A comprehensive review on impact of intensive use of nitrogenous fertilizer on nitrate contamination in groundwater under sugarcane based cropping system in Indo-Gangetic plains of India

Abstract

This study critically examines the impact of intensive nitrogen fertilizer use on nitrate contamination in groundwater within sugarcane-dominated cropping systems in the Indo-Gangetic Plains of India, with a focus on Samastipur district, Bihar. The region's sugarcane cultivation, characterized by high nutrient demand, necessitates substantial fertilizer application. This practice, combined with the area's medium to high rainfall, exacerbates nitrate leaching and runoff, leading to significant groundwater contamination. Unlike existing studies that broadly address agricultural nitrate pollution, this paper uniquely synthesizes thematic analyses, including nitrate chemistry, environmental distribution, leaching processes, and health implications, alongside the effects on sugarcane quality. Novel insights are provided on the interplay between agricultural practices and environmental health, particularly concerning sugarcane cultivation's contribution to nitrate flux. The findings underscore the dire environmental and public health challenges posed by elevated nitrate levels, including methemoglobinemia, ecosystem degradation, and compromised agricultural productivity. Highlighting the inadequacies of current practices, the research advocates for sustainable solutions, such as precision fertilizer application, biological nitrogen sources, and enhanced irrigation management. This comprehensive review contributes valuable perspectives for policymakers, researchers and stakeholders aiming to mitigate nitrate pollution and ensure sustainable agricultural development in similar agrarian landscapes.

Keywords: nitrate contamination, groundwater quality, nitrogenous fertilizers, sugarcane cropping system, leaching, sustainable agriculture

Introduction

The intensive use of nitrogenous fertilizers in agriculture has emerged as a global concern due to its significant environmental and public health implications. Nitrogen, an essential nutrient for crop growth, is often applied in excessive quantities to meet the high demands of nutrient-intensive crops such as sugarcane. Sugarcane, a C4 crop, is a major contributor to the agricultural economy of the Indo-Gangetic Plains of India (Kumar *et al*., 2023a), particularly in Bihar's Samastipur district, where it dominates the cropping system. However, this agricultural practice poses a severe risk of nitrate leaching into groundwater, especially during the rainy season characterized by medium to high rainfall. These conditions facilitate nitrate movement through runoff and deep drainage, contaminating groundwater resources (Kumar et al., 2024a; Singh et al., 2021). Globally, nitrate contamination has been recognized as a critical pollutant of groundwater, leading to widespread environmental degradation and public health crises. Elevated nitrate levels contribute to phenomena such as harmful algal blooms and dissolved oxygen depletion in aquatic ecosystems, with far-reaching consequences for biodiversity and water quality (Ratchawang and Chotpantarat, 2019; Ghiberto et al., 2009). Furthermore, nitrate poses significant health risks, including methemoglobinemia (blue-baby syndrome) and potential carcinogenic effects from the formation of N-nitroso compounds (USEPA, 1985; Sadeq et al., 2008). Despite extensive research on nitrate pollution, the nexus between high nitrogen fertilizer application in sugarcane-dominated systems and its specific impact on groundwater quality in regions like Samastipur remains poorly understood. Existing studies have predominantly focused on general nitrate behaviour in the environment, its sources, and associated health impacts (Spalding and Exner, 1993; Singh and Craswell, 2021). However, there is a critical knowledge gap in understanding how the unique cropping system of sugarcane in the Indo-Gangetic Plains exacerbates nitrate contamination. The soil's properties, agricultural practices, and climatic conditions of this region require specific investigation to identify effective mitigation strategies. While some studies have assessed nitrate's impact on sugarcane quality and leaching dynamics (Muchow et al., 1996; Stewart et al., 2006, De *et al*., 2008), comprehensive research addressing both environmental and health impacts within this cropping system is limited. This study aims to bridge this knowledge gap by providing a detailed review of nitrate contamination under sugarcane-based cropping systems in the Indo-Gangetic Plains. It critically analyzes the pathways of nitrate pollution, including leaching processes, and its multifaceted impacts on groundwater quality, sugarcane productivity, and public health (Kumar and Singh., 2022). By synthesizing existing literature, the study identifies sustainable agricultural practices and policy recommendations to mitigate nitrate contamination in similar agrarian landscapes. This research intends to serve as a valuable resource for policymakers, researchers, and stakeholders working to address the growing issue of nitrate pollution in agriculture-dominated regions.

GENERAL CHEMISTRY OF NITRATE

Nitrate is a nitrogen oxyanion formed by removal of a proton from nitric acid with the formula of NO_3^- and molecular weight of 62.0049. One basal nitrogen atom is surrounded by three oxygen atoms in a triangular planar arrangement and thus forms one nitrate molecule. The nitrate ion [which carries a formal charge of (-1)] can be represented as a "hybrid" of the following three resonance structures:

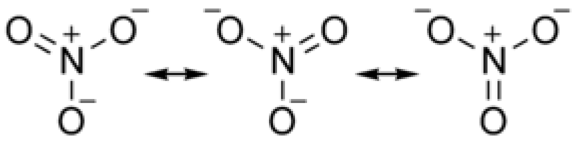

Figure 1.: Resonance structures of nitrate ion

Nitrate ion is the conjugate base of nitric acid. When a cation attached to the oxygen atom of the nitrate ion then nitrate salt is formed. In room temperature almost all inorganic nitrates are soluble in water. Nitrate is a common component of fertilizers and explosives. As nitrates are highly soluble and biodegradable, they are mainly used as fertilizers in agriculture. Ammonium, potassium, sodium and calcium are the main nitrate salts.

NITRATES IN ENVIRONMENT

Nitrate in atmosphere

Nitrogen, comprising N_2, N_2O, NO, NO_2, and NH_3, is the predominant constituent in the earth's atmosphere and soil air. Reacting with rainwater, these gases form ammonium and nitrate ions, integrating into soil or entering aquifer systems. Nitrate sources include lighting, photochemical oxidation, chemical oxidation of ammonia, microbiological synthesis of nitrous oxides, and fossil fuel combustion (Gaillard, 1995). Denitrification, facilitated by nitrate-reducing bacteria, converts atmospheric nitrate back into elemental nitrogen, predominantly occurring in soil (Berner and Berner, 1987). While the nitrogen cycle naturally produces nitrate, anthropogenic contributions, such as septic tanks, nitrogen-rich fertilizers, and agricultural practices, significantly elevate groundwater nitrate levels (Kumar *et al*., 2024a), often surpassing EPA safety limits. Excessive nitrate concentrations pose health risks, including methemoglobinemia, especially in rural wells. To address these issues, prevention measures, such as reducing reliance on nitrogen-rich fertilizers, are crucial, and essential for application of Biological source of nitrogen in different crop like sugarcane (Kumar et al., 2024b), Pea (Kumar et al.,2015) etc to fulfil the nitrogen requirement.

Nitrate in surface and ground water

Thind and Kansal, (2002) studied the variation of nitrate content of ground water at Punjab Agricultural University, Ludhiana. In March 2000, the NO_3^- -N level of deep irrigation tube wells ranged from 1.3 to 10.6 ppm. Shallow irrigation tube wells and hand pumps were found to have NO_3^- -N contents that ranged from 0.4 to 10.8 ppm and 0.6 to 27.7 ppm, respectively. While 18% of shallow irrigation tube wells had NO_3^- -N levels greater than 10 ppm, 55% of them did not. The samples that were taken from dairy, poultry and fodder farms and growing regions had the greatest nitrate concentrations due to the use of a lot of farm yard manure and other organic wastes. One sample from the dairy farm region has 10.6 ppm of NO_3^- -N, which is more than the required limit of 10 ppm for food safety. The farm labour uses every hand pump, including those with toxic nitrate concentrations, for drinking, which is extremely concerning and requires quick care. Adekunle et al. (2007) investigated rural groundwater quality in southwest Nigeria, revealing instances of NO_3^-N levels exceeding 10 ppm. During the dry season, a significant coefficient between nitrate and turbidity was noted at the dumpsite. Nitrate concentrations in the wet season surpassed those in the dry season. Kumar et al. (2024b) reported that the ground and surface water from 12 villages was collected and various water quality parameters were analysed. The nitrate in ground water varied (1.87- 6.19 mg/l) and surface water (1.87 – 3.84 mg/l) being maximum concentration of nitrate in Madhepura district of Bihar. Kumar *et al*. (2023) proposed that soil properties regulate spatial and temporal NO_3^--N patterns in shallow groundwater, with losses occurring due to asynchronous supply and uptake. Globally, agriculture is a major nitrate source in water bodies, driven by nitrogenous fertilizers.

Reddy *et al.* (2009) conducted an experiment and found that excess (> 45 ppm) NO_3^- -N content in groundwater in Andhra Pradesh, India, caused 65% of the total samples to be unsuitable for drinking purpose in the pre monsoon season and 45% in the post monsoon season. The granitic terrain and canal command areas had the highest nitrate content during the post-monsoon season among all seasons and surroundings. In both hydrological setups, nitrate concentration was shown to decrease with depth throughout both the pre- and post-monsoon seasons. The main contributors of nitrate in shallow and moderately deep aquifers were intensive agricultural practices and improper organic waste and sewage disposal (Kumar *et al.*, 2023b). In a study on nitrate contamination of groundwater in sugarcane field in Thailand, Ratchawang and Chotpantarat (2019) determined that the concentration of NO_3^- in the area ranged from 2.39 to 68.19 ppm, with an average concentration of 30.49 ppm and a mean concentration of 35.59 ppm. Additionally, they discovered that one of the groundwater samples surpassed the WHO safety guideline for NO_3^- (50 ppm) and that two of the samples had NO_3^- concentrations that were higher than the Thailand norm (45 ppm). The population in the area, particularly new-borns, is most susceptible to the health dangers posed by nitrate while drinking and utilising well water. In Ludhiana district the current fertilizer use is 345 kg N ha^{-1}. Monitoring of NO_3^- -N in shallow well waters of Ludhiana district from 1975 to 1988 revealed that mean NO_3^- -N concentration increased from 0.42 to 2.29 ppm. This increasing trend was found to be directly related to increase in fertilizer nitrogen use from 56 to 188 kg ha^{-1} y^{-1} (Singh *et al*., 1991). Kumar *et al.* (2010 a) reported that the concentration of NO_3^- in the ground water samples of cultivated areas of Varanasi ranged between 1.95 to 58.52 ppm with a mean value 27.23 ppm.

Their concentration in most of the samples falls within maximum permissible limit, which seems not to pose any serious risk for the population of Varanasi. Kumar *et al.* (2010 b) also detected that the nitrate concentration in the ground water samples of cultivated areas of Mirzapur district ranged between 3.78 to 107.33 ppm with a mean value 31.22 ppm.

Their concentration in most of the samples were within highest permissible limit. The effectiveness of the shallow and deep aquifers for drinking, household, agricultural, and other ecological uses was also examined. In the central-west of Bangladesh, Majumder *et al.* (2008) looked into the spatial distribution of nitrate (NO_3^-). Less than 0.10 to 40.78 ppm and less than 0.10 to 75.12 ppm of nitrate were found in the deep and shallow groundwater, respectively. Nitrate levels in major river water varied from 0.98 to 2.32 ppm, with an average of 1.8 ppm. In a drinking groundwater system of an intensively farmed district in India, Kundu and Mandal (2009) investigated the mechanistic pathways of nitrate enrichment and forecasted the enrichment using modelling. They noted that the post-monsoon season's nitrate concentration (0.87 ppm) was higher than the pre-monsoon season's nitrate content (0.58 ppm). They also demonstrated that when the depth of the studied aquifers increased and N-fertilization reduced, the concentration of nitrate decreased. The variability of its enrichment was increased by soil characteristics including bulk density (r=-0.72), hydraulic conductivity (r=-0.56), clay (r=-0.29), organic carbon (r=-0.72), NO_3^--N (r=-0.82), and potentially plant-available soil nitrogen (r=-0.82).

In Varanasi, greater amounts of nitrate and other pollutants have been recorded by various workers. Singh *et al.* (2013) analysed this information and discovered that nitrate concentrations ranged from 66 to 199 ppm. The dropping water table, increased hardness, and presence of even dangerous trace elements are all deteriorating the quality of the ground water. In a highly polluted agricultural area in Japan, Nakagawa *et al.* (2021) evaluated the spatiotemporal variation of nitrate concentrations in soil and groundwater and found that the mean concentration of nitrate was 14.2 ppm, above the requirements for Japanese drinking water (10 ppm). In samples taken from the soil near the LWDS, nitrate concentrations were relatively high. The link between the nitrate concentrations in soil and groundwater was complex but significant. It has been demonstrated that both soil and groundwater contain nitrates that are transferred downstream from source sites. In order to identify reasonable agri-environmental indicators that support the design, implementation, and surveillance of governmental policies, Wick *et al.* (2012) identified key predictors of groundwater nitrate contamination. They discovered a positive correlation between groundwater nitrate content and the proportion of farmland in a particular area. Environmental elements like temperature and precipitation are also significant co-factors. Lower nitrate pollution of groundwater is a result of higher average temperatures, presumably as a result of higher evapotranspiration (Kumar *et al*., 2018). Nitrate concentration in groundwater is further decreased by higher average precipitation dilution of nitrates in the soil. The gross nitrogen balance is a statistically significant predictor of nitrate contamination, according to regression analysis. Spalding and Exner (1993) reviewed occurrence of nitrate in groundwater by summarizing more than 200000 NO_3^- -N data point. Availability of sources and local environmental conditions are major factor of nitrate contamination in ground water. Regions where most of the soils are under well drainage conditions, dominated by irrigated cropland mostly exceed the safe limit of 10 ppm of NO_3^- -N. Uptake by vegetation, hot, humid and carbon enriched environment are reasons behind the remediation of nitrate in shallow aquifers. Extensive tile drainage also reduce the chances of groundwater pollution by nitrate. The factors affecting the distribution pattern of NO_3^- in ground water are very complex and poorly understood.

Shomar *et al.* (2008) studied nitrate contamination in the ground water and it was reported after 7 years of monitoring that nitrate was one of the major ground water pollutants. 90% of the wells had NO_3^- values that were several times greater than the WHO guideline of 50 ppm. They also came to the conclusion that sludge, synthetic fertilisers with an NH_4^+ and animal manure were possible sources of nitrate. In Gaza, the average levels of nitrogen (N) in the soil, manure, and sludge were 2.9 %, 1 %, and 0.08 %, respectively. The aquifer beneath the Gaza Strip is not experiencing any appreciable bacterial denitrification. Manure was the main source of nitrate while synthetic fertilizers reported to supply a small quantity. Sadeq *et al.* (2008) conducted an experiment to study nitrate in potable water and occurrence of blue baby syndrome among infants and children aged 1-7 years and it was the first-time study about methemoglobinemia in Morocco. In the exposed area, 78 wells had nitrate concentrations that ranged from 15.39 to 246.90 ppm as NO_3^-. 64.2 % of participants drank nitrate-contaminated well water, and 69.2 % of the examined wells had nitrate concentrations higher than 50 ppm. Children in the study had a methemoglobinemia prevalence of 36.2 % in the exposed area and 27.4 % in the non-exposed area. Children in the study who drank water with a nitrate concentration of 450 ppm had greater methemoglobinemia than those who drank municipal water or well water with a nitrate concentration of more than 50 ppm. While the mean methaemoglobin (MetHb) level in the exposed area rose with age, it was largely steady in the unexposed area for the first six years of life. Mean MetHb reached an unhealthy level when the nitrate in the water was between 50 and 90 ppm as NO_3- and was acceptable when it was below 50 ppm as NO_3^-. This final level was statistically comparable to the mean MetHb with nitrate levels more than 90 ppm as NO_3^- (up to 246.9 ppm as NO_3^-). The prevalence of methemoglobinemia and gender did not correlate (Kumari *et al*., 2021). In a portion of the Damodar Valley in eastern India, Batabyal (2018) evaluated the Hydrogeochemistry and water quality of the groundwater and found that, for the majority of the locations, the NO_3^- level was below the detection limit (0.4 ppm). During the pre- and post-monsoon seasons, the NO_3^- concentration at the remaining sites can reach up to 38 and 32.7 ppm, respectively. Wongsanit *et al.* (2015) studied nitrate contamination in groundwater and its effect on human health. The study results indicate that groundwater contaminated by nitrate fertilizer application. Although the results of this study suggested that the majority of the population in the Photharam district was not at risk, there may be a health risk associated with exposure to nitrate in groundwater. In order to prevent the negative impact on human health, it is advised that nitrogen management methods be put into place and groundwater nitrate be monitored. In their 2014 study of the natural and anthropogenic variables impacting groundwater quality, Devic *et al.* discovered that 35% of the wells were contaminated with NO_3^-. This is a worrying outcome, because these are the main things harming Serbia's groundwater's quality. In India's north-western alluvial aquifer system, Lapworth *et al.* (2017) evaluated the quality of the ground water and came to the conclusion that there was evidence of NO_3^- breakthrough from the shallow groundwater to deep. They also came to the conclusion that if the current increases in pumping from the deep aquifers continue, this problem might get worse in the future. The vulnerability of deep drinking water sources to pesticide and other anthropogenic contaminants is also affected by this to investigate the nitrate poisoning of several rural parts of Rajasthan's groundwater In the Indian district of Sri Ganganagar, Suthar *et al.* (2009) collected a total of 64 groundwater samples from 21 distinct villages and sub-villages. Nitrate sulphate and a few other characteristics were examined in those samples. They discovered that the NO_3^- content in groundwater ranged from 7.10 to 82.0 ppm for various samples. However, the average NO_3- for all samples was 60.6 ± 33.6 (SD) ppm, which is too high to drink. The Ljubljansko polje aquifer in Slovenia, which provides the majority of the city's residents with drinking water, was evaluated by Ogrinc *et al.* (2019). This aquifer is extremely susceptible to anthropogenic pollution. In this work, the spatial distribution of processes and nitrate sources in the groundwater from seven wells at three separate water supplies was determined using the geochemistry of main constituents such nitrate pollution. Groundwater nitrate levels ranged from 5.32 to 50.1 ppm, which is significantly higher than the 3-ppm limit allowed for anthropogenic activity. Three sources of nitrate were found using the isotope mixing model: air deposition, fertilisers, and soil nitrogen. Additionally, they stated that sewage-manure and fertilisers (which together account for up to 64 %) are the main causes of the excessive nitrate concentrations in groundwater. Approximately 10 % of the total nitrate in groundwater came from air deposition. The takeaway from this study is that managing sources from urban and agricultural inputs like sewage-manure and fertilisers carefully can help lower the nitrogen load and enhance water quality.

Anornu *et al.* (2017) tracked nitrate source in drinking water and investigated possibly related health risk for rural peoples in the basin of the White Volta River using isotopic approach. In this study, they used hydro-chemical and isotopic technique in an integrated way to detect the sources of drinking water contamination with nitrate in Ghana. The results showed that, nitrate concentrations varied from 0.03 to 28.94, 0.83 to 143.94 and 0.42 to 431.17 ppm with mean values of 5.01, 21.54 and 36.09 ppm for the surface water, boreholes and hand dug wells and respectively. According to these results, 95% of the area's boreholes, hand-dug wells, and 45% of its surface water contain nitrate concentrations that are higher than the reference threshold. The findings indicated that human-caused activities account for 98.4%, 95%, and 64% of the NO_3- in surface water, hand-dug wells, and boreholes respectively. They also confirmed that the majority of the NO_3^- in the samples came from manure (animal and human waste), with some places also experiencing denitrification. The isotopic results also demonstrated that younger waters have higher NO_3^- levels. Oral consumption of the NO_3^-contaminated water demonstrated some level of non-carcinogenic health risk for adults and children, notably for youngsters whose risk is about 72% greater. Rezaei *et al.* (2017) reported nitrate level very between 1.47 and 70.66 ppm in Lar area of south Iran. Distribution of agricultural areas and vertical variation of nitrate concentration have indicated that inorganic fertilizers used during irrigation periods are main source of nitrate in aquifer. The findings also show that denitrification occurs in the aquifer and that nitrate drop is a result of both denitrification and dilution. Buvaneshwari (2017) studied vulnerability of ground water resource and spatial variability of nitrate contamination. Severe nitrate contamination and/or groundwater depletion is associated with groundwater irrigation. They observed nitrate values between 1 and 360 ppm in more than 200 tube wells. Groundwater level and gradient of elevation were found to be in three different arrangements:

1) NO_3^- hot spots linked to very deep aquifer levels and low aquifer elevation gradient suggest a small groundwater reserve with no horizontal flow, followed by degradation of quality of ground water from recycling through pumping and return flow;
2) High aquifer elevation gradient, moderate NO_3^- concentrations suggest that significant horizontal flow prevented NO_3^-enrichment; and
3) Low NO_3—N content, low groundwater elevation gradient, and shallow groundwater levels suggest a great reserve.

From the result they also concluded that irrigating the soil with NO_3^- containing ground water indicates a “hidden” supply of nitrogen to the crop field which can reach 200 kg N ha^{-1} yr^{-1} in hotspot areas, which also enhance ground water contamination. Such hidden sources, if considered into account in fertilizer management, the fertilizer application rate would be optimized.

LEACHING OF NITRATE IN SOIL

One of the major reasons behind elevated level of nitrate-N in water bodies is intensive nitrogenous fertilizer application (Kumar and Jha, 2021; Chattopadhyay *et al*., 2021). When nitrogenous fertilizers, may be urea or ammonium applied in soil, converted biochemically to nitrate. This nitrate is liable to leach beyond the root zone to reach the aquifer. Using an existing model and GIS, Vinod *et al.* (2015) calculated nitrate leaching in groundwater in an agricultural area of Karnataka. It was discovered that agricultural sources had substantially higher levels of nitrate leaching than cesspools did. From cesspools in the research area, it was calculated that 87.81 to 381.96 kg yr^{-1} could leak to groundwater. Nitrate leaching from agricultural sources is predicted to be between 7547.63 and 52857.72 kg yr^{-1}. The comparison investigation reveals that, with the exception of Belagola village, the nitrate concentrations in groundwater in irrigation fields are within the allowable limit, hence water in other villages can be utilised for both drinking and irrigation. In two field studies, Portocarrero and Acreche (2014) investigated downward loss of nitrate in an argiudoll planted with sugarcane. In an argidoll with frequent nitrogen fertilization doses used in the production systems in Tucuma'n, they reported low nitrate leaching from sugarcane cultivation. Nitrate leaching was also noted at the start of the rainy season, when both deep drainage of water and available nitrates are present at the same time. Ghiberto *et al.* 2009, looked into the loss of nutrients from a sugarcane growing region in Brazil. They arrived to the conclusion that under the experimental conditions, 15% of the applied N was leached (dosage of N-fertilizer of 120 kg ha^{-1}, crop plant agricultural cycle, high nutrient demand, high assimilation of vegetal residue by the crop, and occurrence of atypical rainfalls). The results also demonstrate that the majority of the leached nitrogen was made up of natural nitrogen, with only a minor portion coming from N fertiliser. Stewart *et al.* (2006) conducted an experiment to estimate nitrate leaching in sugarcane field using APSIM-SWIM in Australia and reported a flux of 31.9 kg ha^{-1}. The sensitivity analysis's findings suggest that split fertiliser application will probably have little effect on the amount of nitrate lost to ground water. The findings also imply that a sugar cane crop might be grown for at least one season without the addition of fertiliser. Given that 2.4 kg ha^{-1} more NO_3^- -N was retrieved from below 1.5 m depth than was introduced via drainage, this approach may have a restorative impact on ground water nitrate concentrations. Ju and Zhang (2017) recently reviewed the nitrogen cycling and environmental effects in upland agricultural soils in North China and reported that due to excessive nitrogen fertilisation over the previous three decades, a significant amount of NO_3^- has accumulated in the vadose-zone under agricultural soils. Singh and Craswell (2021) reviewed the nitrate poisoning of surface and ground water system and concluded that more than 50% of applied N cannot be used by the field crop, but based on the soil, climate and management practices a fraction of the applied N is lost through different processes including leaching as nitrate. Not only the applied nitrogen fertilizer is the source of nitrate-N in water bodies but also organic matter and manures, city sewage, animal excreta are important source. The best fertiliser management strategy for preventing nitrate-N leaching from the soil-plant system is application of the recommended fertiliser N rates. By altering the time of fertiliser N application to correspond with the N uptake pattern of crops, the amount of nitrate leaching can also be decreased.

In a watershed in Brazil, Dynia (2000) evaluated nitrate retention and leaching in soils with varied electrical charges. All of the soils tested had positive electrical charges and, as a result, had the ability to adsorb nitrate. The findings showed that the subsoils had a greater capacity to retain nitrate than the top layers. Nitrate leaching in soil columns was slowed down in comparison to that of solutions with comparable ionic strengths because of the soils' ability to retain nitrate. The goal of the study of Gheysari *et al.* (2009) was to evaluate the effect of different nitrogen fertilizer levels and irrigation on nitrate-nitrogen leaching in a maize field. To fulfil their goal, they included three N fertilization levels and four irrigation levels, with three replications. To collect soil solution extract ceramic suction cups were placed at 30 and 60 cm soil depths. For the 142 kg N ha^{-1} and over watering (1.13 SMD) treatment, the maximum NO_3^- -N leaching out of the 60 cm soil layer was 8.43 kg N ha^{-1}. At a depth of 60 cm, the seasonal minimum and maximum NO_3^- concentrations were 46 and 138 ppm, respectively. They came to the conclusion that, with the right mix of irrigation and fertiliser management, it is possible to regulate NO_3^- leaching out of the root zone during the growth season. It is a prevalent misconception that organic farming significantly reduces environmental contamination. Dahan *et al.* (2014) conducted research on nitrate leaching from intensive organic farms to aquifer to support this assertion. Surprisingly, nitrate significantly leached downward through the vadose zone to the groundwater in intensive organic agriculture that relied solely on solid organic matter, including composted manure put to the soil before planting. According to their findings, nitrate concentrations under the organic greenhouse's root zone (deeper than 1 m) averaged 357 ppm, with a maximum average concentration of 724 ppm at a depth of 2.5 m. The average value of the nitrate levels below the root zone of the conventional greenhouse was only 37.5 ppm. Contrarily, conventional agriculture, which uses similar intensive techniques and drip irrigation to provide liquid fertiliser, produced substantially lower rates of NO_3^- moving downward via the vadose zone. The takeaway from this study is to utilise precise fertilisation techniques that apply fertilisers through the irrigation system in accordance with crop need during the growing season in order to significantly lower the risk of groundwater contamination from both conventional and organic greenhouses.

HEALTH EFFECTS OF HIGH NITRATE LEVELS IN GROUND WATER

Organisms which intake groundwater contaminated with nitrate nitrogen show harmful biological consequences. Naturally, the first consideration when establishing standards for acceptable limits of nitrate and good agricultural practises is human interest. The permitted limit of nitrate in drinking water, according to the United States Environmental Protection Agency, is 10 ppm (equal to 10 ppm nitrate nitrogen or 45 ppm nitrate), based on the risk to human health from nitrate consumption.

Effects on human health

The toxicity of nitrates is due to conversion of nitrate to nitrite by reduction. This nitrite reacts with haemoglobin of human blood and form methaemoglobin which can’t transport oxygen to tissue and thus lead to possible asphyxia (USEPA, 1985). According to Shuvel and Gruener (1977) Normal methaemoglobin levels in humans range from 1 to 2%. A level greater than 3% is defined as methemoglobinemia. Blue-baby syndrome cases typically arise in rural settings where wells serve as the main source of drinking water. Johnson et al. (1987) claimed that the majority of wells that are bored or excavated close to feedlots, manure lagoons, or other farmed areas become nitrate-contaminated. Wells with inadequate or damaged casings and those that were dug rather than drilled are typically the most affected. Wells with dangerously high nitrate concentrations were typically overlooked until health issues were brought to light until increasing knowledge of the dangers of nitrate-contaminated groundwater encouraged testing for nitrate concentrations along with other contaminants (Kumar *et al.,* 2024c).

Blue baby syndrome

Methemoglobinemia is the condition in the blood which causes infant cyanosis, or blue-baby syndrome. When bacteria convert the nitrate to nitrite in the intestinal tract of a baby then methaemoglobin is formed. Methaemoglobin is formed when one nitrite molecule reacts with two molecules of haemoglobin. The process happens fairly quickly in acidic environments, like the gut. This changed blood protein stops the blood cells from absorbing oxygen, which causes the new-born to slowly suffocate and perhaps die (Gustafson, 1993). The infant will frequently develop a blue or purple tinge in the lips and extremities due to the lack of oxygen, giving the condition the term "blue baby syndrome". Infant methemoglobinemia can also be identified by gastrointestinal issues such vomiting and diarrhoea, a relative lack of discomfort when severely cyanotic but irritability when minimally cyanotic, and blood that is a dark brown colour (Johnson et al., 1987).

Carcinogenicity

It has been demonstrated that nitrite and nitrosatable substances in the human stomach can combine to generate N-nitroso compounds. Although some of the most easily produced N-nitroso compounds, like N-nitrosoproline, are not carcinogenic in humans, several of these N-nitroso compounds have been proven to be carcinogenic in all the animal species studied. The N-nitroso compounds are cancer-causing in animal species and almost certainly also in people. The information from several epidemiological research is, however, only suggestive at best. If relatively high doses of both nitrite and nitrosatable chemicals are given to several animal species at the same time, the endogenous production of N-nitroso compounds is also seen in those animals. As a result, it is conceivable to link the risk of developing cancer to endogenous nitrosation brought on by a high intake of nitrate, nitrite, and nitrosatable substances (WHO, 1996). The endogenous production of N-nitroso compounds may contribute to the known elevated risk of gastric cancer under conditions of low stomach acidity. Patients with achlorhydria were shown to have high mean levels of N-nitroso compounds and high levels of nitrate in their gastric juice, making them a unique risk group for gastric cancer when it comes to nitrate and nitrite levels (WHO, 1996). Nitrate in Public Water Supplies and the Risk of Colon and Rectum Cancers was examined by Roos *et al.* in 2003. According to their findings, there were hardly any correlations between nitrate concentration in public water supplies, including average nitrate and the number of years with elevated average nitrate levels, and colon or rectum malignancies. The odds ratio (OR) for colon cancer was 1.2 [95% confidence interval (CI) = 0.9-1.6] and for rectum cancer was 1.1 (CI = 0.7-1.5) for more than 10 years with average nitrate greater than 5 ppm. However, nitrate exposure (> 10 years with average nitrate > 5 ppm) was linked to a higher risk of colon cancer among those who consumed less vitamin C and more meat (OR = 2.0; CI = 1.2-3.3; 2.2; 1.4-3.6).

Other effects

High nitrate levels in drinking water have been linked to congenital abnormalities. (ECETOC, 1988). Studies linking the impact of nitrate levels in drinking water on cardiovascular health produced mixed results (WHO, 1985). Since nitrate competitively limits iodine uptake, it has been investigated whether there are any links between nitrate intake and effects on the thyroid. Epidemiological research found evidence of a nitrate anti-thyroid effect in humans, in addition to effects on the thyroid seen in animal studies and in livestock. The effect of nitrate is mild, with a tendency to zero, if dietary iodine is present in an appropriate range (equivalent to a daily iodine excretion of 150–300 g/day). If there is also a concurrent nutritional iodine shortage, the nitrate effect on thyroid function is significant (Horing, 1992). According to Van Maanen *et al.* (1994), endemic goitre is mostly caused by inorganic nitrate in drinking water. Both experimental and epidemiological investigations have suggested that "nitrate in drinking-water has a bigger influence on thyroid function than nitrate in diet" which has been confirmed. The different thyroid effects may be due to the different nitrate kinetics after consumption of drinking water versus food. However, there are currently no sufficient research available that address this issue. A few of the aforementioned research also show that dietary iodine shortage is a significantly more potent goitre-causing factor than nitrate exposure. A study in humans revealed that sodium nitrite (0.5 mg of sodium nitrite per kg of body weight per day, for 9 days) caused a decrease in adrenal steroid production, as evidenced by the decrease in 17-hydroxysteroid and 17-ketosteroid concentration in urine, in addition to the effect of nitrite on the adrenal zona glomerulosa in rats (Kuper and Till, 1995; Singh *et al*., 2022).

Effects on animals

The acute oral LD_{50} for sodium nitrate in rats has been observed to range from 46 to 120 mg/kg. The initial lethal impact in some species, such as horses, is caused by nitrite-induced vasodilatation, which causes cardiovascular collapse and shock. This is in contrast to the effect in humans, in which nitrate is thought to be responsible for the synthesis of methaemoglobin (USEPA,1985). In a three-week investigation on mice drinking water, higher methaemoglobin levels were seen in 50-day-old mice given nitrate ion levels of 133 and 178 mg/kg/day, but not at 88 mg/kg/day.

EFFECTS OF NITRATE ON QUALITY OF SUGARCANE

N can be used to change the growth-related time course of sucrose concentration in fresh millable stalks or commercial cane sugar, according to study by Muchow *et al.* from 1996. Low nitrogen supplies can be especially important when early harvest is being considered since they enhance CCS. There is definitely a trade-off when determining stalk sucrose yield because inadequate N supply also lowers fresh millable stalk or cane yield. This study also showed how adding a little bit of N might increase early harvest CCS and cane production. Even though the larger nitrogen treatment in this trial resulted in a lower CCS, the later harvest significantly increased stalk sucrose production. Effects of irrigation and N fertiliser treatment on sugarcane production and quality were explored by Wiedenfeld (1995). With each succeeding harvest, the effects of nitrogen application on production and quality grew and were non-existent in the cane crop. This is also in line with earlier findings (Thomas et al., 1985). This initial absence of a nitrogen reaction suggests that the soil already had enough N to suit the needs of the plant cane crop and that N application was only necessary in the first and second ratoon crops. The goal of study of Hemalatha (2015) was to assess the Impact of Nitrogen Fertilization on Quality of Sugarcane under Fertigation. Five different doses of nitrogen fertilizer starting from 161 kg N ha^{-1} to 299 kg N ha^{-1} were applied. Even though the treatment that received nitrogen at 299 kg ha^{-1} had a greater nutrient content and uptake overall, the parameters for yield and quality are lower at this level and higher in the treatment that received N at 195.5 kg ha^{-1}. Up to 195.5 kg ha^{-1}, the sugarcane production rose steadily with higher nitrogen treatments before beginning to decline. Beyond the amount of 195.5 kg of nitrogen, a negative impact on the sugarcane juice's quality was also noted. The results of field experiment conducted indicate that nitrogen has a negative impact on the qualities of juice. With a higher dose of 180 kg ha^{-1}, the cane sugar output decreased by 8.2% from its peak level of 120 kg N ha^{-1}. Zeng *et al.* (2020) examined the agronomic, yield, and quality parameters of three sugarcane cultivars under various nitrogen levels (0, 150, and

300 kg ha^{-1} urea). The outcomes demonstrated that applying nitrogen fertiliser increased tillering rate, stalk diameter, plant height, stalk weight, millable stalks per hectare, cane yield, sugar yield, and cane juice rate, and that there was a significant difference between N application and non-N application. With an increase in nitrogen application, the cane yield, millable stalks per ha, juice rate, and juice purity all improved, but the milled juice brix and cane sucrose content fell. When 150 kg ha^{-1} of urea was used, the sugar output was highest; when 300 kg ha^{-1} of urea was applied, the cane yield was highest. Rhein *et al.* (2016) investigated the technological quality and yield of sugarcane grown with subsurface drip fertigation and nitrogen dosages. Urea was used in five different treatments (0, 50, 100, 150 and 200 kg N ha^{-1}). 381 days after the third harvest, the technological quality (fiber % cane, Brix% juice, pol% juice, pol% cane, juice purity, and total recoverable sugar) as well as the yield of stalks and sugar were assessed. Nitrogen doses were applied to sugarcane, changing the technological variables brix%, pol% juice, purity%, and total recoverable sugar, with considerable reductions at the dose of 200 kg N ha^{-1}.

Conclusion:

The intensive use of nitrogenous fertilizers in sugarcane-based cropping systems, particularly in regions like the Indo-Gangetic plains, has led to significant nitrate contamination in groundwater. This contamination poses severe environmental and public health risks, including methemoglobinemia (blue-baby syndrome) and potential carcinogenic effects. The reviewed literature highlights the pervasive nature of nitrate pollution, not only affecting human health but also degrading soil and water quality, and impacting agricultural productivity, especially in sugarcane cultivation. The research underscores the need for sustainable agricultural practices that balance the nutrient demands of crops with environmental preservation. Strategies such as optimizing fertilizer application rates, employing biological nitrogen sources, and improving irrigation management can mitigate nitrate leaching and contamination. It is imperative for policymakers and stakeholders to implement these practices to safeguard both public health and environmental quality.

Recommendation:

Several key recommendations can be made to address the significant issue of nitrate contamination in groundwater:

1. **Adoption of Sustainable Agricultural Practices** like ***Precision Farming*****:** Implementing precision farming techniques to optimize the application of nitrogenous fertilizers can significantly reduce nitrate leaching into groundwater. This involves matching the timing and quantity of fertilizer application with crop needs. ***Use of Biological Nitrogen Sources*****:** Encouraging the use of bio-fertilizers and nitrogen-fixing plants (e.g., Rhizobium inoculated peas) as alternative sources of nitrogen can help reduce dependence on chemical fertilizers, thereby minimizing nitrate contamination. ***Split Application of Fertilizers*****:** Fertilizers should be applied in split doses rather than in a single application to reduce the risk of nitrate leaching, particularly during the rainy season when runoff and deep drainage are more likely.
2. **Groundwater Monitoring and Management** includes ***Regular Monitoring*****:** Continuous monitoring of nitrate levels in groundwater, particularly in sugarcane-dominated regions, should be mandated. This can be supported by establishing a network of observation wells. ***Groundwater Protection Zones*****:** Establishing protection zones around critical groundwater resources, where the use of nitrogenous fertilizers is restricted, can help safeguard water quality. ***Water Quality Management*****:** Implementing water quality management

strategies that address both point-source and diffuse pollution from agricultural activities is crucial. These strategies should be integrated into broader watershed management plans.

3. **Public Health Interventions like *Health Risk Assessment*:** Conduct regular health risk assessments in regions with known nitrate contamination, particularly focusing on vulnerable populations such as infants and pregnant women. Public awareness campaigns on the risks associated with high nitrate levels in drinking water should be a priority. ***Alternative Drinking Water Sources*:** In areas where groundwater nitrate levels exceed safe limits, alternative drinking water sources should be provided, such as treated surface water or bottled water.
4. **Policy and Regulatory Recommendations** such as ***Revision of Fertilizer Regulations*:** Revising existing regulations regarding the application of nitrogenous fertilizers, including stricter controls and enforcement of usage limits, especially in vulnerable regions. ***Incentives for Sustainable Practices*:** Providing financial incentives and subsidies for farmers who adopt sustainable and environmentally friendly farming practices, such as organic farming or the use of slow-release fertilizers.
5. **Research and Development** is required for ***Innovative Fertilizer Solutions*:** Investment in research and development of new types of fertilizers that have lower environmental impacts, such as controlled-release fertilizers or nitrification inhibitors. ***Integrated Crop Management*:** Promoting research into integrated crop management systems that combine optimal fertilizer use with other agricultural practices to maintain crop yields while protecting groundwater quality.

Future scope of study:

- **Long-Term Impact Studies:** Conduct long-term studies to assess the effectiveness of the recommended practices in reducing nitrate levels in groundwater.
- **Climate Change Impact:** Investigate the potential impacts of climate change on nitrate leaching and groundwater contamination under different cropping systems.
- **Interdisciplinary Research:** Encourage interdisciplinary research that combines soil science, hydrology, public health, and agricultural economics to develop comprehensive strategies for managing nitrate contamination. These recommendations aim to foster sustainable agricultural practices while protecting groundwater resources and public health in regions where sugarcane cultivation is prevalent.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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