



# Fertilizer inputs and groundwater contamination dynamics

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**Abstract.** Groundwater contamination by agricultural fertilizers has become a major environmental concern due to the widespread use of nitrogen- and phosphorus-based inputs aimed at sustaining crop productivity. Excessive or poorly managed fertilizer applications contribute to nitrate accumulation in the unsaturated zone and elevated nitrate concentrations in groundwater, with potential implications for drinking water quality, ecosystem functioning, and human health. However, the magnitude of groundwater contamination is influenced by multiple interacting factors, including soil properties, hydrological conditions, climatic variability, and the legacy effects of historical fertilization practices. This review synthesizes current evidence regarding the relationships between fertilizer inputs and groundwater contamination dynamics. Particular emphasis is placed on nitrate leaching associated with nitrogen fertilization, the hydrological and soil factors controlling contaminant transport, and the effectiveness of mitigation strategies designed to reduce groundwater pollution. In addition, the review discusses the indirect implications of phosphorus and fertilizer-derived heavy metals for groundwater quality and highlights the importance of integrated nutrient management approaches. The available evidence indicates that groundwater quality responses to fertilizer use are highly context-dependent and may reflect both present and past agricultural practices. Improved fertilizer management, enhanced-efficiency products, optimized application timing, and policy interventions can substantially reduce contamination risks. Understanding these complex interactions is essential for developing agricultural systems capable of maintaining productivity while protecting groundwater resources.

**Keywords:** groundwater contamination, nitrate leaching, fertilizer inputs, nitrogen management, agricultural sustainability.

**Introduction.** Agricultural intensification has played a fundamental role in meeting the increasing global demand for food, largely through the extensive use of mineral fertilizers to improve crop yields and maintain soil fertility. Nitrogen and phosphorus fertilizers have significantly contributed to enhanced agricultural productivity over recent decades. However, the environmental consequences associated with their widespread and, in some cases, excessive application have become a growing concern, particularly regarding the quality of groundwater resources (Bijay-Singh & Craswell, 2021; Duda et al., 2023).

Groundwater represents one of the most important sources of drinking water worldwide and supports numerous ecological, agricultural, and industrial activities. Unlike surface waters, groundwater systems often respond slowly to environmental disturbances because contaminants require extended periods to migrate through soils and aquifers. Consequently, groundwater quality frequently reflects not only current agricultural practices but also the cumulative effects of historical fertilizer applications. This delayed response complicates the identification of pollution sources and the implementation of effective mitigation strategies (Rupp et al., 2024; Halecki et al., 2025).

Among fertilizer-derived contaminants, nitrate has been identified as the most widespread pollutant directly affecting groundwater. Elevated nitrate concentrations in groundwater have been reported in numerous agricultural regions across the world and are associated with potential risks to human health, including methemoglobinemia and possible long-term adverse health outcomes. Furthermore, nitrate contamination contributes to the degradation of aquatic ecosystems and represents a major challenge for achieving water quality objectives established by national and international environmental policies (Plata et al., 2025; Gomes et al., 2023).

The relationship between fertilizer use and groundwater contamination is highly complex and influenced by a range of interacting factors. Soil texture, hydrological conditions, climatic variability, crop type, fertilizer application rates and timing, and nutrient management practices all affect the transport and fate of nutrients within agricultural systems. In addition, legacy effects resulting from decades of fertilizer use may obscure direct correlations between current fertilizer inputs and observed groundwater nitrate concentrations (Krevh et al., 2023; Wen et al., 2024).

Given the increasing pressure to reconcile agricultural productivity with environmental protection, a comprehensive understanding of fertilizer–groundwater interactions is essential. Therefore, this review aims to synthesize current scientific evidence regarding the influence of fertilizer inputs on groundwater contamination dynamics. Particular attention is given to nitrate leaching associated with nitrogen fertilization, the hydrological and soil controls governing contaminant transport, mitigation strategies capable of reducing groundwater pollution, and the indirect implications of phosphorus and fertilizer-derived trace elements for groundwater quality and sustainable agricultural management.

**Nitrogen Fertilizer Use and Nitrate in Groundwater.** Excessive or poorly synchronized nitrogen fertilization increases nitrate leaching from soils, making agriculture a dominant source of groundwater nitrate in many regions (Rupp et al., 2024; Duda et al., 2023; Plata et al., 2025; Lawniczak et al., 2016; Bijay-Singh & Craswell, 2021). Field and lysimeter studies show that nitrate leaching loads rise with nitrogen application, but the relationship is strongly modified by soil type and management. For arable land in a 39-year German lysimeter experiment, annual nitrogen loads in leachate were highest from sand (36.6 kg N ha<sup>-1</sup> yr<sup>-1</sup>) and loamy sand (30.7 kg N ha<sup>-1</sup> yr<sup>-1</sup>), and much lower from loess and loam (12.1–13.1 kg N ha<sup>-1</sup> yr<sup>-1</sup>) under the same fertilization regimes (Rupp et al., 2024). Meta-analysis of 394 observations from Chinese cropping systems confirms that nitrogen fertilizer application significantly increases nitrate leaching in both upland and paddy fields, with leaching positively correlated with application rate (Wen et al., 2024). At landscape scale, groundwater monitoring in agricultural regions often detects a fraction of wells above drinking-water limits. In Southern Alberta (Canada), 10% of >3500 groundwater samples exceeded 10 mg/L nitrate-N, with exceedances mainly in shallow aquifers; positive correlations between nitrate-N, potassium, and chloride indicate synthetic fertilizers and manure as key sources (Plata et al., 2025). Protected areas with high shares of arable land can still show elevated groundwater nitrate. In a Polish national park and buffer zone, catchments dominated by arable fields had significantly higher nitrogen concentrations in groundwater than forested catchments, and nitrogen levels correlated with nitrogen supply (Lawniczak et al., 2016). Long-term and regional analyses emphasize the role of nitrogen surplus and legacy. A global review concludes that, on average, crops directly use less than half of applied fertilizer N, with much of the remainder accumulating in soil organic pools and later leaching as nitrate, so groundwater nitrate trends reflect both current and past fertilization (Bijay-Singh & Craswell, 2021). An EU-wide analysis linking gross nitrogen balance (a proxy for fertilizer surplus) to nitrate levels in surface and groundwater finds that higher nitrogen surpluses are associated with poorer water quality classes across monitoring points, although the relationship is partly masked by long-term effects and local conditions (Halecki et al., 2025) (Table 1).

Table 1

Examples of fertilizer inputs versus nitrate in leachate and groundwater

<i>Context and system</i>	<i>Fertilizer / N balance metric</i>	<i>Groundwater or leachate nitrate response</i>	<i>References</i>
German lysimeter, arable land on sand vs loam	Mineral N at 50–150% of recommendation	Leached N: 36.6 kg ha <sup>-1</sup> yr <sup>-1</sup> (sand) vs 12.1–13.1 kg ha <sup>-1</sup> yr <sup>-1</sup> (loess/loam) under similar fertilization	Rupp et al., 2024
Chinese upland and paddy fields (meta-analysis)	Increasing N fertilizer application rate	Nitrate leaching significantly increases in both upland and paddy; rate positively correlated with leaching	Wen et al., 2024

<i>Context and system</i>	<i>Fertilizer / N balance metric</i>	<i>Groundwater or leachate nitrate response</i>	<i>References</i>
Alberta agricultural region	High N fertilizer and manure inputs	10% of 3500+ groundwater samples >10 mg/L nitrate-N; elevated values in shallow aquifers	Plata et al., 2025
EU agricultural land	Gross nitrogen balance (surplus)	Higher N surplus associated with poorer water-quality classes for nitrate in surface and groundwater	Halecki et al., 2025
Modeled agricultural aquifer	Fertilizer rate scenarios: +2%, -2%, -4%	Business-as-usual raises groundwater nitrate from 14 to 18 mg/L in 10 years; -2 to -4% rates keep maxima <12 mg/L	Zhang et al., 2020.

**Hydrological and Soil Controls on Fertilizer–Groundwater Correlations.** Long-term field monitoring in Croatia over 2009–2020 shows that nitrate leaching depends on the interaction of fertilizer management with soil hydraulic properties, crop rotation, and climate. Principal component analysis identified precipitation patterns, plant uptake, and N application as jointly influencing leaching; most elevated nitrate concentrations in lysimeter outflows occurred during wet periods with saturated soils and low evapotranspiration (Krevh et al., 2023). The German lysimeter study likewise found that soil type and other management factors “mask” simple fertilizer–leaching relationships in arable systems: halving the N rate did not reduce nitrate leaching but reduced yields by up to 29%, and increasing N by 50% did not significantly enhance leaching, emphasizing that strategies beyond rate reduction are needed (Rupp et al., 2024). Meta-analysis across Chinese systems identifies different key drivers in paddy versus upland fields: in paddy fields, soil pH and fertilizer timing dominate nitrate leaching, whereas in uplands, fertilizer rate and pH are most important, and leaching risk is reduced when nitrogen is applied in soils with higher organic matter and moderate total N (Wen et al., 2024). Model coupling between the unsaturated and saturated zones further clarifies temporal connections between fertilizer inputs, soil leaching, and groundwater values. In a Chinese agricultural area, HYDRUS-1D and MT3DMS simulations showed that 64% of annual nitrate leaching occurred between May and September; modest annual changes in fertilizer rate (+2% or -2–4%) translated, over a decade, into groundwater nitrate rising to >20 mg/L or remaining below 12 mg/L, respectively (Zhang et al., 2020). Risk-assessment frameworks explicitly link nitrogen balances to groundwater nitrate. A multicriteria method applied in two European agricultural regions balanced nitrogen inputs from mineral and organic fertilizers and soil nitrogen against crop uptake; nitrate concentration in leachate, compared with natural baseline, was used to classify groundwater risk. Under typical European conditions with total fertilization of 95–120 kg N ha<sup>-1</sup>, groundwater nitrate risk was low to moderate; at 150–180 kg N ha<sup>-1</sup>, a 40–50% reduction in total fertilization was required to achieve low risk (Duda et al., 2023).

**Mitigation Strategies and Their Effects on Groundwater Values.** The evidence indicates that fertilizer–groundwater correlations can be substantially modified by improved nitrogen management, including product type, timing, integration with organic sources, catch crops, and regulatory measures.

Enhanced-efficiency fertilizers (EEFs) and application timing alter nitrate leaching at field scale. In irrigated sandy soils in Nebraska, six treatments at 202 kg N ha<sup>-1</sup> were compared using suction lysimeters at 120 cm depth. Preplant application of urease-inhibitor and dual inhibitor products reduced nitrate leaching by 75% relative to conventional split urea–UAN without reducing maize yield and increased economic return when environmental costs were included. Split EEFs reduced leaching compared to preplant urea in one year but more than doubled leaching relative to preplant EEFs without yield benefit (Singh et al., 2025). Combining organic and mineral fertilizers can decrease leaching risk by better synchronizing nitrogen release with crop uptake. The Chinese meta-analysis found that joint application of chemical fertilizer and organic manure was the most effective method for mitigating nitrate leaching in both paddy and

upland fields (Wen et al., 2024). Alternative nitrogen sources with slower mineralization also influence leaching dynamics. A column experiment on spinach showed that applying microalgal “manure” derived from phycoremediated sewage significantly reduced nitrate in leachate at 0–45 cm depth compared to chemical fertilization: for example, 0–15 cm leachate contained 5.03 mg/L nitrate in the algae-manure treatment versus 8.57 mg/L in the chemically fertilized treatment (Sharma et al., 2022). Policy frameworks also affect observed groundwater nitrate concentrations. In a Portuguese nitrate-vulnerable zone (Esposende–Vila do Conde), 1728 groundwater samples over 2007–2020 showed that points in agricultural areas and artificialized territories had the highest nitrate concentrations, linked to application of organic and chemical fertilizers without good practices. While overall nitrate levels decreased over time under EU Nitrates Directive measures, concentrations remained locally high, indicating that existing mitigation was insufficient (Gomes et al., 2023). At the EU scale, catch crops (green cover) and organic farming emerge as levers that modify nitrogen balances and thus potential leaching. In the gross nitrogen balance analysis, catch crops were associated with higher nitrogen balances (indicating retention of N on land), while Natura 2000 conservation sites were associated with lower balances; the water exploitation index decreased with organic farming, suggesting that practices associated with organic systems can improve resource efficiency while reducing nitrogen pressure on waters (Halecki et al., 2025). Regional case studies show that improving nutrient balance across N, P, and K can reduce nitrogen losses. In the Polish protected area, severe shortages of phosphorus and potassium in fertilizers, relative to nitrogen, were identified as a factor promoting nitrogen leaching because plant uptake of nitrogen was limited (Lawniczak et al., 2016).

**Phosphorus, Heavy Metals, and Indirect Groundwater Implications.** While nitrate is the primary fertilizer-derived contaminant found directly in groundwater, phosphorus and fertilizer-borne trace elements mainly affect soils and surface waters but have indirect consequences for groundwater quality and use.

Long-term application of phosphorus-enriched fertilizers and manures leads to soil P accumulation that can be mobilized via leaching and runoff. Reviews of phosphorus management highlight that highly water-soluble P fertilizers have contributed to eutrophication and hypoxia in surface waters and that integrated management of nitrogen and phosphorus is more effective than P-only strategies for controlling eutrophication (Haque, 2021). Analyses of nutrient losses from Chinese croplands quantify large spatial variability in nitrogen and phosphorus leaching, with net nitrogen leaching for some vegetable systems ranging from 0.78 to 23.66 kg ha<sup>-1</sup> and phosphorus losses driving freshwater and marine eutrophication potential. Provinces with high P characterization factors (e.g., Hainan, Yunnan, Guangdong, Guangxi, Fujian) contribute disproportionately to global freshwater eutrophication potential, and interior “breadbasket” provinces with high N and P losses are hotspots for both freshwater and marine eutrophication (Huang et al., 2017). Fertilizer-derived heavy metals such as cadmium and uranium accumulate in soils with long-term phosphorus fertilizer use, posing future leaching risks to groundwater and direct risks through crop uptake. A Swiss survey of more than 400 soil samples found Cd and U concentrations 58% and 9% higher, respectively, in arable topsoil than in arable subsoil, with geochemical mass balances indicating accumulations of 52% for Cd and 6% for U; mineral P fertilizers were identified as the dominant current source (Bigalke et al., 2017). At smaller scales, analyses of commonly used fertilizers show elevated cadmium and chromium in triple superphosphate and copper and lead in NPK products, with significantly higher heavy-metal levels in soils, vegetables, pond waters, and fish from fertilized sites compared to unfertilized controls; health risk indices for several vegetables and fish muscles exceeded 1, indicating potential human health risks (Tasleem et al., 2023).

Industrial production of phosphate fertilizers adds further contaminant pathways: wastes from phosphogypsum plants contain potentially toxic elements and radioactive substances and can contaminate soil and water if poorly managed (Ahmad et al., 2023). Collectively, these findings show that correlations between fertilizer use in agricultural holdings and groundwater values are strongest and most direct for nitrate, but that

phosphorus and associated trace elements from fertilizers also shape the broader hydrochemical context in which groundwater is used, especially via soil accumulation and eutrophication of connected surface waters.

**Conclusions.** Fertilizer use remains essential for maintaining agricultural productivity and ensuring food security; however, its environmental implications, particularly with respect to groundwater quality, require careful consideration. The evidence synthesized in this review demonstrates that excessive or poorly managed fertilizer applications are strongly associated with increased nitrate leaching and elevated groundwater nitrate concentrations, although the magnitude of these effects varies according to soil characteristics, hydrological conditions, climate, and agricultural practices.

Groundwater contamination dynamics are influenced not only by current fertilization strategies but also by legacy effects resulting from historical nutrient inputs. Consequently, improvements in groundwater quality may occur gradually and require long-term monitoring and adaptive management approaches. The findings also highlight that nutrient management practices, including optimized fertilizer application rates and timing, enhanced-efficiency fertilizers, integration of organic amendments, and complementary agronomic measures, can substantially reduce contamination risks while maintaining crop productivity.

Although nitrate represents the most direct fertilizer-derived threat to groundwater resources, the broader environmental implications of phosphorus accumulation and fertilizer-associated trace elements should not be overlooked. Protecting groundwater quality therefore requires integrated nutrient management strategies that balance agricultural production goals with environmental sustainability objectives.

Overall, achieving sustainable agricultural systems capable of safeguarding groundwater resources will depend on the implementation of science-based management practices, effective policy frameworks, and continued efforts to improve nutrient use efficiency. A better understanding of the complex interactions between fertilizer inputs, environmental conditions, and groundwater responses is essential for supporting both food security and long-term water resource protection.

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