining kriging would improve the potentiation of a plume and, on the other hand, will assist in defining regions of further accumulation of nitrates. These temporal analyses are always characterised by the preeminence of a seasonality over the interannual variations, though when the patterns of the surface water are apparently stable, the data of the district-scale nitrogen surpluses demonstrate the effect of increment in the pressure on the aquifers in the long term (Goyal *et al*., 2024). Hydrogeology and nitrate and co-contaminant vulnerability mapping unanimously identified and classified shallow alluvium and weathered hard-rock environments and agriculturally influenced coastal plains as high-incidence zones (Subramaniyan and Ganesan, 2024).

System	Typical Nitrate Status	Key Controls	Attenuation Potential	Implication
Indo-Gangetic alluvial aquifers	Frequent exceedance in shallow wells (>45 $mg\ L^{-1}$)	High recharge, oxic sands, intensive N inputs	Moderate at depth	Shallow aquifers store legacy nitrate
Hard-rock aquifers	Localized but high exceedance	Fracture flow, thin weathered zone	Low–moderate	Rapid transport, weak buffering
Coastal aquifers	Inland high; near-coast variable	Mixing, salinization, landward recharge	Moderate	Nitrate decoupled from salinity
Major rivers	Moderate concentrations, high flux	Discharge-controlled dilution	Low	Loads underestimated by concentration
Lakes / wetlands	Elevated but variable	Stratification, sediment redox	High (wetlands)	Key zones for N retention/removal

Table 2: Comparative controls on nitrate distribution in major Indian aquatic systems

5.0 Monitoring, Environmental and Health Impact, and Assessment of Nitrate Contamination in India

According to the description in the previous sections, hydrogeological structure, redox environments, land-use practices, and anthropogenic sources of nitrogen are the fundamental controls with reference to nitrate contamination of Indian groundwater and surface waters. The human health, socio-ecological and economic sustainability of these spatially heterogeneous regimes of growth and life lie outside just water chemistry to include human health, ecosystem behaviour and functioning. This section summarises the toxicological, ecological and monitoring evidence of the hydrogeochemical and spatial frameworks set out in Sections 3-4 and especially on the quantitative estimation of risks, coupled biogeochemical processes, and assessment tools most useful in the management of water resources.

5.1 Human Health Implications of Hydrogeochemically Susceptible Environments

The health impacts on humans which result due to exposure to nitrates are closely tied to the shallow groundwater systems which were previously noted as nitrate prone, specifically the alluvial aquifers of the Indo-Gangetic Plain and the eroded hard-rock surfaces. Within such environments ingested nitrate is easily lowered to nitrite and consequently oxidises haemoglobin iron (Fe^{2+} to Fe^{3+}), effectively producing methaemoglobin, which cannot carry oxygen and thus cannot transport oxygen. The control drinking-water endpoint of about 4550 mg/L -NO_3 takes place through this mechanistic route. In its agricultural hubs and peri-urban areas, particularly at India, regular concentrations are recorded by surveying groundwater of 40-60-100 mg/L below the intended limit of 50 mg/L, and this is often exceeded (Sanjupriya *et al*., 2025; Etikala *et al*., 2024).

The repeated findings of risk assessments in these areas of nitrate hotspots are infants and young children as the most vulnerable demographic groups due to both physiological vulnerability and increased intake-to-body-weight ratios. Some basins have reported a non-carcinogenic hazard of drinking water on its own and exhibit values of total Hazard Index that exceed unity among children in the 45-80 per cent range of sampled locations (Islam *et al*., 2025). The results are in line with the redox stratification of the above, whereby the oxic shallow aquifers have retained high levels of nitrates, with the deeper greater strata being the attenuated one arising out of denitrification.

In addition to acute manifestation of methemoglobinemia, an endogenous nitroglyceration of N-nitroso compounds is a matter of concern in the case of chronic exposure to nitrate. Even though the world's preclinical evidence associates nitrate intake with gastric and other associated malignancies, Indian risk evaluations usually do not consider nitrate as a carcinogen because of a few scanty dose-response agencies and the prevailing influencing diet and bacteriological elements (Jodhani *et al*., 2025). However, the comorbidity which takes place with gastrointestinal infection along with dietary precursors in areas of a high level of exposure to nitrate points to the idea that current models might underestimate long-term risk. The exposure of nitrates is also associated with endocrine interference with regional hydrochemistry. Competing with iodide to be taken up by thyroid follicular cells, nitrate was mentioned in previous sections as a spatial competitor to iodine-deficient areas of semi-arid and Himalayan India, where nitrate-rich groundwater overlaps iodine-deficient areas. Such an agreement provokes some questions about subclinical hypothyroidism and its possible neurodevelopmental consequences in children, but direct epidemiological data about this issue in the Indian setting is still scarce (Jodhani *et al*., 2025). The priority in the mitigation strategies is supported by reported hazard indices, with the highest levels reported to be in infants, children and pregnant women (Islam *et al*., 2025).

5.2 Ecosystem Reactions and Biogeochemical Feedbacks

The ecological effects of nitrate contamination are most eminent in surface water, which incorporates diffuse groundwater and exerts nutrient load as a result of agriculture and urban effluents, as has been explained in the spatial analyses of Section 5. Nitrate levels with frequent occurrence of phosphate and organic matter increase the eutrophication in rivers, lakes and reservoirs throughout India. The presence of hypereutrophic situations, low indices of water quality, and predominance of cyanobacteria recorded under high-nutrient settings are recorded in studies of the Ganga household water, Brahmani household water, and urban water bodies skilled in Haridwar (Das *et al*., 2025; Simon□ *et al*., 2025). This change in ecosystems can also be in terms of dynamics of nutrition constraints where the nitrogen enrichment removes the N constraint, enabling the taxa of cyanobacteria to compete more successfully over the diatoms, namely during warm and low-flow climates. The blooms that result cause the increased potential to form toxins and cause hypoxia in the biomass decay which changes fish and macroinvertebrate communities and disrupts the ecosystem level of service. Nitrate forecasting models designed based on machine learning, namely, on the Ganga basin, clearly tie nutrient regulation to fisheries and river health protection, which aids in the additional organisation of management applicability of the 'vulnerability mapping' precedent (Das *et al*., 2025).

Nitrate enrichment affects the nitrogen-phosphorus-carbon cycling at the biogeochemical level. Indian research shows that there is a high covariance among nitrate, phosphate and biochemical oxygen demand and dissolved oxygen, which indicates that there are feedbacks that promote the rapid consumption of oxygen and alterations in carbon processing in water bodies (Das *et al*., 2025; Simon□ *et al*., 2025). The sterling nature of nitrate in oxic regions of groundwater is also a source of nitrite to generate N_2O during partial denitrification, as well as leads to acidity due to releases of protons through nitrification in the ground in weakly buffered waters and reportedly highly vulnerable cases (Jodhani *et al*., 2025).

5.3 Integration of Monitoring, Assessment and Management

In line with the assessment conceptualisations presented by Section 5, the monitoring of nitrates in India is still characterised by laboratory-based UV-vis spectrophotometry according to standardisation and complemented by multi-parameter hydrochemical examination (Sanjupriya *et al*., 2025). ICP based and ion chromatography are used in integrated studies which need to cover wider uses of both ionic and metal datasets (Tiwari *et al*., 2025). The use of remote sensing, which is widely supplemented with field chemistry, makes the basin-level evaluation of trophic status and wetland physiogamy more feasible, complementing the point-based method of monitoring (Mohanty & Pandey, 2025).

Although these advances have been made, there exist limitations of data. The majority of the research based on the seasonal or annual samples is restricted; as such, it impedes the identification of episodic or sporadic nitrate pulses associated with fertiliser application or monsoon recharge as well as sewage overflow. The national assessment is not that representative because spatial gaps continue to be severe in remote and tribal areas. Indicators using water quality and nitrate-specific indices are also very popular in terms of risk communication, and today, machine-learning models can already attain good predictive performance of nitrate susceptibility mapping (R^2 approximately 0.8) in individual basins throughout India (Das *et al*., 2025a; Raheja *et al*., 2024). Integrating these tools with process-based transport models and developing sensor networks provides a route leading to proactive management of the basin-scale in terms of nitrates in accordance with the hydrogeochemical insights gained in previous sections.

6.0 Nitrate Pollution and its Management and Mitigation: Field to Watershed

To mitigate nitrate contamination of aquatic systems in India, an integrated solution will be required by taking into account the struggle of nitrogen sources, the pathways of transformation, and the transportation data of the nitrate to the agricultural terrain, urban surroundings, and aquifer system. The continuation of the nitrate as outlined in previous parts shows the existence of a discordance between the intensity of nitrogen loading and the inherent assimilative or denitrification capacity of the soils, sediments, and waters. Technical intervention therefore follows that management of excess nitrogen can only be effectively achieved by reducing the source of excess and at the same time increasing the paths of attenuation.

6.1 Nitrogen Use Efficiency and Agriculture Source Control

Agriculture is still the leading source of diffuse loading of nitrates in the Indian groundwater and surface water, and thus the focus of improving nitrogen use efficiency (NUE) takes significance in the mitigation measures. Accurate nutrient management strategies that has transformed the 4R framework of the right source, right rate, right time and right placement have continually resulted in nitrogen excess reduction, without reducing yields. The concept of site-specific nutrient management (SSNM), which is based on soil tests, geospatial zoning, and crop sensors, is more precise in matching nitrogen fertiliser with crop demand and reducing the presence of residual nitrate that is prone to leaching (Chatterjee *et al*., 2024; Bhagwan *et al*., 2025). Cereal and milk experiments conducted in the field show that sensors guided SSNM increase grain production as well as the use efficiencies of nitrogen, phosphorus, and potassium by 20-35 per cent compared to blanket recommendations (Bhattacharya *et al*., 2025; Bhagwan *et al*., 2025). On the same note, neem-coated urea and integrated nitrogen management (INM) systems in rice-wheat systems can enhance the ability of the nitrogen recovery and mitigating the nitrate leaching and gaseous losses, hence reducing the overall nitrogen footprint of the production (Garg *et al*., 2024; Walia *et al*., 2024). Improved-efficiency fertilisers, such as coated urea and nitrification inhibitors, also reduce the formation of nitrates in the soils, allowing a decrease in the fertiliser inputs (≈7–9%) with minimal impact on the emissions of nitrogen oxides and the life-cycle intensity of greenhouse gases (Leon & Nedumaran, 2024; Sandeep *et al*., 2025). They are complemented by agronomic interventions that enhance internal complementary agronomic nitrogen cycling. Legume rotations, green manures, and cover crops accumulate with what is leftover of nitrate and enable biological fixation, which enables reduced nitrogen levels with time of DN mineral rates with time (Gatkal *et al*., 2024; Pramanick *et al*., 2024). There is an increase in the soil organic carbon, soil biomass, and the nutrient buffering capacity with long-term INM trials applying farmyard manure, crop residues, and green manures that do not reduce the yields at varying levels of rainfall condition (Devi *et al*., 2025; Garg *et al*., 2024). The use of conservation tillage and the preservation of residual also optimises the soil fabric and water retention, whereas controlled irrigation methods, such as the optimisation of nitrogen management in direct-seeded rice systems, significantly reduce water consumption and the amount of nitrate (Velmurugan and Pandian, 2024). Such efficiency realisations promote evident signifiers of policy reforms. Subsidies like nutrient-based or performance-based subsidies on fertilisers that compensate the growth of NUE instead of the consumption rates of fertilisers have the potential of reducing the nitrate loading without reducing farm profitability (Bhagwan *et al*., 2025; Leon and Nedumaran, 2024).

6.2 Wastewater and Industrial Management of Nitrogen

Point-source nitrogen sources brought about through municipal and industrial effluents are growing to localised hotspots of nitrates that were detected previously during spatial evaluation. Greater biological nutrient removal (BNR) systems such as moving-bed biofilm reactors and membrane bioreactors have been shown to have a high ammonium and nitrate removal efficiency and are optimally suited to high-density urban environments (Sultan *et al*., 2024). Low-energy options, namely aerated vertical-flow and hybrid built wetlands, have been shown to increase the nitrogen-cleaning efficiency breakdown in dual-cycle carbon-nitrogen-sulphur cycling (two fourfold), a Memphis wastewater polishing method of extending a scale to a high level (Soti *et al*., 2024; Krishna and Rakesh, 2025).

In case of industrial effluents produced by fertiliser, chemical, and food-processing industries, there is a trend to use a mixed approach of physicochemical treatment (ion exchange, electrocoagulation) along with zero-liquid discharges. Wetlands and specific microbial communities, which offer affordable secondary treatment of nitrogen-contaminated wastewater with a limited centralised infrastructure, are built under wet conditions (Soti *et al*., 2024; Sultan *et al*., 2024).

6.3 Groundwater Remediation and Nature-based Solutions

In the situations where the pollution of the nitrates has already been confirmed, the remediation is geared towards elimination or mitigation. Physicochemical techniques that are effective in the removal of nitrate are reverse osmosis, nanofiltration, and electrodialysis, but they have drawbacks such as energy use, brine discharge, and cost, which reduces their applications in rural India (Sultan *et al*., 2024; Datta *et al*., 2025). Here, treatment systems in terms of communities are usually more viable as compared to the household based units.

The provided solutions in nature provide complementary solutions by the enhancement of in-situ denitrification and dilution. Meanwhile, artificial wetlands, riparian buffers, floodplain reconnection, and pre-treated water-controlled aquifer recharge facilitate the peddling of microbial nitrate reduction in addition to provision of co-benefits to biodiversity and groundwater bodies (Soti *et al*., 2024; Krishna and Rakesh, 2025). It has also been shown that phytoremediation and vegetated systems are also effective in shallow contaminated aquifers and this has put the emphasis on the possibility of phytoremediation as part of the decentralised remediation (Datta *et al*., 2025).

6.4 Integrated Watershed Management

Sustainable nitrate reduction is eventually subjected to the integrated watershed management coordinated to agricultural best management practices, upgrading of wastewater treatment systems, and protection of aquifers. The engagement of farmers and industries with utility agents is needed to be organised into various participatory frameworks that can cross-volunteer the variability of the interventions across scales (Pramanick *et al*., 2024; Bhagwan *et al*., 2025). By integrating nitrate reduction into national soil health, irrigation and water quality initiatives and indicators of performance (NUE, groundwater nitrate dynamics, and wetland performance), it becomes possible to manage in an adaptive way aligned with the hydrogeochemical controls and susceptibility patterns of the previous sections.

7.0 Research Gaps on Nitrate and Future research

Although the spatial extension of nitrate pollution across Indian waters has been extensively delimited, scholastic investigation has been more of a descriptive nature by using the hydrochemical profiling and statistical examination of the pollution instead of a mechanistic explanation of the subsurface nitrogen cycling. Such empirical validation of denitrification, dissimilatory nitrate reduction to ammonium (DNRA), and anaerobic ammonia oxidation (anammox) has been mostly limited to natural environments engineered with vertical-flow nitrate removal, especially anaerobic aerated vertical-flow constructed wetlands (SAV)—although similar process-level studies in natural systems, in particular those of hard-rock lithology, are also quite few and far between (Soti *et al*., 2024). Moreover, it is clear that the impact of tropical thermal regimes on system modeling and monsoon-induced redox disequilibrium, as well as the potential influences on the distribution of nitrogen between competing biogeochemical pathways, have been quantified inadequately, although process-based models highlight a strong dependence of nitrate levels on levels of rainfall and temperatures (Pareta, 2024).

The existing literature is predetermined by short monitoring campaigns with a limited spatial resolution, which negatively affect the identification of strong temporal patterns, the modelling of development of the legacy nitrate mass, and the identification of the origins (Ali *et al*., 2024; Karunanidhi *et al*., 2025). Sustained and multi-decadal time series have been established and embedded in far larger, nested networks of monitoring networks between individual wells and larger structures; event-based sampling during swells of the monsoon and irrigation perturbations and the use of age-dating methods based on hydrogeologic age constitute a methodological requirement of invaluable significance, but these have remained extremely uncommon (Raheja *et al*., 2024; Prasun and Singh, 2024). The evaluation of public-health outcomes has been minorly limited to either cross-sectional surveys using non-carcinogenic risk indices, a lack of large cohort epidemiological studies, biomarker-based exposure assessments, or burden measures of communities with high levels of nitrate in terms of disability-adjusted life years (DALYs) (Sanjupriya *et al*., 2025). However, there is still a lack of other methodological aspects, such as the relative lack of compound-specific isotope tracing, a relatively low use of metagenomic data, and a relative shortage of process-constrained predictive models. Although even the young implementation of machine-learning applications often does not incorporate quantifying the uncertainty or conducting a scenario analysis in the context of climate change or changing land use (Das *et al*., 2025; Venkatesh *et al*., 2024). The resolution of these gaps requires an integrated, longitudinal, and interdisciplinary research agenda that defines specific connections between the nitrogen biogeochemistry, indicators of human health, and delivery of evidence-based policy provisions (Jodhani *et al*., 2025).

Conclusion

The cost burden of the nitrate contamination in the Indian water bodies is an interaction between the intensive farming activities, heterogeneous hydrogeological environments, and long-term inadequacies in the water governance. The major causes of spatial heterogeneity are changes in land-use patterns and aquifer property, but temporal changes depend on events of recharging caused by monsoons and irrigation practices. Such observations demonstrate the ineffectiveness of single, purely assessments and highlight the importance of complex, process-based systems in general.

Biogeochemical processes based on redox play a crucial role in the control of nitrate transport and degradation, whereas their effectiveness is highly discordant among various aquifer systems. At the same time, their constant violations of drinking water norms endanger human health and freshwater life and worsen the already existing socio-economic vulnerabilities. Thus, the mitigation plans should go beyond the traditional end-of-pipe interventions and include accuracy-controlled nutrients, adjustable irrigation time, and nature-based interventions on a watershed scale. The need to transform academic knowledge into a sustained water quality benefit is impossible without harmonised policy regimes, protracted surveillance and participatory forms of governance. The enhancement of such interrelations would provide a feasible approach toward attaining sustainable nitrogen stewardship in the context of the transforming trends in the environmental and developmental situation in India.

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