JOURNAL OF PHARMA INSIGHTS AND RESEARCH ISSN NO. 3048-5428

REVIEW ARTICLE

Health Effects and Remediation Measures for Nitrate Contamination in Water Resources

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Publication history: Received on 3rd Mar 2025; Revised on 16th March 2025; Accepted on 17th March 2025

Article DOI: 10.69613/acvf0037

Abstract: Nitrate contamination in water resources is a significant environmental and public health challenge globally. This review provides the current knowledge about nitrates in water systems, their sources, detection methods, and health effects. Nitrates, predominantly entering water systems through agricultural runoff, wastewater discharge, and industrial effluents, pose substantial health risks when present in drinking water above permissible limits. The transformation of nitrates to nitrites in the human body can lead to serious health conditions, including methemoglobinemia and potential carcinogenic effects. Various detection methods, ranging from simple colorimetric tests to modern analytical techniques, enable monitoring of nitrate levels in water sources. The effectiveness of remediation measures, particularly reverse osmosis systems, show variable success rates in nitrate removal, with recent studies indicating approximately 85% removal efficiency. It can be concluded that there is a crucial need for regular monitoring, implementation of effective water treatment, and development of innovative solutions to address nitrate contamination in water resources, ensuring safe drinking water accessibility for populations worldwide.

Keywords: Nitrate contamination; Water quality; Methemoglobinemia; Reverse osmosis; Public health.

1. Introduction

The presence of nitrates in water resources has emerged as a critical environmental concern with significant implications for human health and ecological systems [1]. Nitrates, chemical compounds with the molecular formula NO_3^-, represent the stable form of nitrogen commonly found in aqueous environments, characterized by their distinctive molecular architecture and chemical behavior [2]. Their exceptional solubility in water facilitates their mobility through complex soil matrices and diverse aquatic systems, making them particularly persistent and challenging environmental contaminants [3]. The widespread and intensive use of nitrogen-based fertilizers in modern agricultural practices, coupled with accelerating industrialization and expanding urbanization patterns, has led to significantly elevated nitrate concentrations in various water bodies, ranging from surface waters to deep aquifers [4]. Nitrates are sophisticated inorganic compounds comprising one nitrogen atom bonded to three oxygen atoms, forming a distinctive planar molecular structure. This unique structural arrangement results in a delocalized negative charge distribution across the oxygen atoms, which makes nitrates highly soluble in water. The molecular geometry and electronic configuration enable extensive mobility in aqueous environments, contributing to their persistent nature in water systems. The compound's structural characteristics also influence its chemical reactivity and interactions with various environmental constituents [5].

The molecular properties of nitrates encompass a trigonal planar geometry with the nitrogen atom at the center, featuring bond angles of approximately 120 degrees between oxygen atoms. The compound exhibits resonance stabilization which contributes to its chemical stability, along with high solubility coefficients in aqueous solutions. These characteristics are complemented by strong electron-accepting capabilities in reduction reactions, further influencing their environmental behavior and fate. The environmental fate of nitrates is intricately linked to the global nitrogen cycle, representing a complex network of biogeochemical processes and transformations. Natural processes, including bacterial nitrification of ammonium compounds and atmospheric deposition through precipitation and dust particles, contribute to establishing background nitrate levels in environmental systems. However, anthropogenic activities have significantly altered these natural cycles, creating imbalances in nitrogen distribution and transformation patterns across different environmental compartments [6].

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The cycling process incorporates bacterial-mediated transformations in soil and water systems, alongside atmospheric deposition patterns and variations. These mechanisms are further influenced by interactions with soil organic matter and minerals, as well as complex groundwater transport mechanisms. Surface water dynamics and seasonal variations play crucial roles in determining nitrate distribution and concentration patterns. The cycling process involves multiple interconnected pathways and transformation mechanisms that determine the ultimate fate and distribution of nitrates in environmental systems. These processes are significantly influenced by various environmental factors, including temperature, pH, oxygen availability, and microbial community composition.

2. Sources of Nitrate Contamination

2.1. Agricultural Sources

Agricultural activities represent the primary and most pervasive source of nitrate contamination in water resources worldwide. The extensive and often excessive application of synthetic fertilizers and animal manure introduces substantial quantities of nitrogen compounds into soil systems, creating long-term environmental challenges [7]. Modern agricultural practices, characterized by intensive farming methods and high-yield crop production, have led to unprecedented levels of nitrogen input into agricultural ecosystems. These practices often exceed the natural absorption capacity of crops and soil systems, resulting in significant nitrogen surplus. The movement of nitrates from agricultural lands into water resources occurs through complex hydrogeological processes. Precipitation and irrigation practices facilitate the vertical and lateral transport of these compounds into groundwater aquifers and surface water bodies [8]. The timing and intensity of rainfall events, combined with irrigation scheduling and soil characteristics, significantly influence the leaching patterns of nitrates. Seasonal variations in agricultural activities, including fertilizer application periods and crop rotation cycles, create temporal patterns in nitrate loading to water resources. The problem is further exacerbated by the cultivation of nitrogen-intensive crops and the concentration of livestock operations in certain geographical areas.

2.2. Urban Sources

Urban wastewater discharge, including effluents from municipal treatment facilities and septic systems, constitutes a significant and growing source of nitrate pollution in water resources [9]. The increasing urbanization trends worldwide have intensified this problem, with many urban areas experiencing rapid population growth and corresponding increases in wastewater generation. Municipal treatment facilities, despite employing advanced treatment technologies, often struggle to achieve complete nitrogen removal, resulting in consistent nitrate loading to receiving water bodies.

2.3. Industrial Sources

Industrial processes contribute substantially to nitrate pollution through various pathways. Chemical manufacturing facilities, particularly those producing fertilizers, explosives, and synthetic materials, generate significant quantities of nitrogen-containing waste products. Food processing industries, including meat processing plants and dairy operations, also release substantial amounts of nitrogen-rich effluents. These industrial sources, combined with atmospheric deposition from industrial emissions, create complex patterns of nitrate contamination in urban and industrial zones [10]. The concentration of industrial activities in specific geographical areas often leads to localized hotspots of nitrate pollution, presenting unique challenges for water resource management and environmental protection. The interaction between these various sources - agricultural, urban, and industrial - creates cumulative effects that can significantly impact water quality at regional and watershed scales.

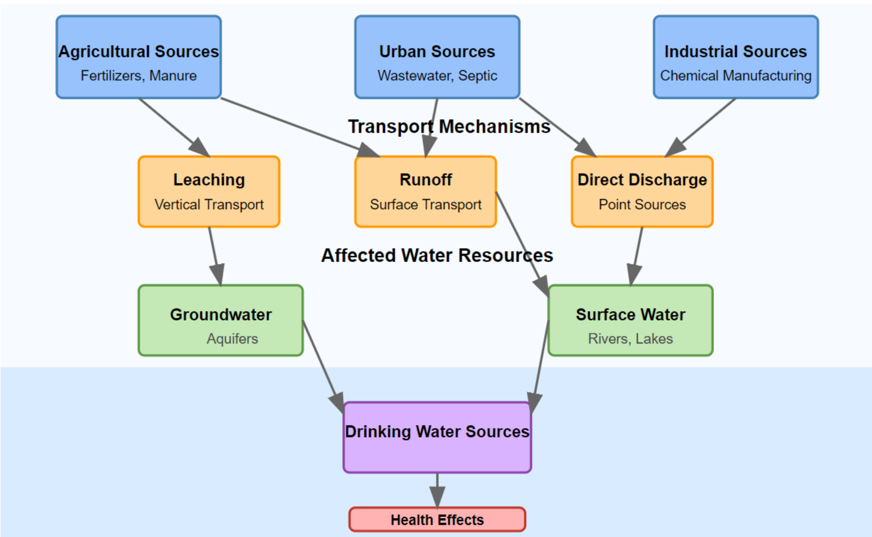

Figure 1. Sources of Nitrate Contamination

3. Methods for Detection and Monitoring Nitrates

3.1. Field Testing

The quantification of nitrate concentrations in water employs a diverse array of analytical methods, ranging from simple field tests to sophisticated laboratory techniques. Colorimetric test kits, widely used in field applications, utilize specific reagents that produce distinct color changes proportional to nitrate concentrations, providing rapid preliminary assessments of water quality [11]. These field methods incorporate various chemical reduction processes, typically converting nitrate to nitrite, followed by diazotization reactions that yield colored compounds. While these approaches offer immediate results and operational simplicity, they face certain limitations in terms of accuracy, detection limits, and potential interference from other chemical species present in water samples.

Field testing methods have evolved to include portable electronic meters and handheld spectrophotometers, enabling more precise on-site measurements. These devices often integrate temperature compensation and multiple wavelength analysis to minimize interference effects. The development of field-deployable testing techniques continues to focus on improving reliability while maintaining the practical advantages of rapid, in-situ analysis.

3.2. Laboratory Analytical Techniques

Advanced analytical methods employed in laboratory settings offer substantially higher precision and reliability in nitrate determination. Ion chromatography represents a powerful separation technique that enables simultaneous analysis of multiple ionic species, including nitrate, while effectively managing potential interferents. UV-visible spectrophotometry, particularly when coupled with automated flow injection analysis systems, provides highly accurate nitrate measurements through carefully controlled reaction conditions and precise optical detection [12]. These sophisticated laboratory methods can consistently detect and quantify nitrate concentrations at parts per billion levels, making them essential for regulatory compliance monitoring and detailed environmental studies [13].

Table 1. Comparison of Different Nitrate Detection Methods

Method	Detection Limit	Analysis Time	Cost	Advantages	Limitations
Colorimetric Test Kits	1-100 mg/L	5-10 minutes	Low	Simple, portable, rapid results	Limited accuracy, subjective color interpretation
Ion Chromatography	0.1-0.5 mg/L	15-30 minutes	High	High precision, multi-ion analysis	Complex equipment, requires expertise
UV Spectrophotometry	0.2-1.0 mg/L	10-15 minutes	Moderate	Good precision, automated	Potential interference from other ions
Ion-Selective Electrodes	0.5-1.0 mg/L	Real-time	Moderate	Continuous monitoring, rapid response	Regular calibration needed, drift issues
Capillary Electrophoresis	0.1-0.5 mg/L	10-20 minutes	High	High resolution, small sample volume	Complex operation, high maintenance

Modern laboratory techniques often incorporate quality control measures such as matrix spike recoveries, certified reference materials, and internal standards to ensure analytical accuracy and precision. The development of hyphenated techniques, combining multiple analytical methods, has further enhanced the capability to analyze complex environmental samples while maintaining high sensitivity and selectivity for nitrate determination.

3.3. Continuous Monitoring Systems

Recent technological advancements have enabled the development of sophisticated real-time monitoring systems utilizing ion-selective electrodes and spectrophotometric sensors. These advanced systems provide continuous data streams on nitrate levels, facilitating immediate response to contamination events and enabling detailed temporal analysis of nitrate behavior in aquatic systems [14]. Modern continuous monitoring platforms integrate multiple sensor types, data logging capabilities, and remote transmission features, allowing for comprehensive water quality surveillance across distributed monitoring networks. The evolution of continuous monitoring technology has led to the implementation of smart sensor networks that can automatically adjust measurement frequencies based on detected concentration changes or environmental conditions. These systems often incorporate anti-fouling mechanisms and self-calibration features to maintain long-term measurement reliability

4. Health Effects

4.1. Methemoglobinemia

The primary health concern associated with nitrate exposure through drinking water is methemoglobinemia, a serious blood disorder particularly affecting infants under six months of age, often referred to as "blue baby syndrome" due to its characteristic symptoms [15]. This potentially life-threatening condition results from the biochemical conversion of nitrate to nitrite in the digestive system, which then interferes with oxygen transport in blood by converting hemoglobin to methemoglobin. The process fundamentally alters the oxygen-carrying capacity of blood cells, potentially leading to severe oxygen deficiency in tissues [16]. The heightened vulnerability of infants stems from their unique physiological characteristics, including higher gastric pH levels, immature enzyme systems, and the presence of fetal hemoglobin, which is more susceptible to conversion to methemoglobin.

4.2. Carcinogenicity

4.2.1. Nitrosamine Formation

The endogenous formation of N-nitroso compounds from nitrites presents significant concerns regarding carcinogenic potential in exposed populations [17]. These compounds form through complex chemical reactions in the acidic environment of the stomach, particularly in the presence of secondary amines and amides from dietary sources. The resulting N-nitroso compounds have demonstrated potent carcinogenic effects in experimental studies, particularly in the gastrointestinal tract, where they can directly interact with cellular DNA and trigger mutagenic changes [18]. The formation of these compounds is influenced by various factors, including dietary composition, gastric conditions, and the presence of inhibitors or promoters of nitrosation reactions.

4.2.2. Epidemiological Evidence

Strong correlations exist with colorectal, gastric, and thyroid cancers, particularly in populations consuming high-nitrate water combined with high meat intake [19]. These associations are strengthened by dose-response relationships observed in long-term exposure studies. The interaction between dietary factors and nitrate exposure appears to play a crucial role in cancer risk, with certain dietary patterns potentially enhancing or mitigating the carcinogenic effects of nitrate exposure.

Table 2. Health Effects Associated with Different Nitrate Exposure Levels in Drinking Water

Concentration Range (mg/L as NO_3^-)	Population Group	Potential Health Effects	Risk Level
0-10	All groups	No adverse effects observed	Negligible
10-50	Infants (<6 months)	Possible methemoglobinemia risk	Low to Moderate
50-100	All groups	Increased methemoglobinemia risk, possible endocrine disruption	Moderate
>100	All groups	High risk of methemoglobinemia, potential carcinogenic effects	High
Chronic exposure >50	Adults	Possible increased cancer risk, thyroid dysfunction	Moderate to High

5. Treatment of water resources

5.1. Reverse Osmosis

5.1.1. Principle

Reverse osmosis (RO) technology represents a sophisticated water treatment approach that employs semi-permeable membranes to remove dissolved contaminants, including nitrates. The process relies on pressure-driven separation, where water molecules pass through the membrane while larger ions, including nitrates, are retained and concentrated in the reject stream [20]. The effectiveness of RO systems depends on membrane characteristics, including pore size distribution, surface charge, and hydrophobicity, as well as operational parameters such as applied pressure, recovery rate, and cross-flow velocity.

5.1.2. Efficiency and Limitations

Recent studies conducted in 2024 have demonstrated impressive results, achieving approximately 85% nitrate removal efficiency using advanced RO systems [21]. However, system performance depends on a complex interplay of various factors, including membrane characteristics, operating conditions, and initial nitrate concentrations [22]. The effectiveness of RO treatment can be influenced by i. The quality of the feed water, including the presence of other dissolved solids and potential foulants ii. Operating parameters such as pressure, temperature, and recovery ratio iii. Membrane properties and their degradation over time iv. System maintenance and cleaning protocols and v. Energy consumption and operational costs.

5.2. Ion Exchange

Ion exchange systems specifically designed for nitrate removal represent a highly effective treatment approach, utilizing specialized resins that exchange chloride ions for nitrate ions through a selective chemical process. These systems consistently demonstrate exceptional efficiency, often achieving removal rates exceeding 90% under optimal operating conditions [23]. The process involves carefully engineered ion exchange resins with specific selectivity for nitrate ions, enabling effective separation even in the presence of competing anions. However, regular resin regeneration and proper disposal of regenerant solutions remain significant operational challenges that require careful management and consideration of environmental impacts [24]. The effectiveness of ion exchange systems depends on various operational parameters, including resin type, bed volume, flow rate, and regeneration frequency. The technology continues to evolve with the development of more selective resins and improved regeneration processes.

Table 3. Efficiency of Different Treatment Methods for Nitrate Removal

Treatment Technology	Removal Efficiency (%)	Initial Investment	Operating Cost	Maintenance Requirements	Waste Generation
Reverse Osmosis	85-95	High	Moderate	Moderate	High (brine)
Ion Exchange	90-98	Moderate	Low	High	High (regenerant)
Biological Denitrification	95-100	High	Low	High	Low
Electrodialysis	65-85	High	High	Moderate	Moderate
Chemical Reduction	70-90	Moderate	High	Low	Moderate

5.3. Biological Denitrification

Biological treatment methods employ specialized denitrifying bacteria to convert nitrates into harmless nitrogen gas through a series of biochemical reactions. This approach offers a sustainable and environmentally friendly solution, particularly for large-scale water treatment facilities, though careful control of operational parameters is essential for optimal performance [25]. The process requires specific environmental conditions, including appropriate carbon sources, temperature ranges, and dissolved oxygen levels, to maintain healthy bacterial populations and efficient denitrification rates. Recent advances in bioreactor design and microbial community management have enhanced the reliability and effectiveness of biological treatment systems.

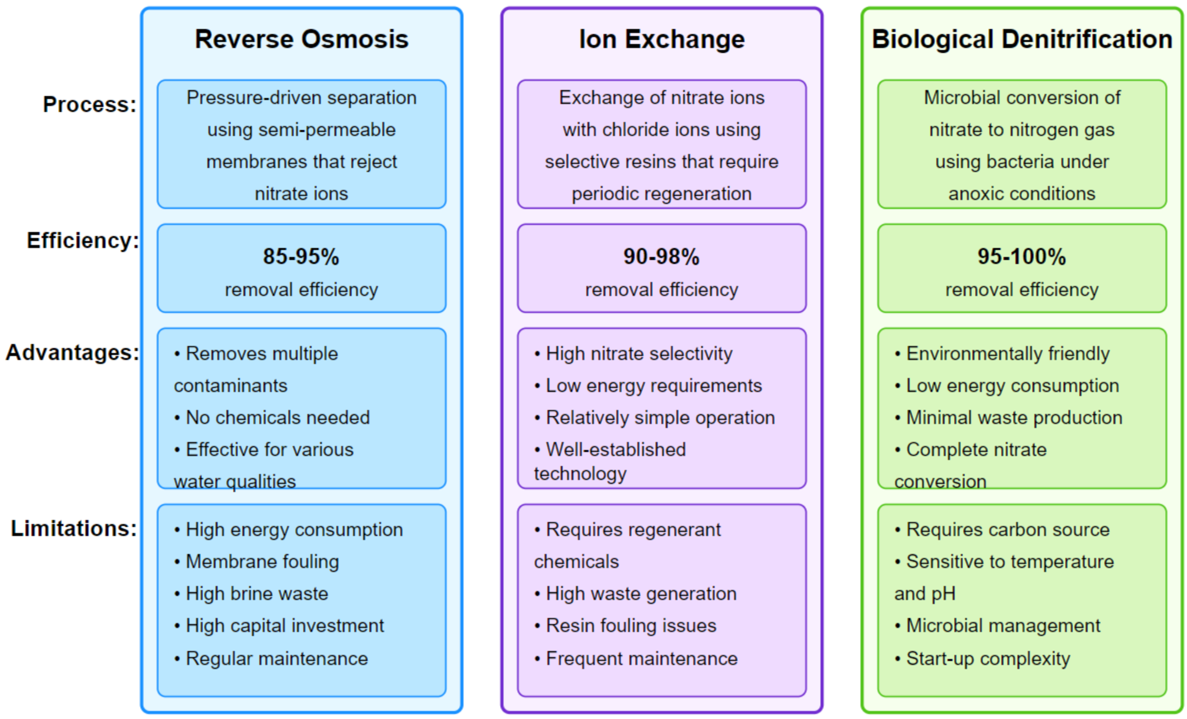

Figure 2. Treatment of Water Resources for Nitrate Removal

6. Standard Guidelines

6.1. International Standards

The World Health Organization (WHO) has established comprehensive guidelines for nitrate concentrations in drinking water, setting the maximum permissible level at 50 mg/L as nitrate [26]. These guidelines serve as a fundamental reference point for national regulatory frameworks worldwide, incorporating extensive toxicological research and risk assessment studies. The WHO guidelines consider various factors, including exposure patterns, vulnerable populations, and technological feasibility of treatment methods. These standards are regularly reviewed and updated based on emerging scientific evidence and evolving understanding of health impacts.

Table 4. Maximum Permissible Limits for Nitrate in Drinking Water

Regulatory Authority/Organization	Region/Country	Maximum Permissible Limit	Year Updated
World Health Organization (WHO)	International	50 mg/L as NO_3^-	2022
US Environmental Protection Agency (EPA)	United States	44.3 mg/L as NO_3^- (10 mg/L as N)	2021
European Union (EU)	European Union	50 mg/L as NO_3^-	2020
Health Canada	Canada	45 mg/L as NO_3^-	2023
Australian Drinking Water Guidelines	Australia	50 mg/L as NO_3^-	2021
Bureau of Indian Standards	India	45 mg/L as NO_3^-	2022

6.2. Regional Variations

Different countries and regions have adopted varying standards based on detailed local conditions and risk assessments specific to their populations and environmental contexts. The United States Environmental Protection Agency (EPA) maintains a more stringent standard of 10 mg/L as nitrogen (equivalent to 44.3 mg/L as nitrate) [27]. These regional variations reflect differences in risk assessment approaches, technological capabilities, and socioeconomic factors. The implementation of these standards involves comprehensive monitoring programs, enforcement mechanisms, and public health surveillance systems.

7. Management of Nitrate Pollution

7.1. Source Control

Implementing agricultural best management practices represents a crucial and proactive approach to reducing nitrate contamination at its source. These practices encompass a wide range of interventions, including optimized fertilizer application methods, improved irrigation efficiency techniques, and the strategic establishment of buffer zones near water bodies [28]. Modern agricultural management approaches integrate precision farming technologies, soil testing programs, and crop-specific nutrient management plans to minimize excess nitrogen application while maintaining agricultural productivity.

7.2. Monitoring and Early Warning Systems

Development of comprehensive monitoring networks and early warning systems enables timely detection and response to nitrate contamination events. Integration of real-time sensors with sophisticated data analytics platforms enhances the effectiveness of water quality management programs [29]. These systems incorporate advanced telemetry, automated sampling procedures, and predictive modeling capabilities to provide early warning of potential contamination events. The implementation of smart monitoring networks allows for adaptive management responses and improved resource allocation in water quality protection efforts.

7.3. Recent Trends

Recent advances in nanotechnology and biotechnology offer promising solutions for nitrate removal, representing potential breakthroughs in treatment efficiency and cost-effectiveness. Novel materials, including functionalized nanoadsorbents and enhanced biological treatment systems, demonstrate significant potential for improved treatment efficiency and operational flexibility [30]

8. Conclusion

The presence of nitrates in water resources poses significant challenges to public health and environmental quality. The complexity of nitrate contamination requires measures like source control, effective monitoring, and advanced treatment technologies. Although treatment methods like reverse osmosis are effective, continued research and technological innovations in this area remains essential. The implementation of prevention and remediation measures, supported by government/administrative policies, are crucial for ensuring safe drinking water supplies and protecting public health.

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