



Nitrate Removal from Contaminated Water Sources Using Pyrite-Based Autotrophic Denitrification

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Article Info

Article type:

Research Article

Article history:

Received: 2026/01/30

Received in revised form:
2026/02/20

Accepted 2026/02/31

Available online: 2026/03/06

Keywords:

Autotrophic denitrification,
Constructed wetland,
Mineral electron donor,
Nitrate removal,
Pyrite (FeS₂).

ABSTRACT

In recent years, autotrophic denitrification has attracted considerable attention as an effective alternative to heterotrophic processes due to its independence from external organic carbon sources, lower sludge production, and reduced operational costs. This review paper examines the role of inorganic electron donors in nitrate removal, with particular emphasis on pyrite (FeS₂). Owing to its natural abundance, chemical stability, low cost, and the simultaneous oxidation of iron and sulfur, pyrite has demonstrated high efficiency in removing nitrate from contaminated water. Furthermore, pyrite oxidation creates favorable conditions for the growth and activity of autotrophic denitrifying bacteria, enabling efficient nitrate removal without the addition of external carbon sources. Recent studies have also shown that FeS₂ can contribute to phosphorus removal through the formation of iron-containing compounds as well as adsorption and precipitation mechanisms. In Iran, nitrate contamination is considered one of the most critical groundwater quality challenges, particularly in arid and semi-arid regions where groundwater serves as the primary source of drinking water. Investigations conducted in several regions of the country, including Tehran–Karaj, Mashhad, Isfahan, Robat Karim, and Kerman, have reported nitrate concentrations exceeding the World Health Organization guideline value (50 mg/L), with levels surpassing 160 mg/L in some wells. The primary sources of this contamination include intensive agricultural activities, excessive application of nitrogen fertilizers, wastewater infiltration, and inadequate groundwater management. The persistence of these conditions poses serious risks to public health, especially for children, and threatens the sustainability of water resources. Therefore, implementing advanced treatment technologies, particularly pyrite-based autotrophic denitrification, represents a promising, cost-effective, and sustainable approach for the simultaneous removal of nitrate and phosphorus and the improvement of groundwater quality in Iran.

Introduction

Water covers more than 70% of the Earth's surface; however, freshwater resources are severely limited, with only about 3% of the total water on Earth being fresh and usable. Of this, nearly 70% is frozen in ice and snow, approximately 29% exists as soil moisture or deep groundwater, and less than 1% is found in rivers and lakes. Although freshwater resources are continuously replenished through precipitation, rapid population growth and declining water quality and quantity have created critical imbalances between water supply and demand in many regions worldwide. According to the European Union Water Framework Directive guidelines "pressure" is defined as the negative effects of human activities on water resources. Among various pollution sources, diffuse pollution from human activities is recognized as the primary source of water contamination. Since the 1970s, nitrate pollution from intensive agriculture has become one of the most significant environmental challenges globally. Nitrate is highly soluble in water and does not readily attach to soil particles, making it susceptible to leaching into groundwater.

The World Health Organization has recommended a maximum allowable nitrate concentration of 50 mg/L in drinking water. High nitrate concentrations can disrupt iodine absorption and cause hyperthyroidism. Furthermore, numerous studies have demonstrated significant associations between elevated nitrate levels in drinking water and food with increased infant mortality, methemoglobinemia, diabetes in children, hypertension, cardiovascular diseases, neurological disorders, congenital anomalies, miscarriage, Alzheimer's disease, and various cancers. In Iran, nitrate pollution is one of the most pressing challenges for groundwater quality, particularly in arid and semi-arid regions where groundwater serves as the primary source of drinking water. Given these concerns, developing efficient nitrate removal methods is essential. While physicochemical processes such as reverse osmosis, ion exchange, and electrodialysis have been employed, they are economically unfeasible for large-scale applications due to high costs and secondary waste production. In contrast, biological denitrification offers a cost-effective and sustainable alternative. Recently, autotrophic denitrification has attracted considerable attention, where inorganic electron donors such as sulfur, iron, and hydrogen replace organic compounds. Among these, pyrite (FeS_2) has emerged as a promising option for natural treatment systems due to its high stability, simultaneous nitrate and phosphate removal capability, and independence from external carbon sources.

Method

This study is a systematic review with an analytical-synthetic approach. The study of population included all scientific articles published in the field of nitrate removal, autotrophic denitrification, pyrite-based treatment systems, and constructed wetlands between 2000 and 2025. A systematic search was conducted in reputable databases including ScienceDirect, Scopus, Web of Science, and Google Scholar using the combined keywords "Nitrate Removal," "Autotrophic Denitrification," "Pyrite (FeS_2)," "Electron Donor," and "Constructed Wetland." Inclusion criteria were: (1) publication in reputable scientific journals with peer review, (2) direct relevance to at least two components of nitrate removal via pyrite-based autotrophic denitrification, and (3) presentation of quantitative or analytical findings usable in research synthesis. Articles that addressed only conventional treatment methods or were unrelated to biological denitrification were excluded. Initially, 87 articles were identified, and after screening, 25 articles were selected for final analysis based on thematic relevance and methodological quality. Data extraction was performed qualitatively using the Directed Content Analysis method, and information was categorized into three main groups: (1) nitrate pollution status in Iran's water resources, (2) conventional nitrate removal methods, and (3) pyrite-based autotrophic denitrification systems. To enhance validity, two researchers

independently reviewed the selected articles, and in cases of disagreement, consensus was reached with the participation of a third author. The main limitation of this review was the heterogeneity of methodologies and measurement indicators across different studies, which precluded quantitative meta-analysis.

Results

Investigations across various regions of Iran have confirmed that nitrate pollution is a serious threat to groundwater quality, particularly in arid and semi-arid areas where groundwater serves as the primary drinking water source. Studies in Robat Karim, Mashhad, Tehran-Karaj, Isfahan, and Kerman have reported nitrate concentrations exceeding the WHO limit of 50 mg/L, with some wells reaching levels above 160 mg/L. The main sources of contamination are agricultural activities with excessive nitrogen fertilizer use, wastewater infiltration, and inadequate groundwater management. Regarding nitrate removal methods, conventional physicochemical processes including reverse osmosis, ion exchange, and electrodialysis can achieve removal efficiencies of 50–99%. However, these methods face significant limitations such as high energy consumption, membrane fouling, brine disposal challenges, and high operational costs, making them economically unfeasible for large-scale applications.

In contrast, pyrite-based autotrophic denitrification has emerged as a promising alternative. Studies have demonstrated that pyrite (FeS_2) can serve as an effective electron donor for denitrification while simultaneously removing phosphate through iron precipitation. Various reactor configurations including biological contactors, constructed wetlands, and microbial fuel cells have achieved nitrate removal efficiencies of 70–99% and phosphate removal of 91–100%. Pyrite-sulfur combined systems (PSAD) showed improved performance with 98.7% nitrate and 100% phosphate removal while producing lower sulfate levels than theoretical values. Pyrite-based constructed wetland-microbial fuel cells additionally generated bioelectricity while removing nutrients. However, the performance of pyrite-based systems depends on mineral characteristics, with different pyrite types showing variable denitrification capabilities due to differences in surface chemistry and crystal structure. Challenges include lower initial denitrification rates, sulfate production as a byproduct, and limited inorganic carbon availability. The integration of pyrite with complementary materials such as sulfur or steel slag has shown synergistic effects in enhancing performance while reducing sulfate production and greenhouse gas emissions.

Conclusions

This review indicates that nitrate contamination of water resources in Iran represents a serious environmental challenge, necessitating the development of effective and sustainable treatment technologies. Pyrite-based autotrophic denitrification offers a promising, cost-effective, and environmentally compatible solution for nitrate and phosphate removal. However, the performance of pyrite-based systems is strongly influenced by operational parameters and mineral characteristics. The integration of pyrite with complementary materials and the optimization of system design are critical for enhancing treatment efficiency. Future research should focus on pilot-scale implementation, long-term stability assessment, microbial community analysis, and economic evaluation to facilitate practical application in Iran's water treatment facilities.

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