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Review

Groundwater contamination with nitrates in Saudi Arabia, and its possible effects on exposed humans' health and body tissues; an environmental and epidemiological review

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Abstract:

Background: Groundwater is an important source of drinking water in rural and agricultural regions of Saudi Arabia. Many people still rely on untreated private wells. Certain "high-risk areas", where the local populations are in danger due to the potential consumption of water contaminated with elevated concentrations of nitrate (NO_3^-) and nitrite (NO_2^-), have been identified. **Methods:** In this narrative review, the published literature on contamination sources, exposure pathways, health implications, and mitigation strategies was synthesised. **Results:** NO_3^- concentrations in Saudi Arabian groundwater range from 12 to 380 mg/L in shallow, unconfined aquifers, particularly in agricultural and semi-urban areas that present a high risk of exposure and vulnerability to human health. NO_3^- may originate from natural or anthropogenic activities, including fertiliser application, livestock farming, septic systems, and wastewater disposal. NO_3^- can then gradually accumulate in water sources and, in some cases, in crops and vegetables. However, it can also contaminate other edible products and drinking water, leading to health problems. While municipal and commercial water usually complies with the guideline limits, numerous private and agricultural wells exceed the World Health Organization (WHO) drinking-water guideline of 50 mg/L for NO_3^-, an ongoing public health concern. **Conclusion:** This review identifies the major regions in Saudi Arabia with elevated NO_3^- concentrations in groundwater. It summarises the possible health effects on exposed organs and tissues. Furthermore, we present selected NO_3^- monitoring, mitigation, and treatment strategies to reduce NO_3^- levels in contaminated waters and prevent its hazards to the population.

Keywords: Saudi Arabia, Nitrite, Nitrate, Methemoglobinemia, Urinary bladder, Thyroid.

1. Introduction

Saudi Arabia's drinking water supply relies on a combination of conventional and non-conventional sources due to the country's extreme aridity and the absence of perennial rivers [1–3]. There has been a significant increase in the use of desalinated seawater, which can help meet growing urban demand [4]. The pattern of groundwater extraction in Saudi Arabia has changed over the past few years [5,6]. In 2023, renewable groundwater abstraction increased to approximately 21% of total groundwater extracted, which can be used to support a sustainable water supply, rising from previous years and contributing to reduced reliance on non-renewable sources[1]. The abstraction of non-renewable groundwater did not stop completely. However, it was reduced to 10,849 million meter ^{3}, making it a smaller portion of total groundwater use, an important indicator of progress[1].

To understand the implications for future water security, this reduction can be used to inform policy changes. However, careful planning is needed to understand the long-term sustainability of water resources, as continued reliance on non-renewable groundwater still poses risks [7]. At the same time, the supply of desalinated seawater, which grew by 31% in 2023, accounted for 50% of the total distributed drinking-water supply, up from 44% by 2022 [1]. This transition illustrates the increasing reliance on desalination alongside groundwater to enhance water security. To understand its effects on drinking-water quality, it should be noted that these sources influence potential exposure to nitrate (NO_3^-) and nitrite (NO_2^-)[8].

NO_3^- in drinking water is a public health concern because the body converts it to NO_2^-, which can convert haemoglobin to methaemoglobin, thereby reducing oxygen transport. Infants and young children are particularly vulnerable because their digestive systems and enzymes are not fully developed[9]. Long-term NO_3^- exposure can also lead to potentially cancer-causing N nitroso compounds (NOCs) and interfere with thyroid function by blocking iodine uptake. Therefore, hormone production may be reduced, particularly in people with low iodine intake[10]. Some studies also report that long-term NO_3^- exposure increases the risk of thyroid cancer[10–12]. The World Health Organization (WHO) recommends that drinking water contain less than 50 mg/L of NO_3^- and 3 mg/L of NO_2 to protect people from these effects [2].

Although several studies have examined groundwater quality and nitrate contamination in different regions of Saudi Arabia, the available literature remains fragmented, region-specific, and mostly focuses on reporting nitrate concentrations rather than integrating environmental exposure with human health implications. Previous reviews have generally discussed groundwater quality, desalination, or general water resource management. However, those did not provide a focused Saudi-based synthesis linking nitrate and nitrite contamination with exposure pathways, vulnerable populations, body tissue effects, and public health risk assessment indicators. A Saudi-focused review is needed because groundwater dependence, arid hydrogeological conditions, agricultural practices, private well use, and regional differences in water treatment create a distinct exposure context compared to other countries. The originality of this review lies in combining Saudi groundwater nitrate evidence with mechanistic toxicology and epidemiological findings to explain how nitrate and nitrite exposure may affect blood, thyroid, gastrointestinal, bladder, hepatic, renal, reproductive, and prenatal health outcomes. By integrating contamination patterns, health risk indices, tissue-level mechanisms, and mitigation strategies, this review offers a comprehensive scientific framework for understanding these issues in Saudi Arabia. Additionally, it identifies priority areas for monitoring, prevention, and future epidemiological research.

Limited studies reported on groundwater quality and NO_3^- contamination in various parts of Saudi Arabia. However, such literature is disjointed, geographically fragmented, and tends to focus on water NO_3^- content rather than integrating groundwater exposure with human health outcomes. Given factors specific to the exposure context in Saudi Arabia, including reliance on groundwater, arid hydrogeological conditions, the agricultural style used, the use of private wells, and regional differences in water treatment, a Saudi-focused review is needed. This review is unique in combining evidence on the presence of NO_3^- in groundwater in Saudi Arabia with the mechanisms of biochemical and toxicological effects and epidemiological results to provide an up-to-date understanding of how NO_3^- and NO_2^- exposure may influence blood, thyroid, gastrointestinal, bladder, kidney, reproductive, and prenatal health. It offers a more detailed, scientific contribution to understanding these issues in Saudi Arabia by incorporating information on contamination patterns, health-risk indices, tissue mechanisms, and mitigation methods. Furthermore, it highlights prioritisation areas for monitoring and prevention, as well as future epidemiological research directions.

The purposes of the present study were to (I) determine the occurrence, spatial distribution, and environmental sources of the NO_3^- and NO_2^- in groundwater used for drinking in the different regions of Saudi Arabia, (II) examine to what extent the type of water source, the hydrogeological characteristics of the aquifers, and the population-related factors influence the exposure levels and how they affect age-specific health risk indices, including the chronic daily intake (CDI), the hazard index (HI), and the hazard quotient (HQ), which are indicators of non-carcinogenic risk and provide a measurable framework for risk evaluation, and (III) determine the effects of exposure to the NO_3^- and NO_2^- on the body tissues and the underlying mechanistic pathogenesis, including impaired oxygen transport, endocrine and thyroid dysfunction, organ-specific damage, oxidative stress, and the endogenous formation of N-nitroso compounds (NOCs), which could increase the potential health burden among the populations relying on groundwater as a primary drinking water source.

2. Occurrence and Environmental Chemistry of Nitrate and Nitrite

There has been a substantial and growing body of research examining the occurrence, distribution, and potential health effects of NO_3^- and NO_2^- in drinking water, providing a better understanding of their environmental chemistry and biological implication[13,14]. NO_3^- and NO_2^- are inorganic nitrogen ions widely distributed in the environment as part of the global nitrogen cycle. They are present in water due to both natural geochemical processes and human activities, including microbial transformations in the soil (nitrification and denitrification), which are important pathways, and the leaching of nitrogen compounds from agricultural runoff and wastewater[15,16]. NO_3^- consists of one nitrogen atom bonded to three oxygen atoms, forming the oxidised anion that is to be regarded as highly stable, whereas NO_2^- consists of one nitrogen atom bonded to two oxygen atoms, which is less oxidised and more reactive, showing what makes it transient in water [17](see Figure 1).

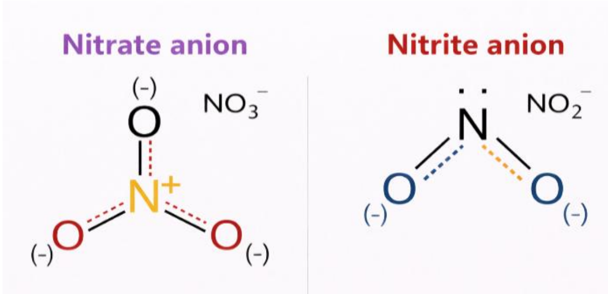

Figure 1. Chemical structures of nitrate (NO_3^-) and nitrite (NO_2^-) anions.

3. Nitrate (NO_3^-) and nitrite (NO_2^-) sources

Water contamination by NO_3^- and NO_2^- results from natural processes and human activities that interact within the environment[18,19]. Therefore, source data must be integrated across different hydrogeological settings[18,19]. NO_3^- occurs naturally as a product of microbial oxidation of organic nitrogen, ia part of the global nitrogen cycle, and contributes baseline levels, while NO_2^- remains low due to rapid oxidation[15–17]. Agricultural runoff from the excessive application of nitrogen-based fertilisers has been considered one of the most significant anthropogenic sources of NO_3^-, which causes NO_3^- leaching into soils and water bodies[20–23]. A growing body of evidence shows that crops typically take up only 40–50% of applied nitrogen fertiliser, with the remainder being lost through NO_3^- leaching, volatilisation, denitrification, or incorporation into soil organic pools [20–25]. Depending on soil type, crop, and management practices, approximately 10–30% of applied fertiliser nitrogen may be lost below the root zone as NO_3^- under typical conditions[20,21,24,25]. Additional sources include livestock waste, septic systems, industrial effluents, and landfill leachate, which release nitrogen compounds into groundwater[25–27]. Atmospheric deposition and irrigation return flows further mobilise NO_3^- into aquifers, thereby increasing NO_3^- concentrations[24,28]. Finally, NO_2^- can form under anoxic conditions or within distribution systems, although its concentrations are usually transient[17,29]. A summary of the sources, mechanisms, and hydrogeological influences is provided in Table 1 below.

Table 1: Major Sources of Nitrate (NO_3^-) and Nitrite (NO_2^-) in Drinking Water

Source Category	Mechanism & Relevance to Drinking Water	Ref.
Natural Background Sources	Nitrogen naturally present in soils, minerals, and organic matter is converted by microbes into NO_3^-. As a result, baseline NO_3^- can occur in groundwater even without human activity. NO_2^- is usually very low because it is rapidly oxidised to NO_3^-.	[15–18]
Agricultural Fertilizers (Non-Point Source)	Excessive application of nitrogen-based fertilisers leads to NO_3^- leaching from soils into aquifers. Irrigation return flow can further transport NO_3^- into drinking water sources.	[20–23,28]
Livestock & Animal Waste	Soil microbes convert nitrogen in manure and animal waste into NO_3^-, which can seep into shallow groundwater and contaminate drinking water sources.	[25,27]
Septic Systems & Sewage	Failing septic tanks and sewage discharges release organic nitrogen and ammonia. Microbial processes convert these compounds first into NO_2^- and then into NO_3^-, leading to groundwater contamination.	[25,27]
Industrial Point Sources	Industrial effluents from chemical manufacturing, fertilizer production, and other waste streams can introduce NO_3^- and related nitrogen compounds into nearby surface water and shallow aquifers.	[27,29]
Atmospheric Deposition	Nitrogen oxides from combustion and industrial emissions deposit as NO_3^- on soils and water bodies. This NO_3^- can infiltrate into aquifers used for drinking water.	[18,19]
Landfills & Waste Disposal	Leachate from landfills contains ammonia and dissolved nitrogen compounds, which are converted by microbial oxidation into NO_3^-, entering local groundwater sources.	[27,29]
Irrigation Return Flow	Irrigation mobilises residual NO_3^- from fertilisers and animal waste in soils, returning it to streams and aquifers that may serve as drinking water sources.	[21,28]
Nitrite Formation (Anoxic Reduction)	Under low-oxygen (anoxic) conditions in sediments or poorly aerated parts of water distribution systems, NO_3^- can be reduced to NO_2^-. However, NO_2^- is typically transient and remains at low concentrations in drinking water.	[16,17]

4. Microbial oxidation, environmental fate, and toxicological iImplications of Nitrate (NO_3^-) and Nitrite (NO_2^-)

Studies have shown that the presence of NO_3^- and NO_2^- in groundwater is influenced by the natural nitrogen cycle and by anthropogenic activities, including fertiliser use, the application of animal waste, and the discharge of urban effluents[20,25–27,30]. These studies highlighted that microbial nitrification converts ammonia (NH_3/NH_4^+) first into NO_2^- by the activity of ammonia-oxidising bacteria and archaea, and subsequently into NO_3^- by the nitrite-oxidising bacteria, such as Nitrobacter and Nitrospira[15,16,30,31]. This sequential microbial oxidation is significant because it enables NO_3^- to persist in groundwater, particularly in shallow aquifers in agricultural regions, due to its high solubility and mobility[18,21,25]. The NO_3^- may be converted through the denitrification pathway into dinitrogen gas (N_2), which naturally limits the accumulation of NO_3^- in aquifers, under anoxic conditions[16,24]. Regarding the toxicological mechanisms, these studies also highlight that NO_3^- is relatively inert in the human body, but that its toxicity arises when it is reduced to NO_2^- by bacteria in the oral cavity and the gastrointestinal tract[9,32,33]. Most studies show that in healthy adults, only about 5% of ingested NO_3^- is converted to NO_2^- because the acidic environment of the stomach and the established gut microbiome limit bacterial activity [9,32,33]. In infants under six months of age, higher gastric pH and an immature gut microbiota promote the formation of NO_2^-, increasing the risk of methemoglobinemia, a condition in which methaemoglobin is formed and cannot effectively transport oxygen to the tissues[2,9,12,13].

5. Review Methods

A comprehensive review was conducted to identify studies on NO_3^- and NO_2^- exposure in Saudi Arabia regarding drinking water and its associated health effects. Studies published from 2010 to 2025, along with key earlier research on context, were systematically screened, extracted, and synthesised. Table 2 summarises the methodology and key findings.

Table 2. Summary of literature search, study selection, and key findings on NO_3^- and NO_2^- exposure in Saudi Arabia

Category	Details
Objective	This study aims to review research on how nitrate (NO_3^-) and nitrite (NO_2^-) in drinking water in Saudi Arabia affect health, including conditions such as methemoglobinemia, thyroid problems, reproductive issues, and other body-wide effects.
Timeframe	Publications from 2000–2025 were systematically searched; key pre-2000 studies were included for historical context.
Databases Searched	ScienceDirect, PubMed, PubMed Central, Web of Science, Google Scholar.
Keywords Used	"Drinking water nitrate Saudi Arabia", "drinking water nitrite Saudi Arabia", "nitrate toxicity", "nitrite toxicity", "methemoglobinemia", "thyroid dysfunction nitrate", "reproductive toxicity nitrate", "placental nitrate exposure", "endocrine disruption nitrate nitrite", "chronic nitrate exposure", "groundwater nitrate contamination", "municipal water nitrate levels", "Saudi Arabia water quality"
Inclusion Criteria	- Full-text peer-reviewed journal articles published in English - Studies reporting NO_3^-/NO_2^- concentrations and health effects - Mechanistic, clinical, epidemiological, and field studies - Studies on nitrate removal techniques relevant to Saudi groundwater management.
Exclusion Criteria	- Articles without full text- non-English publications - Letters to the editor, conference abstracts, book chapters (as these lack primary data).
Screening Process	- Independent screening by title and abstract - Full-text assessment for relevance - Cross-checked references within key studies to identify additional relevant research.
Data Extracted	**Water sources:** • Shallow wells • Deep wells • Municipal water • Agricultural areas **NO_3^- and NO_2^- concentrations:** • Reported range: <1 mg/L to >800 mg/L in Saudi wells • Many samples exceed the WHO guideline of 50 mg/L **High-risk populations:** • Infants and children • Pregnant women • Rural communities relying on untreated wells **Exposure pathways:** • Drinking water • Food chain (via vegetables and fruits irrigated with nitrate-rich water) **Tissue-level toxicity/health effects:** • Blood: methemoglobinemia • Thyroid: hypothyroidism and subclinical thyroid dysfunction • Kidney and liver effects • Reproductive and endocrine system effects
Synthesis Method	Narrative synthesis supported by tables presenting: NO_3^-/NO_2^- concentrations, exposure pathways, age-specific risks, and associated tissue-level effects. Data integrated from historical mechanistic studies, clinical observations, field measurements, and Saudi-specific epidemiology.
Historical Integration	- Early mechanistic and clinical studies (pre-2000) on methemoglobinemia, endogenous N-nitroso compound formation, and nitrate-induced thyroid disruption were included to provide context for evolving risk patterns.
Recent Saudi Evidence (2010–2025)	- Studies report high nitrate concentrations in groundwater (up to 884 mg/L) with clear age-specific health risks in northeastern, central, and semi-urban areas - Biological and chemical nitrate removal strategies (ion exchange, bioremediation, denitrification) are highlighted as feasible interventions for groundwater management.
Outcome	Provides a comprehensive understanding of NO_3^- and NO_2^- exposure, sources, pathways, age-specific and tissue-level health effects, and potential mitigation strategies in Saudi Arabia over two decades.

6. Results

This review was conducted using a systematic review to ensure transparency, rigour, and reproducibility[3]. A total of 710 records were initially identified through the database search. Before the screening, 499 records were removed. The remaining 211 records were screened based on their titles and abstracts. Of these, 149 were excluded because they did not meet the inclusion criteria. Subsequently, 62 records were requested for full-text retrieval. However, nine reports could not be retrieved. As a result, 53 full-text articles were assessed for eligibility. Among these, 47 studies were excluded for specific reasons, including lack of relevance to nitrate (NO_3^-) and nitrite (NO_2^-) exposure in Saudi Arabian drinking water (n = 11), being review articles (n = 17), non-English publications (n = 11), and other reasons such as irrelevant or incomplete data (n = 8). Ultimately, six studies met all eligibility criteria and were included in the final review.

6.1. Characteristics and key findings of Studies on groundwater Nitrate (NO_3^-) in Saudi Arabia

The studies indicated that NO_3^-contamination in Saudi Arabian groundwater is a significant environmental and public health concern, with large spatial variability across the Kingdom [5,6,13]. Most studies describe how NO_3^- concentrations are higher in shallow and unconfined aquifers. In contrast, deeper and confined aquifers generally exhibit lower levels due to natural filtration and longer residence times [5,6,13]. For instance, a nationwide survey of 1,060 wells conducted by Alabdula'aly et al. (2010) reported that NO_3^- concentrations ranged from 1.1 to 884 mg/L, with the highest mean levels observed in Jizan, Asir, and Qassim. These studies highlighted that 213 wells exceeded the national drinking water limit of 45 mg/L for NO_3^-, indicating the spatial heterogeneity of contamination and the risk to populations that rely on untreated groundwater[34]. However, regions with limited or absent water treatment infrastructures were particularly vulnerable, emphasising the importance of targeted monitoring and risk management plans [34] (see Table 3).

Regarding the rural consumption of untreated water, Khanfar et al. (2010) evaluated NO_3^- and NO_2^- in groundwater using the Palintest Photometer Method, and these studies highlighted that NO_3^- was the dominant species and that seasonal variations, particularly during the rainy season, could influence groundwater chemistry [35]. Another study explained that while concentrations were generally below WHO limits, agricultural inputs and local spatial variations could pose future health risks if monitoring and mitigation were not maintained [35]. Similarly, Al-Harbi and El-Sorogy (2023) assessed 36 wells and boreholes in the Wasia Well Field, Wadi Nisah, and Jubailah in central Saudi Arabia. These studies highlighted that NO_3^- concentrations ranged from 0.70 to 47 mg/L, all below the WHO guidelines. However, the non-carcinogenic hazard indices indicated the potential risk for the infants and children due to the co-occurring fluoride contamination [36].

In the northeastern region of Saudi Arabia, $NO_3^-$was measured in several types of wells, including commercial treated wells for drinking, commercial untreated wells for domestic use, private domestic wells, and agricultural wells [37,38]. These studies highlighted that untreated and private wells often exceeded the WHO guideline of 50 mg/L, with values ranging from 16 to 380 mg/L, whereas treated commercial wells remained below 50 mg/L [37]. Mamun et al. [38]conducted a detailed assessment of 45 wells in semi-urban areas. They found that approximately 35% of the samples exceeded safe limits, with infants and children identified as the most vulnerable groups, often showing exposure above the U.S. EPA reference doses[38]. These studies also highlighted the use of indices such as the nitrate pollution index (NPI), chronic daily intake (CDI), and hazard quotient (HQ) to quantify health risks [37].

Another study explained the spatial distribution of NO_3^- and its associations with the other water quality parameters using the ion-selective electrodes, photometric techniques, and the Geographic Information System (GIS)-based spatial interpolation, and these studies highlighted that the contamination hotspots were influenced by the human activities, the agricultural runoff, and the local geology [39]. Higher NO_3^- levels were observed in the shallow wells, while the lower concentrations were generally measured in the deeper wells. This is due to natural filtration and longer residence times, with filtration considered the most significant factor in reducing NO_3^- levels[39]. Additionally, a strong correlation between NO_3^- and the electrical conductivity (EC) was observed in controlled solutions ($R^2 \approx 0.99$), and a moderate correlation was also observed in the agricultural groundwater. In contrast, a weak negative correlation with pH was noted. It is recommended that EC be combined with total dissolved solids (TDS) to enable a more comprehensive assessment and prioritisation of vulnerable wells [39].

Table 3. Characteristics and key findings of included studies on groundwater nitrate in Saudi Arabia.

Ref.	Year	Region (Saudi Arabia)	Sample Size / Wells	Well Type / Aquifer	NO_3^- Range (mg/L)	Mean / Avg Nitrate (mg/L)	% > WHO MCL (50 mg/L)	Key Outcome
[34]	2010	Nationwide (13 regions: Jizan, Asir, Qassim, Hail, Makkah Al Mukarramah, Madina Al Munnawara, Al Baha, Najran, Tabouk, Eastern Prov., Riyadh, Al Jouf, Hadwed Shamalyah)	1,060 wells	Mixed aquifers	1.1–884.0	Regional averages: Jizan 65.7; Asir 60.3; Qassim 60.0; Hail 51.3; Makkah 41.8; Madina 41.3; Tabouk 30.7; Hadwed Shamalyah 9.1	~20.1% (213/1060)	NO_3^- levels were highly variable; many wells, especially in agricultural and residential areas, exceeded the World Health Organization Maximum Contaminant Level (WHO MCL, 50 mg/L as NO_3^-); the highest regional mean nitrate concentrations were observed in Jizan, Asir, and Qassim.
[35]	2010	Asir: Al-Mahareth village (southwest KSA)	5 sources (quarterly)	Rural drinking wells	23.09–25.06	23.09–25.06 *(Nitrate)*	0%	NO_3^- was the dominant dissolved nitrogen species in rural drinking wells and stayed below WHO MCL; seasonal variation (higher in rainy season) observed; NO_2^- and ammonia (NH_3) remained low.
[36]	2023	Central KSA: Wasia Well Field, Wadi Nisah, Jubailah	36 wells / boreholes	Boreholes (mixed depths)	0.70–47.0	Mean nitrate: Wasia 2.79; Wadi Nisah 21.0; Jubailah 37.93; Overall ~22.59 *(Nitrate)*	0%	NO_3^- concentrations were below WHO MCL in all samples. However, fluoride often exceeded its guideline, and non-carcinogenic Hazard Index (HI) values indicated potential risk for infants and children.
[37]	2024	Northeastern arid KSA: Hafr Al Batin	45 wells	Commercial treated/ untreated,	16–380	Mean nitrate by well type: Treated ~23.0; Untreated ~47.3; Private domestic	~33–50% untreated/ private/agri	NO_3^- contamination was high in shallow, untreated, and private

				private domestic, agricultural		~114.6; Agricultural ~80.0		agricultural wells; many exceeded WHO MCL, while treated commercial sources mostly met WHO guideline.
[38]	2025	Semi-urban northeastern KSA: Hafr Al Batin & surroundings	45 wells	Treated /untreated commercial, private domestic, agricultural	12–380	Mean nitrate by category: Treated 16–43; Untreated 33–49; Private 12–380; Agricultural 80–250	~35%	Around one-third of wells exceeded WHO MCL; infants and children had the highest health risk based on Chronic Daily Intake (CDI) and Hazard Quotient (HQ) metrics; untreated private wells posed greatest exposure.
[39]	2025	Northeastern KSA: Hafr Al Batin & region	*Not specified*	Shallow & deep wells	Not reported	*Not reported*	N/A	The study examined groundwater across different locations and found that NO_3^- levels show clear spatial patterns. NO_3^- was strongly linked with electrical conductivity (EC, $R^2 \approx 0.70$) and total dissolved solids (TDS), meaning that areas with higher EC and TDS generally had higher nitrate concentrations. These results suggest that EC and TDS can be used as simple, indirect measures to estimate NO_3^- levels in groundwater.

7. Discussion

The occurrence of NO_3^- contamination in groundwater in several regions of Saudi Arabia has been reported in the reviewed studies, with some concentrations exceeding recommended drinking water limits[5,6,13,34–38]. However, the health impacts of NO_3^- exposure in Saudi Arabia have been examined only in a limited number of studies. Therefore, international research findings should be considered to understand the potential health implications[9–12,14]. Previous studies reported that elevated NO_3^- levels in drinking water may be associated with health conditions such as methemoglobinemia, thyroid dysfunction, and certain cancers[11,12,14]. These findings provide useful insight into the possible risks associated with groundwater contamination. The international evidence is consistent with the NO_3^- concentrations reported in the reviewed Saudi studies, indicating potential public health concerns[5,6,13,36]. For example, an increased risk of thyroid cancer has been associated with NO_3^- ingestion from public water supplies, as reported by Ward et al.[40]. These findings are considered biologically plausible based on the known mechanism by which NO_3^- competes with iodide uptake in the thyroid gland[40].

Notably, the multiple health endpoints in this review were from international epidemiological studies on thyroid, bladder, and gastrointestinal cancers and reproductive or prenatal effects, rather than Saudi population studies. Therefore, the results of this study should be interpreted with varying degrees of uncertainty. Available Saudi Arabian studies mainly focus on groundwater NO_3^- contamination and potential exposure to it, with limited epidemiological studies demonstrating an association between exposure to groundwater NO_3^- and outcomes of particular interest. Importantly, these associations require confirmation in ongoing Saudi-based cohort, case-control, and biomonitoring studies.

The following sections discuss the primary health impacts of NO_3^- exposure.

7.1. Public health implications of Nitrate (NO_3^-) exposure

7.1.1. Blood disorders

When NO_3^- is ingested through drinking water, it may be converted by gastrointestinal bacteria into NO_2^-. This compound oxidises the iron in haemoglobin to form methaemoglobin, which cannot effectively transport oxygen to body tissues, as described above[2,33]. Baseline methaemoglobin levels in healthy adults are typically below 1–3% of the total haemoglobin, which has been shown to generally not cause symptoms, as the body's oxygen delivery is sufficient to meet the metabolic needs [41]. Moderate symptoms, including weakness, headache, dizziness, and hypotension, tachycardia, and tachypnoea, often develop when methaemoglobin concentrations reached 25–50%, indicating that oxygen transport to the tissues is impaired [41]. These clinical features can be used to assess hypoxic severety and guide clinical management. Additionally, levels above 50–70% are considered life-threatening, with progressively severe hypoxia [41]. At these concentrations, patients may be at risk of seizures, coma, or death if treatment is not provided [41].

Sadeq et al. [42] investigated the nitrate-contaminated wells in Salé, Morocco, where the NO_3^- levels ranged from 15.4 to 246.9 mg/L. They found that the children aged 1–7 years who consumed the water with $NO_3^- > 50$ mg/L had significantly higher methaemoglobin levels than those who drank the water with < 50 mg/L ($p = 0.001$). The prevalence of methemoglobinemia was 36% in the high-nitrate group, compared with 27% in the low-nitrate group. This demonstrates that a clear relationship exists between the nitrate-contaminated well water and the elevated methaemoglobin formation [42] (see Table 4).

7.1.2. Thyroid effects of Nitrate (NO_3^-) exposure

There has been a growing concern regarding chronic NO_3^- exposure through drinking water because of its potential effects on thyroid function in human populations. García-Torres et al. [43] conducted a study in a rural Mexican population, which is advancing understanding of how NO_3^- consumption may be associated with subclinical hypothyroidism. In this study, 45% of participants had subclinical hypothyroidism, 45% had elevated thyroid-stimulating hormone (TSH), 49% had reduced total triiodothyronine (T3), and 19.6% had reduced total thyroxine (T4), indicating a clear disruption of thyroid hormone homeostasis [43]. This effect is considered to be related to systemic NO_3^- assimilation and its metabolic reduction to NO_2^-, which can impair the iodine uptake necessary for normal thyroid function [10,12,40]. These disruptions can occur at exposure levels relevant to contaminated drinking water [43]. This study was conducted to identify the relationship between NO_3^- exposure and altered thyroid biomarkers in order to understand the potential health risks for vulnerable populations [43].

Evidence from other countries supports the biological plausibility of NO_3^- related thyroid effects. For example, a long-term study of 21,977 older women in Iowa found that higher NO_3^- levels in drinking water and food were linked to an increased risk of thyroid cancer [40]. Compared with women in the lowest quartile of average NO_3^- levels in public drinking water (less than 0.36 mg/L NO_3^- N), women who consumed public water with NO_3^- N concentrations above 5 mg/L for five or more years had a 2.6-fold higher relative risk (RR) of thyroid cancer [40]. Increasing intake of dietary NO_3^- was also associated with thyroid cancer, with the highest versus the lowest quartile of dietary NO_3^- intake having a relative risk (RR) of 2.9 [40]. While drinking water NO_3^- was not associated with the prevalence of self-reported hypothyroidism or hyperthyroidism, higher dietary NO_3^- intake was modestly associated with a greater prevalence of hypothyroidism (odds ratio [OR] ~1.2) [40]. NO_3^- may affect thyroid function by inhibiting iodide uptake via the sodium iodide symporter (NIS) and by forming endogenous NOCs, which have carcinogenic potential, providing biological plausibility for the observed associations [40].

7.1.3. Gastrointestinal health effects and cancer risks associated with Nitrate (NO_3^-) exposure from drinking water

Exposure to NO_3^- from drinking water has been widely investigated because of its potential effects on the gastrointestinal tract and its possible association with gastrointestinal cancers influenced by chemical exposures [2,3,33,44]. After NO_3^- is ingested, it is rapidly absorbed from the upper gastrointestinal tract into the bloodstream, and approximately 20–25% of the absorbed NO_3^- is actively secreted into saliva, where oral bacteria convert part of it into NO_2^- [44]. When this nitrite-containing saliva is swallowed, it reaches the acidic environment of the stomach, where NO_2^- may be converted into nitrous acid and other reactive nitrogen species. These may then react with amines and amides present in food to form NOCs via nitrosation [14,33,44].

Several epidemiological investigations have examined whether NO_3^- contamination in drinking water is associated with cancers of the gastrointestinal tract [3,14,33,45]. Although the findings vary across studies, a large systematic review and meta-analysis published in 2022 screened 9,835 records. Ultimately, 111 studies that reported health outcomes related to NO_3^- or NO_2^- exposure from drinking water were identified. Of these, 60 studies specifically examined cancer outcomes.These studies were mostly conducted in the United States, Europe, and Taiwan, where long-term monitoring data on drinking water quality are available [45]. Because the researchers conducted pooled analyses of four studies that specifically investigated gastric cancer, they observed a statistically significant association between NO_3^- exposure and stomach cancer risk [45]. When NO_3^- concentrations in drinking water increased by 10 mg/L, the risk of gastric cancer also increased, which was reflected by an odds ratio of 1.91 (95% confidence interval: 1.09–3.33) [45].

Additional meta-analyses support these findings [3,46]. Although several epidemiological studies have examined this relationship, a systematic review analysing multiple studies reported that NO_3^- intake from drinking water showed a significant association with stomach cancer risk in a meta-regression analysis ($t = 3.98$, $p = 0.0001$). This indicates that higher NO_3^- exposure levels may contribute to increased gastric cancer risk across study populations [46]. Modest associations between NO_3^- exposure and colon cancer risk were also reported in the systematic review, with the highest and lowest exposure categories compared. Although the association for colon cancer was weaker than that observed for gastric cancer, the pooled odds ratio for colon cancer was calculated as 1.11 (95% CI: 1.04–1.17) when the highest and lowest NO_3^- exposure groups were compared. An odds ratio of 1.14 (95% CI: 1.04–1.23) was reported in combined analyses of higher exposure levels, indicating that increased risks of certain gastrointestinal cancers may be contributed to by elevated NO_3^- exposure. However, the magnitude of the risk varies across populations and study conditions [46].

However, epidemiological findings are inconsistent across gastrointestinal cancer types. Although a link between NO_3^- exposure and gastric cancer has been established, no significant association between NO_3^- exposure in drinking water and colorectal cancer was found in the same 2022 systematic review, with a pooled odds ratio of 1.02 (95% CI: 0.96–1.08) reported across ten studies [45]. Because the potential health effects of NO_3^- exposure may differ depending on cancer type, exposure levels, and population characteristics, research in regions where NO_3^- contamination of drinking water is more common remains limited. Most available studies were conducted in high-income countries [45].

7.1.4. Nitrate (NO_3^-) exposure and bladder cancer risk

There has been growing interest in investigating the potential association between NO_3^- in drinking water and bladder cancer, a concern of significant public health importance. This relationship remains inconsistent across the epidemiological studies evaluating the long-term effects of chronic NO_3^- intake [47–50]. In a recent meta-analysis conducted by Arafa et al.[47], the data from five epidemiological studies, including three retrospective case-control studies and two prospective cohort studies, were combined to compare the risk of bladder cancer between individuals with high and low long-term NO_3^- exposure. When NO_3^- exposure was measured by its concentration in drinking water, the pooled OR for bladder cancer comparing the highest and lowest exposure groups was 0.98 (95% CI: 0.60–1.57), indicating no significant increase in risk. Likewise, the pooled OR was 1.00 (95% CI: 0.69–1.45) when the daily NO_3^- intake was examined, suggesting that higher intake did not raise the risk [47]. In contrast, substantial heterogeneity was observed across the included studies, with I^2 values of 80.8% for NO_3^- concentration and 65.0% for daily intake. This reflects differences in the study design, population characteristics, exposure assessment methods, and confounder adjustments, thereby reducing the confidence in the pooled estimates [47]. When the studies that were considered to be at a high risk of bias were excluded, the pooled OR for the NO_3^- concentration was increased to 1.36 (95% CI: 1.03–1.79; $I^2 = 0.0\%$), which was statistically significant. In contrast, the pooled OR for the daily NO_3^- intake was increased to 1.14 (95% CI: 0.90–1.46; $I^2 = 8.4\%$), which was not statistically significant. These results suggest that the association may be influenced by the quality of the studies, with stronger associations observed in higher-quality studies. Although a definitive association between the NO_3^- exposure in drinking water and bladder cancer has not been conclusively established, it has been suggested that higher exposure levels may be associated with an increased risk in certain populations. Therefore, further high-quality prospective studies are required to clarify the long-term effects and to provide more robust evidence for public health policies [47].

Several large studies have examined the link between NO_3^- in drinking water and bladder cancer [47–49]. For example, a study in Iowa, USA, included 808 people with bladder cancer and 1,259 people without bladder cancer. The researchers collected accurate NO_3^- data from the participants' public water supplies to measure the amount of NO_3^- each person was exposed to[49]. In this population, the median nitrate-nitrogen level among the controls was 1.3 mg/L (interquartile range 0.6–3.0 mg/L), and the 90th percentile was 5.5 mg/L, allowing exposure across a wide range to be evaluated [49]. After adjusting for age, sex, smoking, and other confounders, no increased risk of bladder cancer was observed with higher NO_3^- levels, and no interaction was detected for the combination of low vitamin C intake with high NO_3^- exposure [49]. These findings indicate that long-term NO_3^- exposure did not appear to increase bladder cancer risk in this population. However, further studies in diverse populations are needed to confirm these results and assess the influence of diet, lifestyle, or other environmental factors [49].

Similarly, a large cohort study has investigated the potential relationship between NO_3^- exposure in drinking water and bladder cancer, providing valuable insights into how long-term NO_3^- intake may affect health [50]. As the Iowa Women's Health Study followed 34,708 postmenopausal women for bladder cancer incidence, the ability to evaluate long-term drinking water exposure allowed researchers to assess bladder cancer risk in detail. It was shown that women in the highest quartile of average drinking water NO_3^- concentration had a non-significant higher hazard of bladder cancer (HR = 1.48; 95% CI: 0.92–2.40) than those in the lowest quartile [50]. In order to understand the effects of longer exposure, women exposed for ≥4 years to water with nitrate ≥5 mg/L nitrate-nitrogen were also analysed and could be observed to have a 62% increased risk of bladder cancer (HR = 1.62; 95% CI: 1.06–2.47; $p = 0.03$) [50]. Among current smokers with the highest NO_3^- exposures, hazard ratios did not remain low and were even higher (e.g., HR = 3.67; 95% CI: 1.43–9.38), suggesting a possible interaction between smoking and NO_3^- exposure. These findings highlight the need for additional studies to confirm these associations in other populations [50].

Additionally, a large study has been conducted to investigate the potential link between exposure to NO_3^- in drinking water and bladder cancer risk [51]. The investigators assessed NO_3^- exposure from both public water and modelled private well sources. Including multiple sources of drinking water enabled detailed risk evaluation [51]. An increased odds of bladder cancer (OR = 1.50; 95% CI: 0.97–2.30; $p = 0.01$) was associated with average drinking water nitrate concentrations in the highest category, defined as above the 95th percentile and greater than 2.07 mg/L nitrate-nitrogen [51]. Positive interactions were observed between drinking water nitrate and the intake of both red meat and processed meat, which are dietary sources that can promote NOC formation, to better understand the role of dietary factors [51]. These findings could be interpreted to suggest that, although a general link between NO_3^- exposure and bladder cancer has not been fully proven, a higher risk could be associated with specific dietary and exposure conditions. However, there is a need for further studies in other populations to confirm these associations [51].

NO_3^- contamination in Saudi groundwater occasionally exceeds international safety guidelines [5,6,34,36–38]. However, no Saudi study has directly assessed bladder cancer risk from NO_3^- exposure, and research from other countries has produced mixed findings regarding this association [47–51]. The biological plausibility of NO_2^- formation via nitrosation is supported by further research [44,45]. This suggests that, although a general link has not been established, specific exposure conditions, particularly when combined with dietary or lifestyle risk modifiers, could be associated with increased bladder cancer risk. This highlights the need for high-quality targeted studies in the Saudi population [47,48,51].

7.1.5. Hepatic and renal effects of nitrate (NO_3^-) exposure

Direct human evidence linking drinking water NO_3^- and NO_2^- exposure to clinical liver or kidney disease is limited, inconsistent, and generally considered insufficient to draw firm conclusions [52]. For example, large analyses of the agricultural cohorts reported no clear association between drinking water NO_3^- exposure and end-stage renal disease (ESRD). However, subgroup analyses suggested possible links between NO_2^- or NO_3^- exposure from processed meats and ESRD among participants with low antioxidant intake or high iron intake, underscoring the complexity of the exposure sources and effect modifiers [53]. In contrast, animal and laboratory studies have suggested that NOCs, which can form NO_2^-, may be toxic to liver and kidney cells at high doses. However, these effects have not been consistently observed in humans at the levels of NO_3^- and NO_2^- typically found in drinking water [54,55].

In regions such as Saudi Arabia, groundwater quality is regularly monitored for NO_3^- levels as part of the public health surveillance. However, the health of local populations' livers and kidneys in relation to NO_3^- and NO_2^- exposure has not been systematically studied. Therefore, there is a lack of local human evidence about whether exposure via drinking water contributes to organ-specific diseases in those populations [34,36,37].

7.1.6. Prenatal and reproductive health effects of Nitrate (NO_3^-) exposure from drinking water

This is the body of research that has been conducted and examined the effects of NO_3^- in drinking water on reproductive and developmental outcomes, and how maternal and foetal health may be influenced by prenatal exposure [56]. A systematic review and meta-analysis were carried out for the purpose of evaluating the risk of preterm birth. Higher concentrations of NO_3^- in drinking water were associated with a small but statistically significant increase in the risk of preterm delivery [56]. In this analysis, a pooled odds ratio of approximately 1.05 (95% CI 1.01–1.10) was observed when comparing the highest and lowest exposure categories. This indicated that women in the highest NO_3^- exposure group had modestly higher odds of preterm birth than those in the lowest exposure group [56]. However, inconsistent findings regarding altered foetal growth, including in small-for-gestational-age infants, have been reported across studies, and no statistically significant association was identified in pooled analyses [56]. Some case-control studies suggested that higher NO_3^- exposure may be associated with increased odds of neural tube defects. However, this finding was inconsistent across all studies in the review, and the overall evidence remains limited [56]. These findings are considered important because potential risks associated with environmental NO_3^- exposure are highlighted and the need for further well-controlled epidemiological studies that account for maternal nutrition, iodine status, and other confounders is demonstrated [56] (see Table 4).

Complementing this evidence, a large body of research has been conducted in Denmark to understand how the risk of preterm birth may be associated with NO_3^- in household tap water and to what extent gestational age may be affected by maternal exposure [57]. In this population-based cohort, maternal NO_3^- exposure was estimated by linking residential addresses to NO_3^- concentrations in household tap water. This was used to identify exposure–response relationships considered critical for public health assessment [57]. Approximately 1.05 times higher odds of preterm birth (95% CI 1.00–1.10) were observed among pregnancies exposed to NO_3^- concentrations above 25 mg/L compared with lower exposures. Additionally, a modest exposure–response association per 10 mg/L increase in NO_3^- during pregnancy was also identified [57].

A large Danish cohort study estimated maternal prenatal NO_3^- exposure by linking individual residential addresses to measured NO_3^- levels in household tap water, enabling examination of how NO_3^- levels during pregnancy relate to various categories of birth defects [58]. An exposure–response relationship between NO_3^- exposure during pregnancy and birth defects of the eye was identified, with an odds ratio of 1.29 (95% CI 1.00–1.66) reported for the highest exposure group (≥25 mg/L) compared with the lowest exposure group [58]. Statistical interactions between maternal age and continuous NO_3^- exposure were observed for nervous system birth defects, indicating increased risk among children born to mothers younger than 25 years of age [58]. Evidence of an interaction between maternal age and NO_3^- exposure for ear, face, and neck birth defects was detected, which indicates an increased risk among babies born to mothers younger than 25 years [58]. Conversely, the study observed inverse exposure–response relationships (i.e. lower odds with higher nitrate) for several other broad birth defect categories, including birth defects, digestive system defects, female genital defects, and urinary defects [58].

Previous observational studies in the United States have examined how higher maternal NO_3^- intake from drinking water is associated with selected congenital anomalies [59]. The National Birth Defects Prevention Study showed that increased maternal nitrate intake during early pregnancy was associated with higher odds of limb deficiencies, cleft lip, and cleft palate than in control mothers [59]. A study using the Missouri birth defect registry reported a positive association between the NO_3^- levels in drinking water consumed by mothers and limb deficiencies (rate ratio per 1 mg/L NO_3^- = 1.26) [60]. In contrast, weaker or inconsistent associations have been reported between the congenital heart and neural tube defects [60]. These findings suggest that prenatal NO_3^- exposure may increase the risk of specific birth defects. However, causality could not be established, and potential confounding factors, such as maternal nutrition and socioeconomic status, should be considered when interpreting the results [60].

7.2. Strengths and limitations of the study

This study has several strengths that improve the reliability and importance of its findings. It reviews a wide range of research on NO_3^- and NO_2^- contamination in groundwater and their possible health effects, helping explain where these contaminants come from, how they move through water systems, and how people may be exposed to them[2,5,6,9,13,15,17,18]. This study also draws on knowledge from different fields, including environmental science, hydrogeochemistry, toxicology, and public health. This helps provide a clearer understanding of how groundwater contamination occurs and how it can affect human health[2,3,10,33,42]. This study followed a systematic and transparent literature review to ensure the inclusion of reliable studies [3,45,46,61,62].

Although this study has several strengths, it also has some limitations. The available literature contains helpful information on NO_3^- contamination and related health impacts. However, these findings should be interpreted cautiously because of inconsistencies in the literature. Some studies report an association between exposure to NO_3 with thyroid, gastric, bladder, or reproductive outcomes, while others report weak, non-significant, and/or inconclusive findings. Heterogeneity in the study design, sample size, exposure period, exposed population, water source, regional environmental factors, and other factors may explain these differences. Some confounding variables may also have affected the reported associations, including dietary nitrate, vitamin C, and iodine intake, smoking status, pregnancy status, socioeconomic factors, and co-exposure to other contaminants (fluoride). Furthermore, there are variations in how exposure was measured across studies, such as direct groundwater sampling, data from public water supplies, exposure modelling, and self-reported water consumption, which can lead to exposure misclassification. These associations are suggestive, but cannot be interpreted as causal until additional epidemiological data specific to Saudi Arabia are available. While this review integrates regional and international groundwater data and provides a comprehensive assessment of exposure and health risks, the data gaps and spatial variability in the available studies introduce uncertainty into the findings[5,6,18,21,25]. However, reliance on modelled exposure and limited local epidemiological evidence may affect the precision of the findings and limit the generalisability of the results[34,36–38]. These limitations underscore the need for more extensive field-based monitoring, standardised data collection, and locally focused epidemiological studies to better inform risk assessment and intervention strategies[61,62].

Table 4: Health impacts of nitrate (NO_3^-) exposure.

Health Effect / Outcome	Route of Exposure	Mechanism / Exposure	Associated Risks / Potential Health Outcomes	Key Findings	Ref.
Methemoglobinemia / Hypoxia	Drinking water (NO_3^- ingestion)	NO_3^- reduced to NO_2^- by gut bacteria; NO_2^- oxidises haemoglobin → methaemoglobin, impairing O_2 transport	Mild: <1–3% methaemoglobin usually asymptomatic; Moderate: 25–50% → weakness, headache, dizziness, tachycardia; Severe: >50–70% → seizures, coma, death	Children (1–7 y) consuming water >50 mg/L NO_3^- had 36% prevalence of methemoglobinemia vs 27% in <50 mg/L group (p = 0.001)	[2,33,41,42]
Thyroid Dysfunction / Subclinical Hypothyroidism	Drinking water (chronic NO_3^-)	NO_3^- metabolised to NO_2^- → inhibits iodide uptake via sodium-iodide symporter (NIS) → disrupts thyroid hormone synthesis	Subclinical hypothyroidism, elevated TSH, reduced T3/T4; thyroid cancer risk increased with long-term exposure	Mexican rural study: 45% had subclinical hypothyroidism, 45% elevated TSH, 49% reduced T3, 19.6% reduced T4; Iowa cohort: RR thyroid cancer 2.6 for high water NO_3^-, RR 2.9 for high dietary NO_3^-	[10,12,40,43]
Gastrointestinal Cancers (Stomach, Colon)	Drinking water (NO_3^-)	NO_3^- → NO_2^- → nitrous acid in stomach → reacts with dietary amines/amide → N-nitroso compounds (NOCs)	Gastric cancer, modest colon cancer risk	Meta-regression: stomach cancer t = 3.98, p = 0.0001; colon OR = 1.11 (95% CI 1.04–1.17); combined higher exposure OR = 1.14 (95% CI 1.04–1.23); colorectal cancer pooled OR = 1.02 (95% CI 0.96–1.08)	[3,14,33,44–46]
Bladder Cancer	Drinking water (NO_3^-)	NO_3^- → NO_2^- → NOCs formation; potential interaction with diet (red/processed meat) and smoking	Possible increased bladder cancer risk under high exposure or dietary/smoking interactions	Mixed evidence: pooled OR highest vs lowest NO_3^- 0.98–1.00; excluding high-bias studies OR 1.36 (95% CI 1.03–1.79); Iowa cohort: HR 1.62 (95% CI 1.06–2.47) for ≥4 yrs exposure ≥5 mg/L nitrate-N	[47–51]
Hepatic / Renal Effects	Drinking water (NO_3^-/NO_2^-)	Formation of NOCs; potential organ toxicity at high doses	End-stage renal disease (ESRD) and liver toxicity not consistently observed in humans	Evidence insufficient in humans; animal studies show toxicity at high doses; Saudi populations not studied	[52–55]

Preterm Birth / Prenatal Effects	Maternal drinking-water exposure (NO_3^-)	Maternal NO_3^- exposure → systemic NO_2^- → placental transfer → potential fetal hypoxia/oxidative stress	Preterm birth, small-for-gestational-age infants, neural tube defects, birth defects of eye, limb, cleft lip/palate	Pooled OR preterm birth ~1.05 (95% CI 1.01–1.10) for highest vs lowest exposure; Danish cohort: eye defects OR = 1.29 (95% CI 1.00–1.66) at ≥25 mg/L	[56–58]
Congenital / Birth Defects	Maternal drinking-water exposure(NO_3^-)	Maternal NO_3^- exposure → fetal NOC formation/oxidative stress	Limb deficiencies, cleft lip, cleft palate; inconsistent associations with heart and neural tube defects	US National Birth Defects Study: increased maternal nitrate intake associated with limb deficiencies, cleft lip/palate; Missouri registry RR per 1 mg/L NO_3^- = 1.26 for limb defects	[59,60]

7.3. Future directions for managing groundwater Nitrate and Nitrite

There is growing concern regarding NO_3^- and NO_2^- contamination in Saudi Arabia, which may help guide future water safety strategies[1,5,6]. Future efforts should focus on comprehensive monitoring with accurate identification of both high- and low-concentration groundwater sources, which will enable targeted interventions with the potential to reduce human exposure[5,6,13,36]. Contaminated wells should be replaced or blended with cleaner sources. In contrast, long-term prevention should be ensured by controlling agricultural runoff, livestock waste, and untreated effluents, all of which are recognised as major contributors to groundwater contamination [5,20,22,28].

The NO_3^- levels can be effectively reduced by technical treatments, such as ion exchange and reverse osmosis, although these methods are costly and energy-intensive[8,63–65]. Biological denitrification is a practical and highly efficient method for removing NO_3^- from groundwater[66], making it a promising approach for treating contaminated water. In laboratory studies, the nitrate-reducing bacteria immobilised on microbial cellulose reduced NO_3^- concentrations from 100 mg/L to 1.9 mg/L within 18 hours, demonstrating the effectiveness of the method under controlled conditions[67]. Solid-phase denitrification that uses the biodegradable polymer poly (butylene succinate) as the carbon source achieved 88–97% NO_3^- removal. However, the effluent concentrations still ranged from approximately 3.3 to 8.8 mg/L, demonstrating the long-term stability and high efficiency of the approach [68]. The factors that affect NO_3^-/NO_2^- contamination include geography, shallow wells, hydrogeology, fertiliser use, and wastewater management, indicating that a coordinated approach, including monitoring, regulations, early-warning systems, and community engagement, is needed to ensure safe water[5,6,18,20,28].

8. Conclusion

Much research has been conducted in the past decades to investigate NO_3^- and NO_2^- contamination in groundwater used for drinking purposes, particularly in arid and semi-arid regions such as Saudi Arabia. Various regional and national studies have assessed groundwater quality and human exposure, and a wide range of nitrate concentrations has been reported, from background levels below 10 mg/L to extremely elevated concentrations exceeding 300–800 mg/L, mainly in shallow and unconfined aquifers. Most studies have been preliminary and region-specific, and a gap remains between the identification of nitrate-contaminated groundwater sources and comprehensive epidemiological and population-based health outcome studies. While treated municipal and commercial drinking water supplies generally complied with international guidelines, untreated private domestic and agricultural wells frequently exceeded the World Health Organization (WHO) guideline value of 50 mg/L for nitrate, representing the most important pathway for chronic exposure in rural communities. Infants and children have been identified as the most vulnerable population groups in most published health risk studies, with chronic daily intake and hazard quotient values often exceeding acceptable thresholds. In recent years, there has been an increase in the application of hydrogeochemical mapping, spatial analysis, and human health risk assessment approaches, which are highly important for identifying contamination hotspots and prioritising mitigation strategies. NO_3^- toxicity is mainly driven by its conversion to NO_2^-, leading to methemoglobinemia, thyroid dysfunction, birth defects, preterm delivery, oxidative stress, and possible carcinogenic N-nitroso compound formation, with increased risk of gastric, bladder and thyroid cancers. However, further focused studies are needed in Saudi Arabia. Evidence linking NO_3^- exposure with gastric, bladder, and thyroid cancers is inconsistent and mainly based on international studies. These outcomes should be considered possible associations and require further Saudi-specific epidemiological research. Furthermore, mitigation strategies, monitoring costs, and management effectiveness should be compared with alternative water supply and treatment approaches. Overall, this work gathered the most relevant available research on NO_3^- and NO_2^- contamination in groundwater, which is important for consolidating current knowledge and supporting sustainable solutions that ensure safe access to potable water in contaminated areas.

Data Availability:

Data and materials of this study are openly available.

Declaration:

The author declares that there are no conflicts of interest.

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Abbreviations List (Table)

Abbreviation	Full Form
NO_3^-	Nitrate
NO_2^-	Nitrite
WHO	World Health Organization
CDI	Chronic Daily Intake
HQ	Hazard Quotient
HI	Hazard Index
NOCs	N-Nitroso Compounds
GI	Gastrointestinal
Hb	Hemoglobin
metHb	Methemoglobin
NH_3	Ammonia
NH_4^+	Ammonium
EC	Electrical Conductivity
TDS	Total Dissolved Solids
GIS	Geographic Information System
NPI	Nitrate Pollution Index
EPA	Environmental Protection Agency
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
MCL	Maximum Contaminant Level

Declaration of Generative AI and AI-assisted technologies in the writing process: During the preparation of this work the authors used ChatGPT 4.0 and Google Gemini in order to enhance the writing of this manuscript. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication).

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