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Strategies for Mitigating Nitrate Leaching: A Comprehensive Methodological Examination for Agricultural Sustainability

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Abstract

Nitrogen (N) serves as a fundamental nutrient crucial for promoting plant growth. However, the mismanagement of nitrogen fertilization within agricultural contexts has led to significant instances of nitrate leaching, particularly pronounced within fruit production systems. Empirical research has underscored the danger of elevated nitrate levels in potable water, posing potential threats to human health. Furthermore, the widespread presence of nitrates in riverine ecosystems accelerates eutrophication, thereby imposing detrimental effects on aquatic ecologies. The present study provides a comprehensive examination of methodological strategies and techniques aimed at mitigating nitrate leaching within orchard environments. Various methodologies, including the establishment of grass cover, the deployment of controlled-release nitrogen fertilizers, and the use of nitrification inhibitors, underwent thorough evaluation. Notably, these methodologies demonstrate substantial potential in reducing nitrate leaching occurrences within orchard settings. However, a significant observation emerges: the pursuit of agricultural sustainability and environmental protection requires an integrative paradigm that orchestrates a convergence of multifaceted measures aimed at achieving overarching objectives. This paper discusses sound solutions to the important environmental issue of controlling nitrate leaking through agricultural practice modifications. The reasons of nitrate leaching from agricultural land are briefly discussed, and current techniques for reducing nitrate losses are defined, studied, and appraised. Nutrient leaching reduction does not depend on organic or conventional farming, but rather on the implementation and application of effective remedies. We offer the following guiding principles for reducing leaching from agricultural soils.

Keywords: Nitrogen Fixation, Nitrate Leaching, Fruit Production system, Eutrophication, Agricultural

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INTRODUCTION

The most crucial nutrient for the development of plants is nitrogen (N). However, poor management of nitrate fertilization in agriculture has resulted in significant nitrate leaching, which is particularly true in systems used for fruit production. According to studies, the human body can get harmed by drinking water with excessive nitrate concentrations. Eutrophication and harm to the aquatic ecosystem result from too much nitrate in rivers. This study examined strategies for decreasing nitrate leaching in orchards. Some methods for decreasing nitrate leaching in orchards, such as employing grass cover, providing controlled-release N fertilizer, adding nitrification inhibitors, etc., were assessed. Although these techniques have a significant impact on minimizing nitrate leaching in orchards, coordinated strategies are more crucial. According to reports, the usage of chemical N fertilizer in the 1960s in the United States and Europe led to nitrate poisoning of groundwater. The typical renewal period for groundwater is 1400 years, despite the fact that it has some ability for self-purification. As a result, it is very difficult to rely on the groundwater's natural cleansing and repair processes. Groundwater nitrate contamination must be stopped with efficient solutions. Standards for nitrate concentrations in groundwater have been developed by several nations and organizations across the globe.(1) For instance, the World Health Organization (WHO) mandates that the nitrate content in drinking water should not exceed 50 mg L1, which is equivalent to 11.3 mg L1 for NO 3 N; the European Union suggests that the highest nitrate concentration should not exceed 50 mg L1; the recommended allowable NO 3 N concentration is 5.6 mg L1; and the US EPA, Japanese, and Canadian environmental organizations mandate that the maximum limit of NO 3 N in gram. Although drinking water with high nitrate levels can present a number of survival issues, research over the past 30 years has demonstrated that bringing groundwater's nitrate levels down to safe levels for humans to drink will eventually result in by-products, which will result in higher processing costs. It is difficult to remove nitrate from drinking water, therefore prevention at the source is the best remedy. In this work, we examined the most pertinent policies and techniques for lowering nitrate leaching in orchards. First, we assessed the isotope tracer method's shortcomings in locating the source of groundwater nitrate contamination. The use of several numerical models was then assessed. We then summed up how managing water and fertilizer more effectively has helped to reduce nitrate leaching. Finally, we assessed how well alternative techniques, such as biochar and ground vegetation cover, reduced nitrate leaching in orchards. (2)

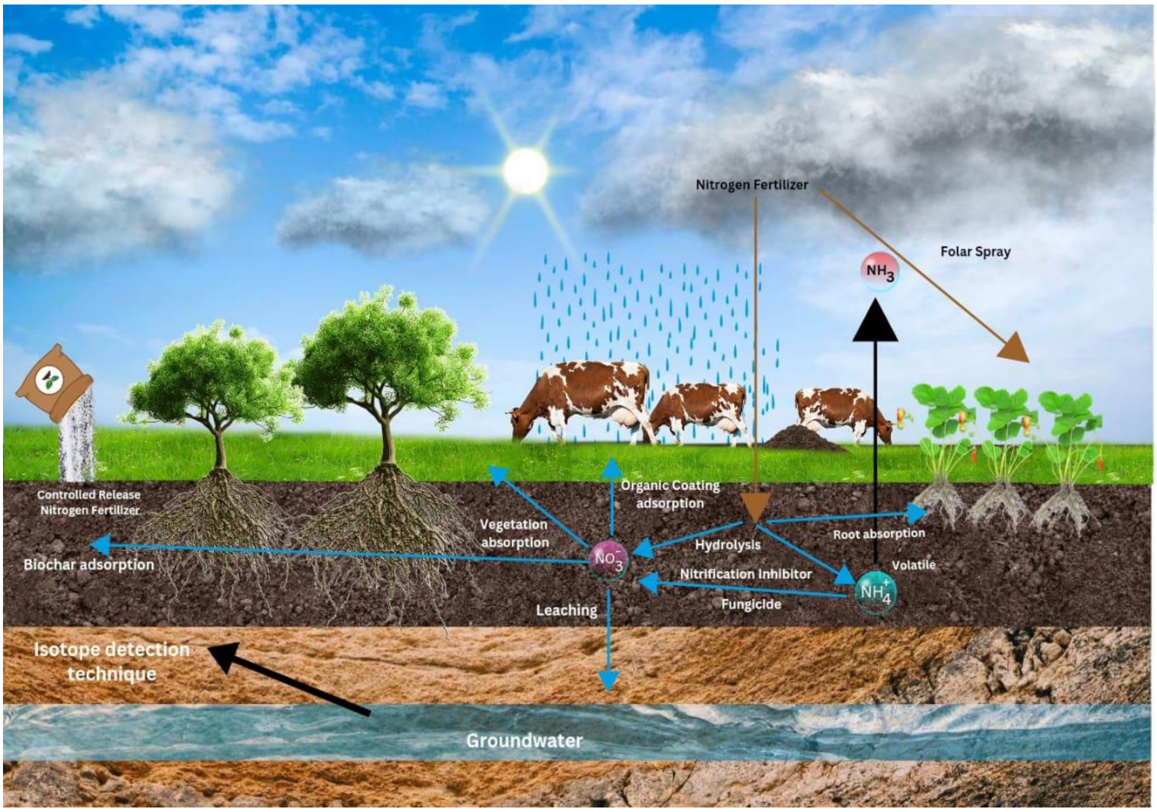

Figure 1: Graphical Abstract

Methodology

Avoid Excessive Water

Including stored soil water, rainfall, and irrigation water, a full-season fully irrigated corn crop consumes around 26" of water. Significant losses through soil evaporation and deep percolation may necessitate the use of more water. It is frequently impossible to avoid deep percolation in the spring before the crop uses a lot of water, especially for sandier soils in Nebraska. Such deep percolation not only transports NO3- to groundwater but also frequently contributes ultimately to aquifer recharge. In order to allow for the soil's ability to store precipitation, deep percolation can be minimized through carefully planned irrigation and soil water depletion as a crop matures. The procedures covered below can lower soil NO3- concentrations. (3)

Cropping System

In comparison to continuous corn, corn-soybean rotation has a higher rate of fertilizer-N recovery, which is measured as the increase in pounds of nitrogen taken up by the above-ground crop per pound of fertilizer-N applied. Aside from the fact that soybean, on average, receives 55-70% of its plant's N from biologically fixing atmospheric N and efficiently scavenges soil inorganic N to fill the remaining N need, the greater recovery with rotation is due to soybean's improved N recovery efficiency by using it as the previous crop rather than corn.

For continuous corn in Nebraska, the average quantity of nitrogen taken from the grain during harvest is around 0.7 lb/lb, but for corn-soybean rotation, it is closer to 1.0 lb/lb. When corn and soybeans are planted in rotation, around 40% less nitrogen is added than when corn is grown continuously. The vadose zone (the depth from the rooting zone to the top of the water saturation aquifer) is where NO3-1 is loaded and moved into groundwater. The increased recovery efficiency and the much lower fertilizer-N used are predicted to reduce this loading and movement. In a 20-year research in Nebraska, corn-soybean rotation reduced nitrate accumulation to a depth of 60 feet by 28% compared to continuous corn,(4) however this result was understated due to excessive soybean irrigation and excessive N administration to corn after soyabean.

Alfalfa in Rotation

Since many years ago, it has been understood how important alfalfa in rotation with annual crops is for decreasing NO3-leaching loss. The amount of fertilizer-N needed for such a rotation with alfalfa is roughly 45% less than that needed for the corn-soybean rotation, even with the use of NO3- applied in irrigation water and alfalfa uptake of inorganic N to about 10–12 foot deep. The profitability of alternating 5 years of alfalfa with 5 years of corn and soybeans may be higher than that of corn and soybean rotation. Comparing the corn-soybean rotation to one that includes alfalfa for 50% of the years results in 42% less nitrate loss to tile drainage in Iowa.(5) For community well-head protection regions, alfalfa in the rotation seems especially deserving of consideration.

Double Cropping

Whether grazed or cut for harvest, growing a cover crop or an annual forage crop boosts residual inorganic N intake in comparison to the growth attained. Depending on the species and growth stage, the N intake maybe 25–30 lb per 1000 lb of dry matter. The depths 0 to 12 will see the most uptake, whilst depths more than that will see the greatest leaching of nitrate below the primary crop's rooting depth.(6) A portion of the plant nitrogen (N) from the cover crop is likely to be available for the primary crop's later growth, and extra plant N will likely be mineralized after the main crop has stopped utilizing it. As a result, extra N fertilizer is frequently used.

Nitrification inhibitors and special N- Fertilizers

Since the 1960s, there have been products on the market that slow down the conversion of fertilizer N to highly mobile NO3. It is simple to find a lot of information. With sandy loam or sandier soil, these products, when used properly and in a timely manner, can play a small but significant role in reducing the leaching of NO3- from fertilizer-N but not from residual soil NO3-. Although there is a lot of opportunity for NO3-leaching in sandy soil throughout the year, the best times for most Nebraskan fields to do so are in May and early June. It is important to time the administration of nitrification inhibitors or N fertilizer products to reduce nitrification of fertilizer-N before and during the period of high leaching potential, such as from April to June. During 20 years of continuous irrigation of corn in Nebraska, the administration of excessive nitrogen fertilizer (nitrogen fertilizer) had a significant impact on leaching while the use of nitrification inhibitors was ineffective.(7) The findings show that nitrification inhibitors have limited potential for usage in silt loam, silty clay loam, and finer texture soils to prevent NO3- leaching to the vadose, most likely because less water percolates below the root zone than in sandier soils.

If a field has some sandy loam or soil, using a nitrification inhibitor along with late-fall-applied anhydrous ammonia may limit NO3- leaching to the vadose and have led to some production gains for eastern Corn Belt states. In Iowa, using an inhibitor with fall-applied anhydrous ammonia has been linked to a 7% decrease in nitrate runoff into tile drainage, but using an inhibitor with spring application is not part of their plan. In Iowa, the loss of nitrate due to tile drainage was 6% higher with fall N application compared to spring N application and 4% lower with in-season application compared to pre-plant treatment.(4) With the use of an inhibitor for fertilizer-N applied to sandy loam or sandier soil in Nebraska, some reduction in NO3-leaching is anticipated.

Manure Nitrogen

The amount of organic N applied to Nebraska agriculture each year is equivalent to 150 lb/ac of fertilizer N applied to around 1.3 to 1.6 million acres. It is difficult to forecast how much organic N will be present in manure added to the soil and other organic materials. Although the UNL standards for manure N availability are conservatively low to guard against production loss, they are too low for NO3- leaching to be minimized. In the three years after application, for instance, only 47% of the organic N in cattle feedlot manure is currently recognized, although the average credit is closer to 75%.(8) If protecting groundwater quality is a top priority, then much more credit should be provided.

Avoid Excessive N Application

The leaching of NO3- is significantly influenced by the fertilizer-N rate. The equivalent of around 20% of the additional 134 lb/ac/yr accumulated in the vadose zone to 30 ft depth after 20 years of continuously irrigated corn on a silt loam soil when N rate was increased from 150 kg/ha/yr to 268 lb/ac/yr. The loss of the second rate increment of 134 lb/ac/yr was likely >25% for N greater than 200 lb/ac because more NO3- accumulated beyond the 30 ft depth, according to likelihood. Unless the majority of the fertilizer-N was administered in-season in response to the predicted crop N need, this loss probably would have been greater with sandy loam or sandier soil. The projected mean crop yield response to N for irrigated corn after corn in Nebraska is depicted as having a curved shape, with yield increases declining to zero as the N rate increases. Once the most profitable N rate (economically optimal N rate, (EONR) is exceeded, the value of yield increases is less than the cost of fertilizer-N consumption.(9)

With higher fertilizer-N rates, the efficiency of fertilizer-N recovery therefore declines. Based on how Nebraska's high-yield corn responded to fertilizer-N, the average recovery efficiencies for corn after corn for increments of 50 lb/ac N were 53% for 100 to 150 lb/ac N, 38% for 150 to 200 lb/ac N, and 24% for 200 to 250 lb/ac N. Similar to how soybeans recover after being planted in corn, corn's recovery rates for N rate increments of 50 lb/ac were 74% for 50 to 100 lb/ac N, 51% for 100 to 150 lb/ac N, and 28% for 150 to 200 lb/ac N. The average EONR for irrigated corn in the state is around 220 lb/ac for corn following corn and 174 lb/ac N for corn following soybeans with sandy loam or sandier soils.(10) A target yield of 220 bu/ac (based on the average irrigated corn yield for the State), $700/t for anhydrous ammonia (purchase plus application cost), $350/t for 32% UAN, 2.0% soil organic matter, 10 ppm NO3-N in irrigation water with 10 inches of application, and 60% of fertilizer-N applied in-season. Although yields have improved significantly without a corresponding increase in the amount of fertilizer N applied since the 1960s, fertilizer-N recovery has nearly doubled, and growers' mean N rates may be 20–30 lb/ac higher than EONR.(7) Only 24% of this extra fertilizer's N is recovered on average for corn after maize and 28% for corn after soybeans, with a significant portion being lost to leaching of NO3-.

Multiple Benefits of N rate Reduction

N rate is correlated with nitrogen losses via leaching, volatilization, denitrification, and N2O emission. As a result, reducing the nitrogen content of fertilizer can have many advantages to reduce NO3- leaching, and N2O plus carbon dioxide equivalent (CO2e) emission, fertilizer-N rate decreases are discussed. Low-cost reductions in NO3-leaching, N2O (and CO2e) emission can be made possible by EONR's N rate reductions, which are at N rates where lower fertilizer-N has little impact on yield. The cost of reducing NO3- leaching with fertilizer-N reductions of up to 50 lb/ac varies from $0.29 to $0.69/lb of leached nitrate-N for corn after corn and $0.53 to 1.18/lb N of leached nitrate-N for corn after soybean (1.7 to 4.1% reduction in net return to fertilizer-N).(11) Likened to anticipated costs per ton of decreased CO2e emission as a result of fertilizer-N reductions

Monitoring Groundwater Quality

Direct monitoring of groundwater abstraction in individual water wells using meters typically yields reliable results but can be expensive to operate and challenging to sustain (especially in developing nations) without the full participation of water users. The regulatory authority often receives water meter readings from the water user. Periodic inspections are also conducted by the authority, assuming they have enough personnel and transportation. Additionally, it is feasible to gather useful information by indirectly monitoring groundwater abstraction through the following methods: collection of indicative data—for instance, irrigation groundwater use can be indirectly approximated using hours of pump operation multiplied by the average pumping rate (from energy consumption).(12)

Optimizing Chemical Nitrogen Fertilizer Usage

In the experimental site, wheat (Triticum aestivum L.) was the previous crop. Agronomic management procedures, including weeding, earthing up, and managing pests and diseases, were carried out by the Nepal Agricultural Research Council's (NARC) standard protocols. The crop was grown in a rain-fed condition.(13)

Soil, Plant, and Grain Analysis

At the National Soil Science Research Centre, Khumaltar, Lalitpur, soil samples were taken from various locations within each plot (0–20 cm depth), combined into a single composite sample for each treatment, and examined for their physicochemical characteristics (pH, OM, total N, available P and K, soil texture). Before examination, soil samples were dried in an oven and sieved through a 2 mm screen. For the soil texture soil pH organic matter , total N , Olsen's for available P2O5, and available K2O analysis, the hydrometer technique was employed. The soil was found to be a textured sandy loam (pH: 6.45), with 65% of sand, 35.4% silt, and 15.4% clay. Samples of grain and stover were taken from each treatment plot after harvesting to measure the amount of N absorbed by the plants overall. Samples of plants were oven-dried for 72 hours at 65 °C. Before plant N measurement, the dry materials (grain and plant) were crushed and sulphuric acid was digested. By employing the Kjeldahl digestion–distillation process, the nitrogen content was found. Different components of nitrogen usage efficiency (NUEs) were later determined using the N content (%) in grain and plant samples.(11)

Precision Farming Technology

Precision farming aims to increase crop quality and profitability by utilizing contemporary technology like field mapping and satellite images. It also maximizes the utilization of conventional resources. As a result, this agricultural management system helps to foster sustainable agriculture, which helps to address the growing ecological and economic issues. Drones, satellite imagery, and GPS are a few of the technologies included in this system. Farmers receive information on all important topics, such as crop status, weather forecasts, environmental changes, etc., based on this data. Another significant distinction between precision farming and conventional agriculture is the latter's inability to manage fields as a unified block and instead must be divided into several sections.(14) Diversifying management options for particular field segments is made possible by this type of zoning, which includes reducing fuel use, maximizing technique mobility, and modifying fertilizer quantity. It significantly raises agricultural productivity while saving money precision agricultural technology allows farmers to remotely manage every aspect of the operations. Large fields or a collection of tiny regions can be managed by even small farms. It significantly raises agricultural productivity while saving money and enhancing crop efficiency.(15) The latter point is crucial since, initially sight, precision agricultural technology appears to be expensive. Long-term savings, however, are substantially greater than with conventional farming techniques. Growers can therefore calculate the precise quantity of fertilizer needed and identify the best kinds of fertilizer for a certain region. Precision farming technologies are also significant because they enhance long-term agricultural operations planning and enable real-time strategy adjustments in the event of a force majeure. It limiting the price of supplies and resources, such as fuel, water, seeds, and other materials; preserving soil health by using fewer pesticides; reducing the reliance of agriculture on the weather; and maximizing the genetic potential of the crops produced. Precision farming offers several benefits that enable farmers to lower expenses while producing goods of a much higher. (12)

Controlled Released Fertiliser

Farmers all throughout the world use fertilizers to boost yields and create better harvests. They can provide a variety of nutrients, including several micronutrients that support plant development in addition to the three primary macronutrients (nitrogen, phosphorus, and potassium). There are many kinds of fertilizers and ways to apply them, like granular fertilizers, liquid or WSF, application before planting or seeding, broadcasting, top dressing, side dressing, drip lines, or foliar feed. When choosing a fertilizer and method of application, it's important to take your crop's nutrient requirements, the properties of the soil, and your time and resources into account. (16)

Drip Irrigation System

The most effective method of delivering nutrients and water to crops is drip irrigation. It provides precisely what each plant needs, when it needs it, to grow to its full potential by delivering nutrients and water straight to the root zone of the plant at the appropriate times and amounts. Farmers may increase yields while using less water, fertilizer, energy, and even crop protection goods by using drip irrigation. Pipes known as "dripper lines," which include smaller components known as "drippers," are used to transport water and fertilizers across the field. A field's worth of plants receives a consistent supply of water and nutrients sent straight to their root zones thanks to the droplets that each dripper releases, which are loaded with both fertilizer and water. (11)

Rainwater Harvesting for Sustainable Irrigation

One of the most crucial inputs needed for crop production is water. Rainwater collection is a useful tool for farms that want to become more efficient and reduce their water usage. The system is made specifically to meet your demands. The process of gathering, storing, and preserving nearby surface runoff for use in agriculture is known as rainwater harvesting. Many villages may see respite from their water scarcity problems with the use of efficient water management and rainwater gathering techniques. It is among the simplest methods for holding rainwater for use in irrigation. Because rainwater is not treated with chemicals, it is safe for plants and may be used for both garden watering and irrigation.(10)

Biochar Application and Nitrate Leaching

Nitrate leaching from farmland pollutes the surrounding environment, such as groundwater, causing health hazards to inhabitants. To mitigate the leaching, biochar can be applied. The effect of biochar application differs depending on the application depth; however, the effect of the application depth remains unclear. To evaluate the effect, we conducted a pipe experiment with no plant using bagasse biochar with four treatments: no biochar application, surface application (0−5 cm), plow layer application (0−30 cm), and subsurface application (25−30 cm). The results showed that surface and plow layer applications reduced nitrate leaching, whereas subsurface application did not affect leaching. This difference was due to changes in the soil water movement and water budget. Surface application reduced evaporation, inducing increases in both drainage and the amount of water in the pipe. The increased amount of water might contribute to an increase in the amount of nitrogen in the pipe, reducing the leaching. Plow layer application increased evaporation, leading to decreased drainage and nitrate leaching. The subsurface application did not affect drainage and nitrate leaching; however, the change in the volumetric water content at a depth of 10 cm was the most significant among the treatments. Our study indicated that, although the same amount of biochar was applied, the effect of biochar application differs depending on the application depth. (8)

Mechanism of Nitrate Adsorption

Certain chemical-reducing agents or materials, such as hydrogen, sodium sulfite, zero-valence metal, hydrazine, etc., can be used to remove nitrate by chemical reduction. Particularly, zero-valent metals—zero-valent magnesium, zero-valent aluminium, and zero-valent zinc—have been employed to reduce nitrate from the aqueous solution because of their potent reduction capabilities, ease of usage, and straightforward maintenance requirements. Due to their affordability, availability, and environmental friendliness, zero-valent iron (ZVI), ZVI-based materials, or nano-ZVI, have drawn more attention to the reductive removal of nitrate in water treatment applications. Nevertheless, nitrate reduction may produce ammonia, which should be avoided by increasing the nitrate reduction's N2 selectivity.(13)

Strategies for Mitigating Nitrate Leaching

Over the past 60 years, it has been discovered that applying nitrogen (N) fertilizer is an effective way to raise crop yields. Except for legumes, which utilize rhizobium to fix nitrogen organically, most crops need nitrogen to produce seed and fodder. The two main plant-available forms of nitrogen in soil are nitrate (NO3 +) and ammonium (NH4 +). Nitrate has a six-fold greater mobility than ammonium and is consequently more susceptible to leaching loss. Low N usage efficiency and contaminated subsurface water streams are caused by nitrate leaching down the soil profile, and this is one of the main ways that NO3 enters the food chain. Regulations concerning nitrate, its effects on health and the environment, the role that food and water play in nitrate intake, and the primary methods by which nitrate moves through soil have all been outlined to enhance comprehension of the variables influencing NO3 leaching. Many processes influencing the concentration and mobility of residual NO3 in soil are responsible for nitrate leaching. These variables, which include soil conditions, seasonal variations, climatic shifts, and plant traits, are covered in depth. This chapter has mostly focused on managing NO3 leaching, and its management solutions may be divided into three categories: soil, fertilizer, and irrigation. Fertilizer management strategies involve utilizing fertilizers in a balanced manner, applying fertilizers at the proper time and dose, and utilizing nitrification inhibitors and slow-release fertilizers to limit the release of nitrogen. Options for managing soil include conservation tillage, planting crops during high-leaching risk seasons, and organic agriculture. The primary focus of irrigation management is evapotranspiration-based scheduling irrigation and making prudent use of deficit irrigation.(7) To put it succinctly, the chapter aims to provide the reader with a thorough overview of the issue of NO3 leaching, its potential impact on the environment and human health, and strategies for managing the problem without sacrificing crop yields.

Promoting Organic Farming Practice

Sustainable development, according to the W.C.E.D. Brundtland Commission Report from 1987, is described as a development that aims to meet the requirements of the current generation without overusing resources to protect the needs of future generations. At the World Summit on Sustainable Development in Johannesburg in 2002 and the United Nations Conference on Environment and Development in Rio de Janeiro in 1992, this was further reinforced. Both the anthropocentric and ecocentric value components are included in the ecological interpretation of sustainability and the newly developed conservation concept of ecosystem health. The goals of sustainable development are crucial because they will undoubtedly contribute to the creation of a sustainable biome. The UNCED materials from Rio+20 make it very evident that the plan to maintain sustainable development goals must be applicable realistic, simple to comprehend and convey, restricted to exercise, motivating, and globally applicable to all countries while taking into account their specific national policies and goals. Particularly in poor nations, organic farming can be a surefire route to socio-economic and environmentally sustainable development. The USDA defines organic farming as a system that, to the greatest extent practical, relies on crop rotations, crop residues, animal manures, off-farm organic waste, mineral-grade rock additives, and biological systems of nutrient mobilization and plant protection. It also avoids or largely excludes the use of synthetic inputs (such as fertilizers, pesticides, hormones, feed additives, etc.). Organic agriculture was described by the FAO as "Organic farming."(9)

Crop rotation

The biological and physical conditions of the soil are fundamental to organic farming. Crop rotation, mixed crops, and intercropping are a few of the organic farming techniques that are thought to contribute to the increase of soil life by improving the characteristics and biological activity of the soil. "Rodents balance soil-building crops (soil improvement crops) and cash crops, and can allow for bare fallow periods to break weed cycles and incorporate plant matter into the soil," says farmer Jean-Paul Courtens. Thus, after a legume harvest, there may be a crop that requires a lot of nitrogen and then a crop that requires fewer nutrients in the years that follow. This technique controls the growth of weeds and aids in the ecosystem's recycling of nutrients. Furthermore, intercropping is a crucial technique for maintaining equilibrium. environment in which an intense agricultural program is implemented. This allows for the simultaneous growth of several crops with various needs in the same field. Two distinct plants' seeds can be sowed simultaneously or apart for a certain amount of time.(17)

Organic Manure

Using organic manures or fertilizers is essential for maintaining healthy, sustainable soil. They enhance soil quality without jeopardizing the stability of ecosystems. Composting may be done with a variety of biological sources, such as leftover plant or animal matter. Organic manure improves soil biological activity, which raises soil humus levels and boosts inorganic nutrient availability for healthy crop yields. The National Organic Program (NOP) has established guidelines for using organic manure correctly with conventional farming techniques. Bulky and concentrated organic manures are the two main categories of organic manure. Bulky organic manure, often known as "farm yard manure," is made up of decomposing animal excrement such as dung and urine as well as other agricultural wastes. Compost and—above all—green manures are also included in bulky organic manure. Compost is a substance that resembles humus that is created from organic waste by microorganisms working in anaerobic environments. Both home and agricultural trash may be turned into compost.(14)

Grown for the benefit of the soil, green manures are truly crops. By adding excess inorganic nutrients, organic matter, microbial development, and humus, green manure not only makes the soil more fertile but also stops weed growth, soil erosion, and nutrient leaching. For annual cropping systems that are sustainable, green manures are typically utilized. These plants are cultivated exclusively for the advantage of the soil rather than for harvesting or grazing. Crop rotation involves the use of green manure plants. Because nitrogen-fixing bacteria are found in legume root nodules, legumes are an essential source of green manure because they help fix atmospheric nitrogen into the form that is accessible in the soil. Sesbania aculeate (Dhaincha), Vigna unguiculata (Cowpea), Melilotus parviflor (Senji), Chamopsis tetragonoloba L. Taub. (Cluster Bean), and Crotalaria juncea (Sun hemp) are a few legume plants that are utilized as green manures.(13)

On-Farm Waste Recycling

Recycling organic waste is critical to sustainable farming because it reduces the need for costly and dangerous chemical fertilizers. Cropped branches, straw, and leftover portions of fruits and vegetables are among the farm and home wastes that go through anaerobic digestion, composting, and thermo-chemical treatments (catalytic, pyrolytic, and hydrothermal), all of which maximize recycling. As a result, less traditional chemical fertilizers and other energy sources are used. A significant portion of organic waste also consists of home, industrial, and MCD wastes. Organic agriculture uses sustainable and alternative weed management techniques in place of chemical and herbicide use on farms. (17)

Biofertilizers

Symbiotic Fixation of Nitrogen

Symbiosis is one kind of biotic interaction that helps fix atmospheric nitrogen into the soil in different forms that plants can easily exploit. To fix nitrogen in the soil, legume plants and Rhizobium bacteria have a symbiotic connection that is particularly beneficial. Leguminous plants have root nodules that are home to rhizobium bacteria, which release atmospheric nitrogen into the soil for plant uptake.(9)

A Symbiotic Fixing of Nitrogen

Without developing a symbiotic relationship with other organisms, certain organisms, such as blue-green algae (BGA), *Mycorrhizae*, bacteria like *Azospirillium* and *Azotobacter*, and *Azolla* (a small aquatic plant), can break down soil organic matter and chemically convert atmospheric nitrogen into forms that are available in the soil, such as nitrates, nitrites, ammonia, etc.(9)

Utilizing Biopesticide

Toxins produced by biological agents that are detrimental to plant-invading pests are known as biopesticides. Alkaloids, phenolics, terpenoids, and other secondary metabolites are generated as potent biopesticides that combat worms, insects, fungus, and other pests. Biopesticides destroy pests such as fungus, flies, nematodes, and others by preventing their development. Biopesticides include, among others, pyrethrum, nicotine, neem, margosa, and rotenone.(10)

Vermicompost

Certain earthworm species are utilized in vermicomposting, where they are fed organic waste materials and, following digestion, produce the granular form known as vermicompost (cocoons). Modest environmental conditions are necessary for vermicomposting because it involves the usage of earthworms and microorganisms. Vermicompost has a high concentration of macro- and micronutrients, phytohormones, and microflora—all of which are necessary for plant development. (14)

Harnessing the Potential of Catch Crops

Reduced ecological services and deteriorated soil, encourage unsustainable agricultural growth. This is the case despite the fact that intensive agriculture is essential to supplying the world's expanding food needs. Intensive farming and tillage practices are two of the most significant anthropogenic activities that have significantly impacted soil health. A significant factor influencing soil sustainability and productivity is the deterioration of soil health resulting from tillage and multiple-cropping practices. Soil organic carbon (SOC) levels have dropped and soil chemical, physical, and biological properties have degraded as a result of extensive tillage farming techniques.(18)

Modification of Soil Structure

Strategic tillage seeks to enhance soil structure by fostering favorable circumstances for ideal plant development. This aids in establishing an atmosphere that promotes moisture retention and root growth. Research has shown that strategic tillage may significantly alter the porosity and structure of the soil, improving root development and water transfer. It can support agricultural systems' productivity and long-term sustainability. According to research investigations, strategic tillage can raise the amount of organic carbon in the soil, boost nutrient availability, and improve soil biological activity.(8)

Weed Control

By sabotaging weed development, burying weed seeds, and uprooting existing weeds, tillage is an essential part of weed management. Research has indicated that strategic tillage is a useful tool for controlling weed populations and lowering weed biomass. A key component of weed management is tillage. Herbicide use can be decreased and weed populations can be reduced with the use of strategic tillage techniques, such as timely tillage operations and burying weed seeds.(8)

Crop Residue Management

By incorporating agricultural residues into the soil, strategic tillage promotes their breakdown and nutrient release. The process of incorporating crop waste and soil amendments like manure and lime into the soil is made easier by strategic tillage. As a result, nutrients are distributed more fairly, plants have better access to them, and runoff losses of nutrients are decreased. Research indicates that strategic farming can enhance the pace at which crop wastes break down, which can enhance soil organic matter content and nutrient cycling.(9)

Water Intake and Storage

By improving soil structure, strategic tillage maximizes the absorption, storage, and transport of water in the soil profile. By enhancing water infiltration, decreasing runoff, and boosting water-holding capacity, it lessens the likelihood of drought stress and enhances agricultural water use efficiency.(8)

Root Zone Deepening

Deliberate tillage can improve root penetration into the subsurface by breaking through compacted layers like hardpans. This improves agricultural yields and plant health by allowing crops to reach deeper water stores and nutrients.(9)

Integrated Weed and Pest Control

More comprehensive weed and pest management plans might incorporate strategic tillage. Tillage can help lessen the need for pesticides and herbicides by upsetting the life cycles of weeds and creating an environment that is conducive to natural predators. Research has demonstrated how strategic tillage may be used in integrated weed management techniques to increase weed control and decrease the use of herbicides.(8)

Strip-till Rigs

As a method aimed at conservation, strip-tillage is becoming more and more well-liked. The purpose of strip-till rigs is to till small strips between rows, usually 6–12 inches wide. This method preserves larger quantities of soil organic matter, decreases soil erosion, accelerates soil warming, and uses less energy and fuel.(10)

Tools for Vertical Tillage

This method breaks down crop residue and loosens the top 2-3 inches of soil. It produces more homogeneous field conditions, increases infiltration, decreases runoff, and improves soil contact with residue. Equipment makers have merged the benefits of classic disks, vertical tillage, and soil-finishing technologies into a single instrument. (9)

Rotating Finishers

These are cutting-edge instruments for conditioning soil. After performing initial tillage operations, they use rolling baskets or rotary harrows to further aerate the soil surface. These tools aid in strengthening soil structure, enhancing moisture retention, and improving seedbed preparation.(10)

Role of Cover Crops in Nitrate Uptake

One of the main causes of freshwater pollution is nitrate (NO3-–N), which is produced at rates higher than those of efficient nitrogen usage in livestock and synthetic fertilizers. Because the soil cation exchange complex repels nitrate anions, irrigation or precipitation water can mobilize them. Nitrate readily flows downward with the moisture front because it is not as susceptible to breakdown, plant absorption, or air dispersion below the root zone. For instance, nitrate leaching accounted for 66% of the N fertilizer application in potato production systems in the northern and central United States. When nitrate builds up in groundwater, it can make the water dangerous to drink, and when it moves to surface waterways, it can harm aquatic ecosystems. The concentration of soil nitrate and the flow of water and solute are the main factors influencing the leaching process in farmlands. Nitrate leaching may be minimized by keeping an eye on the water balance in the root zone and using effective irrigation management. Nonetheless, the growth of irrigated areas is often accompanied by rising water usage efficiency. Furthermore, to prevent the buildup of excess salts in the root zone, periodic overirrigation is unavoidable in many agricultural systems. It is anticipated that soil's excess salt accumulations will be amplified by global warming and the ensuing rise in summer droughts. Reusing water for irrigation has increased in recent decades due to dwindling freshwater supplies, especially in arid and semi-arid areas.(13)

There are several designed and natural methods available for remediating groundwater nitrate. These approaches, which include bacterial denitrification, adsorbents, membranes (such as osmotic and bioreactor), and electro-dialysis, are often based on groundwater pumping techniques. These techniques, as opposed to cover crops, concentrate on nitrate that has already seeped into groundwater from the soil profile. The majority of these techniques are expensive and frequently result in byproducts that need to be treated again. It has been demonstrated that no-tillage (NT) decreases nitrate leaching in addition to cover crops. Increased denitrification losses due to the greater water retention capacity under NT are thought to be the cause of the decreased nitrate leaching. The duration of NT management is a significant driver of the effect of tillage on nitrate leaching, and the reaction may differ significantly across soil types. As a result, whereas some studies found little to no effect of NT on nitrate leaching, others claimed that NT lowers nitrate leaching. However, little is known about the complementary and independent impacts of NT and cover crops on nitrate leaching and water drainage.(7)

Balancing Nitrogen Fertilization Intensity

The significant input of fossil fuels that are utilized in both "direct energy" (fuel and electricity used on the farm) and "indirect energy" (energy used outside the farm to make machinery, fertilizers, plant protection agents, etc.) characterizes modern crop production. "Support energy" refers to energy sources other than solar radiation, wind, etc. Adding support energy to agricultural systems might result in a higher percentage of solar radiation being absorbed by the plants. The amount of support energy used in crop production varies greatly on a worldwide basis. While energy input on arable land can approach 30 GJ ha^{-1} in certain contemporary high-input farming systems in western Europe, it can be less than 1 GJ ha^{-1} in some low-input arable farming systems, such as those found in significant parts of Africa. In the latter production methods, high-power, labor-saving machinery and extensive use of herbicides and fertilizers are characteristics. The amount of fossil energy input increased dramatically once these approaches were introduced. Crop yields rose steadily as a result of growing agrochemical inputs and the development of more productive cultivars. This begs the issue of how high-input energy balance Over the past few decades, farming techniques have evolved.(18)

Site-Specific Nitrogen Management

The amount of nitrogen (N) fertilizer applied worldwide has expanded significantly in recent years, and by 2050, it is expected to surpass 186 million Mg N yr^{-1}. Nitrate leaching causes agricultural systems to lose between 10 and 30 percent of their total N inputs on average. This has raised concerns about the usage of N fertilizers and contamination of the environment. For cereal-based cropping systems to be sustainable, alternative N management techniques must be developed. Due to the temporal and geographical variability in crop N intake, which influences soil residual- and possibly leachable-N, managing N to reach yield potential and prevent losses to the environment is difficult. Potential N leaching losses can be predicted from the quantity of nitrate deposited in the lower layers of the unsaturated zone in the soil profile. In extended tests involving maize crops on Pampas Region soils, the average nitrate-N leaching losses at 150 cm soil depth over eight consecutive seasons rose in proportion to the increase in N fertilizer rate; these losses were 20, 38, and 56 kg N ha−1 for the three N rates of 0, 100, and 200 kg N ha−1, respectively. This suggests that adjusting N fertilizer rates appropriately is essential to minimizing N losses to the environment. One method to lessen the danger of N leaching in cropping systems is nitrogen fertilizer using site-specific management (SSM). The advantage of using SSM is that it allows you to manage homogenous sections in a field and modify the amount of N fertilizer applied based on crop requirements. These regions—often referred to as "management zones"—are identified as sub-regions with comparable limiting constraints for crop output and grain quality. Zone-based yield potential can be obtained by analyzing multi-year yield maps to establish site-specific fertilization rates. The varied landscape systems with coarse-textured soils that vary significantly in agricultural production potential over relatively short distances define the Inland Sandy Pampas sub-region. Grain yields of the main cereals (corn, wheat, and soybean) in the lowland positions of cropping soils in the Inland Pampas with notable topographic gradients can be two to three times higher than the yields in the upland locations . Consequently, extremely variable soils observed at the field size have an impact on the availability of water and nitrogen for crop production in the inland sandy Pampas. (14) While corn's N use efficiency depends on the crop's reaction to both N and water availability during the growing season, increasing corn's water use efficiency can increase its N use efficiency. Figure 2 explains about the sustainable Nitrogen Management system.

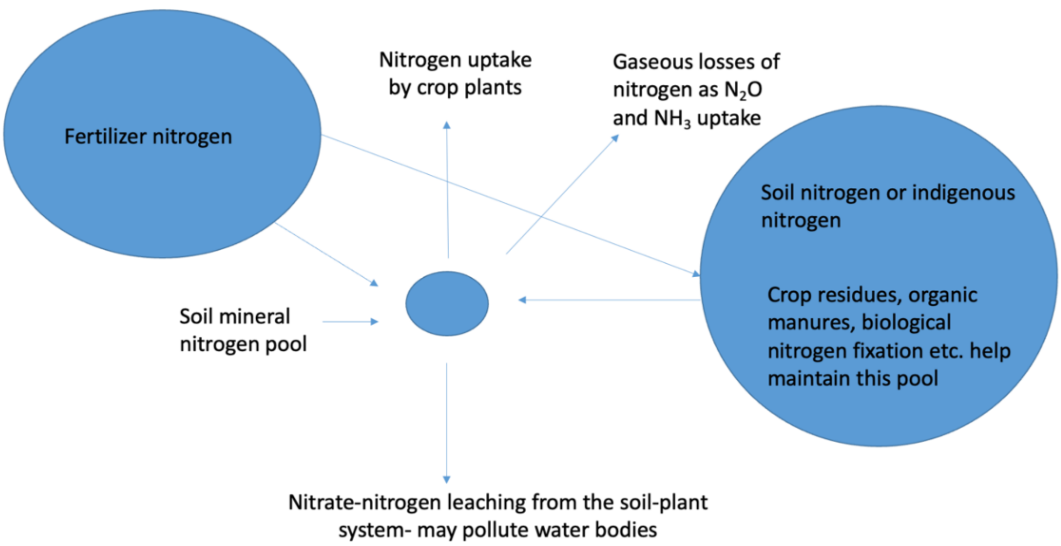

Figure 2: Groundwater nitrate response to sustainable Nitrogen Management

Nitrogen Cycling and Utilization Efficiency

Enough food must be produced to feed the world's expanding population. A significant quantity of mineral fertilizer input is necessary in such circumstances since the agroecosystems often contain a dominating ecological force of considerable swings in fertilization inputs and production outputs. Nonetheless, a substantial body of research suggests that NUE is low in the majority of global agroecosystems, often less than 40%, and especially in those ecosystems that get an excessive amount of input from mineral fertilizers.(19)

Increased or uneven mineral inputs can result in nutritional residue building up in the soil profile and acidification of the soil. In the meanwhile, it has been demonstrated that these problems lower nutrient consumption and the microbial activity that cycles nutrients. On the other hand, under biotic and abiotic stress, balanced nutrition provision helps to raise the NUE and promote plant fitness. Combining organic and mineral fertilizers is the best approach for increasing NUE, according to a large body of experimental and observational studies conducted in a variety of ecosystem types. These studies also highlight the critical role that soil and rhizosphere microbiomes play in enhancing NUE. To increase crop yield and improve NUE, it is crucial to understand the microbiological processes underlying the relationship between fertilization management and NUE. This study emphasizes how crop NUE and production are controlled by the microbiological process of functional compensation in response to fertilizer management. According to our findings, the bacterial community—particularly the rhizosphere bacterial community—is the primary mechanism via which fertilization management techniques can impact the biological characteristics of the soil. The use of mineral and organic fertilizers together produced a modest level of compensatory intensity for the nutrient cycling-related. (16) Figure 3 exhibit information about the pollution of Fertilizers and Nitrate to Surface and Ground water.

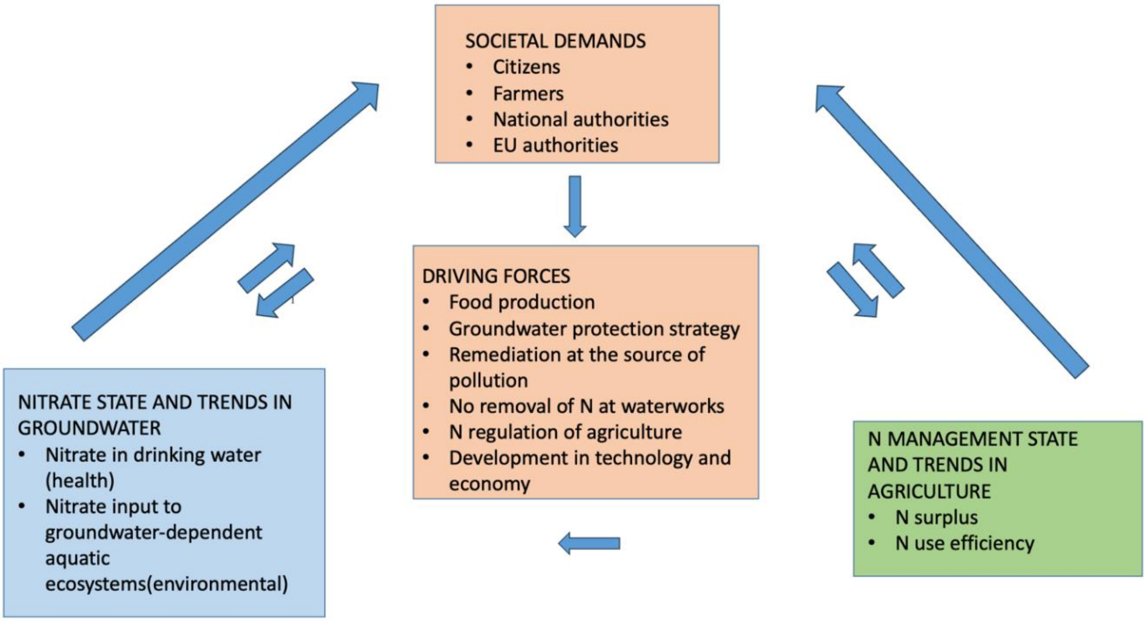

Figure 3: Fertilizers and Nitrate Pollution of surface and ground water: an increasingly pervasive global platform.

Nanotechnology for Nitrate Leaching Control

Water contamination is a serious problem that affects all forms of life on Earth. Anthropogenic activities and industrial pollutants are its primary causes. The global nitrogen cycle has seen substantial alteration in the last 200 years. Nitrogen is becoming more mobile and available throughout a significant portion of the planet. In addition, various human activities like runoff from agriculture and cities, the use of pesticides, the use of organic or inorganic compounds, the incorrect handling of industrial wastes, the leaching of waste into groundwater, and the discharge of sewage into waterways all contribute to the introduction of inorganic nitrogen, such as nitrates ($NO3^{-}$), into the environment, particularly in aquatic systems. One of the main environmental concerns is nitrate concentrations in different water sources that are higher than the permitted limit, as specified by international regulations. The most stable form of combined nitrogen for oxygenated environments is this ion, which occurs naturally. It also provides plants with a vital supply of nitrogen. Due to its high-water solubility, it is a common contaminant. It is known to produce eutrophication and impacts several drinking sources. When present at high concentrations, it has been linked to several health issues, including methemoglobinemia, diabetes, and infectious disease outbreaks. Additionally, they hurt marine and freshwater creatures, with freshwater fish being particularly vulnerable to high nitrate levels in the water. Cattle are also severely impacted by it due to nitrate toxicity. Removal of nitrate from environmental sources, such as bodies of surface water and ground water is therefore necessary to avoid these problems.(1)

Bioremediation Strategies for Nitrate Contaminated Soil

Although mining-related land degradation occurs all across the world , dry regions have historically been particularly vulnerable . In the past, mining and milling operations usually did not include environmental protections to avoid soil and aquifer contamination since sparsely populated desert places were seen as having minimal economic value . The detrimental impacts of mining and milling can last far longer in dry climates than in mesic climates because of the low biological and hydrological activity of desert ecosystems. Because of this, environmental managers now have to deal with the legacy of previous environmental harm to thousands of hectares of drylands. (7) The water balance in mesic ecosystems invariably favors contaminants seeping into groundwater or runoff onto surface waterways. Therefore, in order to remove the pollutants from the environment, many large-scale attempts to remediate contaminated soil and groundwater have concentrated on engineered strategies like pump/treat and excavation/disposal; however, in fragile landscapes, these methods may cause additional environmental harm (National Research Council, 1994). In dry areas , when potential evapotranspiration (ET) surpasses precipitation, a different approach may be available. In arid regions, whether the water balance favors recharge or outflow is mostly dependent on the plant state of the land.(19)

Phytoremediation and Nitrate Uptake

Since pore water is the primary method by which material exchange in sediment is performed, the change in sediment quality in these settings is quite restricted when compared to saltwater. Anoxic conditions are created at the sediment–water interface by the breakdown of stored organic matter, specifically because of the low exchange rates in the semi-closed bay. As a result of these circumstances, issues include a decline in microbial activity, a reduction in biodiversity, and an accumulation of harmful gases (such as hydrogen sulfide and ammonia). Physical techniques (dredging and aeration), chemical techniques (additional yellow loess, slag, and oyster shell), and biological techniques (microbial activity) have all been employed to remediate the eutrophic coastal sediments. The primary energy source for microalgae's photosynthesis is light. Numerous physiologic processes,26including pigment composition, photosynthesis, chemical composition, growth rate, and ion transport, are known to be impacted by the spectrum quality of light. The effects of monochromatic light on the development of various microalgae have been studied by a few researchers. A variety of wavelengths (blue, yellow, and red) have been used to grow various diatoms (like *Chaetoceros sp*. *And Skeletonema costatum*), blue-green algae (like Spirulina platensis), and green algae (like *Chlorella sp*. *And Nannochloropsis sp.*). It has been observed that the ideal wavelength for each species varies.(17)

Agroforestry for Nitrate Regulation

Reactive nitrogen (N) gives plants and soil microorganisms nitrogen (N), but it also harms the environment by lowering the standard of air and water, which has an effect on human health1. Therefore, we must minimize reactive N's harmful effects on the environment while optimizing its positive effects1. Among many other variables, the destiny of soil N is influenced by the rate of N fluxes and the chemical form of N2. An insight of the internal N cycle may be gained from soil gross N cycling rates. To explain how the internal soil N cycle contributes to persistent N losses from terrestrial ecosystems, a process-based knowledge of global gross N transformations is still necessary. Considering how crucial soil gross N cycling rates are the variability of soil gross N cycling rates arising from the worldwide geographical variety of climatic and edaphic factors is crucial for calculating the potential risk of N loss. Still, there is still a lack of knowledge regarding the worldwide geographic variability in soil gross N transformation rates.(20)

Sustainable Water Management in Changing Climate

Living in river deltas requires careful management of water resources. Water management is coming under more and more strain due to population increase and possible climate change. Our ignorance of how the future will pan out is the issue. Despite this uncertainty, judgments must be made since policies must be implemented gradually and their effects might be substantial. Furthermore, certain techniques (especially those involving spatial planning) could be workable now but not in the future. Water managers have historically employed "best estimates" of the future, which are extrapolated from existing socioeconomic and water system patterns and based on central forecasts of climate change. Such a strategy could work for issues that are well-understood, but not for intricate issues with deep , like long-term water management in dynamic environments.(19)(20)

CONCLUSION

Worldwide, nitrate (NO3 -) concentrations in surface and ground waters are on the rise, with the blame attributed to nitrate leaching from agricultural production systems.This research examines the evidence of NO3-leaching losses from a range of land use systems, such as organic farming, horticulture systems, grazed pastures, cut grassland, arable cropping, mixed cropping with grazing leys, and forest ecosystems. We talk about soil, climate, and management aspects that influence NO3-leaching. When there is a buildup of NO3 - in the soil profile, nitrate leaching happens when there is a period of high drainage that either precedes or follows the accumulation. Thus, there is a chance that highNO3 -leaching losses will result from using excessive amounts of nitrogen (N) fertilizer or waste effluent, applying N at the incorrect time of year (such as late autumn), plowing pasture leys early in the fall, or leaving land fallow for extended periods of time.

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