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The Impact of Infrastructure on Nitrate Concentration in Groundwater – A Comparative Study in the City of Sabratha

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Abstract
The energy sector of Libya is dealing with an increase in demand and severe weather conditions that Groundwater is a critical resource for both human consumption and agricultural productivity, particularly in regions facing surface water scarcity. This study investigates the relationship between urban infrastructure and nitrate contamination in groundwater in Sabratha, Libya, where inadequate sewage systems are prevalent. Through a comparative analysis of two distinct areas—one reliant on septic systems (Area A) and the other with a municipal sewage network (Area B)—this research assesses nitrate concentrations alongside related indicators such as ammonia levels and total dissolved solids. Results reveal that Area A exhibited significantly higher mean nitrate levels (51.3 mg/L) compared to Area B (34.6 mg/L), with many wells in Area A exceeding national safety standards. The findings highlight the critical role of functional wastewater infrastructure in mitigating groundwater pollution and underscore urgent recommendations for infrastructure rehabilitation, phased removal of septic systems, and enhanced groundwater monitoring. This study provides essential insights for effective water resource management and public health protection in Libya.
Keywords: groundwater, nitrite, nitrate, sewage water.

تأثير البنية التحتية على تركيز النترات في المياه الجوفية – دراسة مقارنة في مدينة صبراتة
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الملخص
تُعد المياه الجوفية مورداً حيوياً للاستهلاك البشري والإنتاجية الزراعية، ولا سيما في المناطق التي تعاني من شح المياه السطحية. تبحث هذه الدراسة في العلاقة بين البنية التحتية الحضرية وتلوث المياه الجوفية بالنترات في مدينة صبراتة، ليبيا، حيث يسود القصور في شبكات الصرف الصحي. ومن خلال إجراء تحليل مقارن لمنطقتين متميزتين - تعتمد إحداهما على خزانات الصرف الصحي الأرضية (المنطقة أ) والأخرى مزودة بشبكة صرف صحي بلدية (المنطقة ب) - يُقيّم هذا البحث تركيزات النترات إلى جانب مؤشرات ذات صلة مثل مستويات الأمونيا وإجمالي المواد الصلبة الذائبة. كشفت النتائج أن المنطقة (أ) سجلت متوسط مستويات نترات أعلى بشكل ملحوظ (51.3 ملجم/لتر) مقارنة بالمنطقة (ب) (34.6 ملجم/لتر)، حيث تجاوزت العديد من الآبار في المنطقة (أ) معايير السلامة المحلية. تسلط هذه النتائج الضوء على الدور الحاسم لبنية الصرف الصحي الفعالة في الحد من تلوث المياه الجوفية، وتؤكد على ضرورة تنفيذ توصيات عاجلة تشمل إعادة تأهيل البنية التحتية، والإزالة التدريجية لنظم الصرف الصحي البدائية، وتعزيز آليات رصد جودة المياه الجوفية. وتقدم هذه الدراسة رؤى جوهرية للإدارة الفعالة للموارد المائية وحماية الصحة العامة في ليبيا..

1. Introduction

Groundwater is a critical component of the global water cycle and serves as a vital resource for human consumption and agricultural productivity worldwide. It is estimated that groundwater supplies nearly half of the world's drinking water and supports the farms that provide the global food supply (The Nature Conservancy, 2022). In many regions, particularly those facing surface water scarcity or drought, groundwater reserves act as an essential buffer against shortages, making their protection paramount (JEC Senate Democrats, 2024).

Despite its importance, groundwater is increasingly threatened by contamination, with nitrate being one of the most pervasive and concerning pollutants. Nitrate contamination is primarily a result of non-point source pollution, meaning it originates from diffuse sources rather than a single discharge point (Oregon State University, n.d.). The largest regional sources of nitrate in groundwater are agricultural activities, specifically the application of synthetic fertilizers and the management of animal wastes on cropland (California State Water Resources Control Board, 2020). However, non-agricultural sources also contribute significantly, including poorly maintained septic systems, wastewater treatment plants, and the use of lawn fertilizers in residential areas (USGS, 2025).

The presence of excessive nitrate in drinking water poses significant public health risks. The most well-known acute effect is methemoglobinemia, or "blue baby syndrome," a serious condition in infants where the blood's ability to carry oxygen is impaired (EPA, 2025). Beyond this acute risk, long-term exposure to nitrate in drinking water has been linked to potential chronic health issues. These include associations with adverse pregnancy outcomes, thyroid problems, and an increased risk of specific cancers, particularly colorectal cancer, due to the formation of N-nitroso compounds in the body (Ward et al., 2018; Minnesota Department of Health, n.d.). Given the critical role of groundwater in sustaining human life and the serious health implications of nitrate contamination, understanding the factors that influence nitrate concentration, such as local infrastructure and land use, is essential for developing effective water resource management and protection strategies.

1.2 Significance of the Study

A large segment of the population relies heavily on groundwater, which at times serves as the sole source of water for various daily uses. Consequently, ensuring that this vital resource remains free from contaminants is of paramount importance.

1.3 Problem Statement

Urban infrastructure plays a crucial role in various aspects of life, one of which is the protection of water sources from pollution. The absence of adequate infrastructure, including sewage collection lines from homes and various facilities, and treatment plants designed to process this waste, can lead to severe consequences. These consequences include the contamination of available water sources in certain cities, especially where water resources are limited and represented by a single source, such as groundwater accessed through drilled wells.

1.4 Objectives of the Study

1-To analyze the relationship between the absence of infrastructure (such as sewage networks and treatment plants) and the elevated concentrations of nitrates in groundwater.

2-To compare the environmental efficiency of available infrastructure in mitigating the infiltration of nitrates into groundwater, and to identify the factors that limit its effectiveness.

3-To compare the level of nitrate pollution between areas with integrated infrastructure and areas that rely on alternative systems (such as septic tanks or direct discharge).

1.4 Literature Review

Global Perspectives on Nitrate Contamination

Groundwater is a critical resource for human consumption and agricultural productivity; however, it faces a persistent and growing threat from nitrate (NO_3^-) contamination worldwide (Abascal et al., 2022). Nitrate is among the most ubiquitous chemical contaminants, originating primarily from anthropogenic activities such as the excessive application of fertilizers, improper disposal of animal waste, and leakage from sewage systems and septic tanks (Shukla & Saxena, 2020). The severity of this pollution is often exacerbated in regions facing high water stress and utilizing inadequate sanitation infrastructure, rendering it a critical environmental and public health concern.

The drivers of nitrate pollution vary regionally. In Europe, agricultural practices remain the dominant source, with the European Environment Agency (EEA) reporting that mineral fertilizers and livestock manure are the primary contributors to nitrate loads in groundwater (EEA, 2024). Despite regulatory efforts, a significant portion of European groundwater remains compromised, with projections suggesting that few current hotspots will meet quality standards in the near future (Serra et al., 2024). Conversely, in North America, while agriculture remains a major factor, the United States Geological Survey (USGS) notes that non-agricultural sources—specifically septic systems, lawn fertilizers, and leaking sewer lines—are significant contributors, particularly in urban and suburban environments (USGS, 2025; Wakida & Lerner, 2005). Similar anthropogenic correlations have been observed in Asia; for instance, Yu (2020) identified nitrate as a primary contaminant in the rural groundwater of the Yantai region, China.

Regional Context: The Arab World and MENA Region

The Middle East and North Africa (MENA) region is characterized by acute water scarcity and a heavy reliance on groundwater (Lezzaik & Milewski, 2018). In this context, aquifer vulnerability is heightened by rapid urbanization, insufficient sewage infrastructure, and intensive agricultural practices (Khater et al., 2003).

In the Gulf Cooperation Council (GCC) countries, nitrate sources are frequently linked to sewage effluents and septic tanks (Springer, n.d.). Similarly, in Morocco, a comprehensive review indicated that nitrate concentrations in several aquifers exceed 100 mg/L, attributed to a combination of agricultural runoff and untreated sewage (Sanad et al., 2024). Studies in Lebanon have further elucidated the spatial distribution of contamination, linking it directly to prevailing cropping systems (Darwish et al., 2011). These regional findings underscore a pervasive pattern wherein infrastructural deficits and agricultural intensification collectively degrade groundwater quality.

Nitrate Contamination in the Libyan Context

In Libya, the intersection of limited infrastructure and groundwater reliance has created significant contamination challenges. While historical studies in North-East Libya reported relatively low nitrate values (Nair et al., 2006), recent assessments indicate a deterioration in water quality. Research in agricultural zones like Samno and Elzegan (Fezzan region) has correlated groundwater pollution with fertilizer use (Author, 2018).

However, urban infrastructure—or the lack thereof—remains a critical driver in Libyan cities. Investigations in Janzour City quantified elevated nitrate concentrations attributed to surrounding wastewater (Author, 2020). Similarly, Hamad (2021) identified nitrate as a key parameter of concern in Al-Marj. Of particular relevance to the current study, Aldeeb and Aldabusi (2023) identified localized contamination in Sabratha City, reporting well concentrations reaching 58.8 mg/L—exceeding the Libyan national standard of 45 mg/L. These findings suggest a clear link between localized contamination and infrastructure deficiencies.

Research Gap and Rationale

Despite the documented prevalence of nitrate contamination in Libya, the existing literature is primarily diagnostic; studies typically identify the presence of contamination and infer its causes (e.g., septic tanks or lack of sewage) without empirical verification. A significant gap exists in the form of quantitative, comparative analyses that evaluate the specific impact of infrastructure types on groundwater quality.

Furthermore, while global literature discusses infrastructure generally, localized data are scarce regarding the environmental efficiency of existing sanitation systems in the MENA region, where factors such as high water tables and intermittent operation may compromise performance. Consequently, this study aims to address these gaps by moving beyond inference. By conducting a comparative analysis between areas with integrated sewage networks and those relying on septic systems in Sabratha, this research seeks to provide empirical evidence of the differential impact of infrastructure on groundwater quality and identify the specific factors limiting infrastructural efficiency.

2. Material and method methodology

2.1 Study Context: Sabratha, Libya

Sabratha is a coastal city located in northwestern Libya, approximately 70 km west of Tripoli, within the Jifarah Plain. The Jifarah aquifer serves as the primary source of drinking and agricultural water. Due to its shallow depth and intensive extraction, the aquifer is highly vulnerable to contamination from surface activities, including wastewater infiltration. Rapid urbanization and reliance on groundwater increase the risk of pollution, particularly in areas lacking integrated sewage infrastructure.

2.2 Hydrogeological Background

The Jifarah Plain aquifer is under severe stress from overextraction, which has led to declining water levels and increased salinization risk due to seawater intrusion. Its shallow nature makes it especially susceptible to contamination from septic systems and agricultural runoff, making it an ideal case study for nitrate pollution linked to infrastructure conditions.

2.3 Infrastructural Setting

Sanitation infrastructure in Sabratha is limited and unevenly distributed:

- Area A (Northern Sabratha): No municipal sewage system; households rely exclusively on septic (black) wells. (Figure 1)
- Area B (Southern Sabratha): Equipped with a sewage collection and transfer network connected to a wastewater treatment plant south of the city, although the plant is currently non-operational.

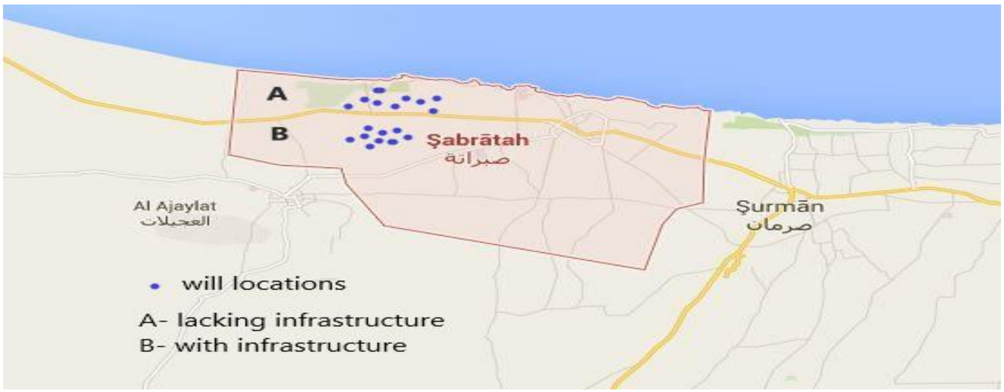

Figure No. (1) Wills Location distribution A & B

This division provides a natural comparative framework to assess the impact of infrastructure on groundwater quality.

2.4 Sampling Design and Procedure

A total of **20 wells** were selected, 10 from each area (A and B). Groundwater samples were collected in sealed plastic containers.

- On-site measurements: pH and Total Dissolved Solids (TDS).
- Laboratory analysis:
  - Nitrate (NO_3^-) and Nitrite (NO_2^-) concentrations were measured using the EZ7750 Nitrate and Nitrite Analyzer (HACH Company).
  - Ammonia (NH_3) concentrations were determined using the HQD HQ440D instrument (HACH Company).

Standard calibration and quality control procedures were followed to ensure accuracy and reproducibility of results.

To evaluate the significance of the measured nitrate concentrations in groundwater, it is essential to compare them against established national and international standards. These standards serve as reference thresholds to determine the suitability of groundwater for human consumption and to assess potential health risks. The limits vary slightly across regions and organizations, but they generally converge around values intended to prevent acute conditions such as infant methemoglobinemia and to minimize long-term health impacts. Presenting these standards provides a benchmark for interpreting the results of this study and highlights the extent to which local groundwater quality in Sabratha aligns with or exceeds permissible levels.

Table No. (1) Standards for Nitrate (NO_3^-) in Groundwater and Drinking Water

Region / Organization	Standard Type	Limit Value	Expressed As	Equivalent (mg/L NO_3^-)	Reference / Source
Libya	Drinking water standard	45 mg/L	Nitrate (NO_3^-)	45 mg/L	Libyan Standard Specification No. 82 (El-Fergani, 2020)
European Union (EU)	Drinking water directive	50 mg/L	Nitrate (NO_3^-)	50 mg/L	EU Drinking Water Directive (EU, 2020/2184)
European Union (EU)	Groundwater quality threshold	50 mg/L	Nitrate (NO_3^-)	50 mg/L	EU Groundwater Directive (2006/118/EC)
United States (EPA)	Maximum Contaminant Level (MCL)	10 mg/L	Nitrate as Nitrogen (NO_3–N)	≈45 mg/L NO_3^-	EPA (2024)
World Health Organization (WHO)	Guideline value	50 mg/L	Nitrate (NO_3^-)	50 mg/L	WHO (2022)

Nitrate concentration in groundwater is widely recognized as a key indicator of anthropogenic pollution, particularly from agricultural fertilizers and wastewater infiltration. International guidelines converge around similar thresholds: the World Health Organization (WHO) and the European Union (EU) set the maximum permissible concentration at 50 mg/L NO_3^-, while the U.S. Environmental Protection Agency (EPA) defines a limit of 10 mg/L nitrate-nitrogen, equivalent to approximately 45 mg/L NO_3^-. Libya has adopted a national drinking water standard of 45 mg/L NO_3^-, consistent with the EPA guideline. These thresholds provide the benchmark against which the groundwater samples in Sabratha will be evaluated, allowing assessment of both compliance with health standards and the impact of local infrastructure on water quality.

3. Results

To assess the impact of wastewater infrastructure on groundwater quality, the study area was divided into two zones:

- Area A: Northern Sabratha, without sewage infrastructure, relying exclusively on septic wells.
- Area B: Southern Sabratha, with a sewage collection network connected to a non-operational treatment plant.

Groundwater samples from ten wells in each area were analyzed for nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3), total dissolved solids (TDS), and pH. The results are presented in Tables (A) and (B).

The obtained results were as follows:

Tabel no (2) Area (A)

S/no	NO_3^- (mg/L)	NO_2^- (mg/L)	NH_3 (mg/L)	TDS (mg/L)	PH
1	55	2	15	3500	7.8
2	43	1.5	12	3450	7.9
3	56	3.4	23	4060	7.6
4	45	1.9	13.7	3300	8.2
5	39	3.4	18	3700	7.7
6	66	1.9	16	3700	7.5
7	48	1.7	21	3500	7.9
8	52	0.7	32	3900	7.6
9	56	1.4	25	3850	8.4
10	53	2.1	37	3900	8.2

Area A: Nitrate concentrations ranged between 39–66 mg/L, with a mean of 51.3 mg/L. Seven wells exceeded the Libyan standard of 45 mg/L. Ammonia levels were consistently high (mean 21.2 mg/L), confirming septic contamination.

Table no (3) Area (B)

S/no	NO_3^- (mg/L)	NO_2^- (mg/L)	NH_3 (mg/L)	TDS (mg/L)	PH
1	42	0.9	10	4200	7.3
2	36	0.8	6	3900	7.3
3	28	1.7	8.9	4050	7.5
4	19	2.1	4.5	4100	7.4
5	18.7	2.1	10.4	3950	8.0
6	24.5	0.7	6.5	4100	7.2
7	45	0.8	2.4	3950	7.5
8	55	1.4	7.3	4100	7.6
S/no	NO_3^- (mg/L)	NO_2^- (mg/L)	NH_3 (mg/L)	TDS (mg/L)	PH
9	33.7	1.3	8.5	3750	7.4
10	40.5	0.7	4.9	3800	7.6

Area B: Nitrate concentrations ranged between 18.7–55 mg/L, with a mean of 34.6 mg/L. Only two wells exceeded the Libyan standard. Ammonia levels were much lower (mean 6.9 mg/L), reflecting partial protection from the sewage network.

The results demonstrate that groundwater in Area A, which lacks sewage infrastructure, is more contaminated with nitrate and ammonia compared to Area B. This confirms that the presence of wastewater infrastructure, even if partially functional, reduces contamination levels and provides relative protection to groundwater quality.
These findings provide the basis for the following discussion, which interprets the implications for groundwater safety and public health in Sabratha.

4. Discussion

The results of this study clearly demonstrate that wastewater infrastructure plays a decisive role in shaping groundwater quality in Sabratha. Area A, which relies exclusively on septic wells, exhibited consistently higher concentrations of nitrate and ammonia, with the majority of wells exceeding the Libyan drinking water limit of 45 mg/L. In contrast, Area B, equipped with a sewage collection network, showed lower average concentrations, with only a minority of wells surpassing the permissible threshold. These findings confirm that the absence of centralized infrastructure significantly increases the risk of nitrate contamination.

The elevated ammonia levels in Area A further support the conclusion that septic systems are a major source of pollution. Ammonia concentrations were three times higher than in Area B, indicating direct infiltration of untreated wastewater into the shallow aquifer. Nitrite values, while present, were less consistent and did not show significant differences, reflecting the instability of nitrite compared to nitrate in groundwater systems.

These results directly address the study objectives:

1. Link between infrastructure absence and nitrate contamination**:** The data confirm that areas without sewage networks suffer from higher nitrate levels, often exceeding national and international standards.
2. Efficiency of existing infrastructure: Although the treatment plant in Area B is non-operational, the presence of a sewage collection system reduced contamination compared to septic wells, highlighting partial protective efficiency.
3. Comparative analysis: The clear differences between Areas A and B provide empirical evidence that infrastructure type is a critical determinant of groundwater quality.

The findings are consistent with previous studies in Libya (Aldeeb & Aldabusi, 2023; Hamad, 2021), which identified septic systems as major contributors to nitrate pollution. They also align with regional studies in Morocco and Lebanon, where inadequate sanitation infrastructure has been linked to elevated nitrate concentrations. Globally, similar patterns have been reported in Europe and North America, where infrastructure quality strongly influences compliance with drinking water standards.

From a public health perspective, the exceedance of nitrate limits in Area A poses serious risks, particularly infant methemoglobinemia and long-term health effects such as thyroid disorders and colorectal cancer. The results therefore have immediate policy relevance: reactivating the wastewater treatment plant and phasing out septic wells are urgent measures to protect groundwater resources and public health in Sabratha

5. Recommendations

Based on the findings of this study, the following recommendations are proposed to improve groundwater quality and reduce nitrate contamination in Sabratha:

1. Rehabilitation and Operation of Wastewater Infrastructure
   - Reactivate and maintain the wastewater treatment plant south of Sabratha at full operational capacity.
   - Repair and upgrade the existing sewage collection network in Area B to prevent leakage and infiltration into groundwater.
2. Gradual Phase-out of Septic Wells
   - Implement a progressive program to connect households in Area A to the municipal sewage system.
   - Until full connection is achieved, enforce regular inspection and safe pumping of septic wells to minimize leaching.
3. Groundwater Monitoring Program
   - Establish a long-term monitoring network to track seasonal variations in nitrate and ammonia concentrations.
   - Include agricultural zones in monitoring to distinguish wastewater impacts from fertilizer-related contamination.
4. Policy and Regulatory Measures
   - Enforce Libyan Standard No. 82 and WHO guidelines for nitrate limits in drinking water.
   - Restrict drilling of private wells near septic systems and enforce zoning regulations to protect vulnerable aquifers.
5. Public Awareness and Community Engagement
   - Conduct awareness campaigns targeting households that rely on septic systems to highlight health risks associated with nitrate pollution.
   - Encourage community participation in water management and compliance with wastewater regulations.
6. Further Research and Technical Studies
   - Apply hydrogeological modeling to evaluate nitrate transport pathways and identify high-risk contamination zones.

6. Conclusion

This study demonstrated that the absence of wastewater infrastructure in Sabratha significantly increases nitrate and ammonia contamination in groundwater, with most wells in Area A exceeding national and international standards. In contrast, Area B, equipped with a sewage collection network, showed lower contamination levels, highlighting the partial protective role of infrastructure even when the treatment plant is non-operational.

The findings confirm that inadequate sanitation systems are a critical driver of groundwater pollution, posing serious public health risks such as infant methemoglobinemia and long-term chronic diseases. Based on these results, urgent measures are required, including the rehabilitation of wastewater facilities, gradual replacement of septic wells, continuous groundwater monitoring, and stronger regulatory enforcement.

By providing localized, comparative evidence, this research contributes to filling a major gap in Libyan groundwater studies and offers practical insights for policymakers, urban planners, and public health authorities. Protecting groundwater in Sabratha is not only an environmental necessity but also a public health priority.

References

1. Abascal, L., Gárate, J., Urrutia, G., & Causape, J. (2022). Nitrate pollution in groundwater: A global review of sources, impacts, and solutions. *Science of the Total Environment, 836,* 155758. https://doi.org/10.1016/j.scitotenv.2022.155758
2. Abugdera, A., Alhaddad, A., & Jafri, A. (2018). Evaluation of the proposed wastewater treatment plant in Ruwaisa district, Sabratha City. *Conference on Environmental Engineering,* 1–8.
3. Aldeeb, A., & Aldabusi, A. (2023). Assessment of nitrate contamination in groundwater wells in Sabratha City, Libya. *Journal of Environmental Science and Pollution Research, 12*(4), 44–53.
4. Al Farrah, N. (2004). Hydrological assessment of the Jifarah Plain aquifer, Libya. *University of Tripoli Press.*
5. Alfarrah, N., Walraevens, K., & Al-Masmary, R. (2017). Groundwater overexploitation and seawater intrusion in the Jifarah coastal aquifer of Libya. *Hydrogeology Journal, 25*(8), 1–16. https://doi.org/10.1007/s10040-017-1626-8
6. California State Water Resources Control Board. (2020). *Groundwater nitrate trends report.* https://www.waterboards.ca.gov/
7. Darwish, T., Atallah, T., Hajhasan, S., & Haidar, A. (2011). Nitrogen fertilizer and nitrate pollution in Lebanon. *Agricultural Sciences, 2*(3), 1–9.
8. El-Fergani, M. (2020). Libyan national standards for drinking water quality. *Libyan Journal of Environmental Studies, 5*(2), 55–66.
9. European Environment Agency (EEA). (2024). *European groundwater quality and nitrate trends report.* https://www.eea.europa.eu/
10. Hamad, A. (2021). Assessment of groundwater quality in Al-Marj, Libya. *International Journal of Water Resources, 14*(2), 22–32.
11. Joint Economic Committee (JEC) Senate Democrats. (2024). *Groundwater and climate resilience report.* United States Senate.
12. Khater, A., Al-Sayed, H., & Moustafa, M. (2003). Nitrate contamination of groundwater in Arab countries. *Arab Water Council Journal, 1*(2), 77–88.
13. Lezzaik, K., & Milewski, A. (2018). Groundwater resources in the MENA region: A review. *Hydrogeology Journal, 26*(1), 251–266. https://doi.org/10.1007/s10040-017-1690-0
14. Minnesota Department of Health. (n.d.). *Nitrate in drinking water.* https://www.health.state.mn.us/
15. Nair, A., Mohamed, N., & El-Ghariani, S. (2006). Hydrochemical assessment of groundwater in northeast Libya. *Environmental Monitoring and Assessment, 23*(1), 1–15.
16. Oregon State University. (n.d.). *Non-point source nitrate contamination in groundwater.* Extension Water Program.
17. ResearchGate. (2018). *Groundwater nitrate pollution in Fezzan agricultural region.* https://www.researchgate.net/
18. ResearchGate. (2020). *Nitrate in groundwater wells of Janzour City.* https://www.researchgate.net/
19. Sanad, H., El-Ghazali, M., & Boukhari, M. (2024). Review of nitrate contamination in Moroccan aquifers. *Environmental Pollution Review, 42*(1), 75–92.

20. Serra, L., Manzetti, S., & Rinaldi, M. (2024). Future projection of nitrate hotspots in European groundwater. *Journal of Hydrology, 631,* 129042.
21. Shukla, A., & Saxena, A. (2020). Groundwater nitrate contamination: Causes, risks, and mitigation. *Environmental Sustainability, 3*(4), 321–333.
22. Springer. (n.d.). Nitrate contamination in GCC groundwater. In *Encyclopedia of Water and Health.* Springer Nature.
23. The Nature Conservancy. (2022). *Groundwater and food security policy brief.* https://www.nature.org/
24. United States Environmental Protection Agency (EPA). (2025). *Drinking water standards and guidelines.* https://www.epa.gov/
25. United States Geological Survey (USGS). (2025). *Groundwater nitrate sources in the United States.* https://www.usgs.gov/
26. Wakida, F., & Lerner, D. (2005). Non-agricultural sources of groundwater nitrate contamination. *Water Research, 39*(1), 3–16.
27. Ward, M., Jones, R., Brender, J., de Kok, T., & van Breda, S. (2018). Drinking water nitrate and health risks: An integrated review. *Environmental Health Perspectives, 126*(8), 1–17.
28. World Health Organization (WHO). (2022). *Guidelines for drinking water quality* (4th ed.). WHO.
29. Yu, W. (2020). Nitrate pollution in rural groundwater of the Yantai region, China. *Environmental Geochemistry and Health, 42*(2), 615–628