Review Article

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A Comprehensive review on Use and Abuse of Nitrogen in Agriculture

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Abstract

Nitrogen, a vital element for plant growth, is pivotal in modern agricultural practices. Its responsible application enhances crop yields, ensuring food security for a growing global population. Nitrogen-based fertilizers have revolutionized agriculture by supplying plants with the nutrients necessary for robust growth and increased productivity. However, the widespread use of nitrogen fertilizers has led to unintended consequences, such as water pollution, greenhouse gas emissions, and soil degradation. While proper nitrogen fertilization boost crop yields and addresses nutrient deficiencies, excessive application can result in the release of reactive nitrogen compounds into the environment. These compounds can contaminate water bodies through runoff, leading to harmful algal blooms, oxygen depletion, and aquatic ecosystem disruption. Additionally, nitrogen fertilizers contribute to nitrous oxide emissions, a potent greenhouse gas that exacerbates climate change. Mitigating the negative impacts of nitrogen abuse in agriculture requires a multifaceted approach. Precision agriculture techniques, such as targeted fertilization based on soil nutrient levels, can minimize excessive nitrogen application. Cover cropping, crop rotation, and agro forestry practices improve soil health, reducing the need for synthetic fertilizers. Enhanced nitrogen recovery systems and the adoption of organic farming methods also hold promise in curbing nitrogen-related issues. Nitrogen's indispensable role in modern agriculture is undeniable, but its misuse poses significant environmental challenges. Striking a balance between harnessing nitrogen's benefits and mitigating its detrimental effects is essential for sustainable agricultural practices and safeguarding the planet's ecosystems. Adapting innovative farming strategies and fostering awareness about responsible nitrogen use will be crucial in addressing the complexities surrounding this vital element in agriculture.

Key Words: Nitrogen, Fertilizers, Pollution, Policies, Economic Instruments

1. Introduction

The fundamental elements upon which life is dependent are nitrogen, nitrogen oxides, carbon atoms, hydrogen atoms, oxygen atoms, and phosphorus atoms. [1]. Among them, N is the fundamental element in the formation of amino acids, which, in turn, are the basic components of proteins. Nitrogen (N) makes up 78 % of the air, where it is virtually inert and largely non-reactive, existing mainly in molecular (N_2) form. Nitrogen gas cannot be absorbed by living matter in the atmosphere. Human protein consumption depends on the ability of plants to incorporate N into their food chain and it requires certain transformations to be used by plants and later by animals for this to happen.

Fertilizing with nitrogen (N) has proven to be one of the most effective methods of increasing crop yield over the past 60 years. Nitrogen induced increase in yield may be related to increased production of panicles in cereals and pods in legumes. Nitrogen also decreases the sterility of grain and increases the weight of grain [2, 3]. The NO_3^- movement in soil profile is six times higher than NH_4^+ with flowing water and is therefore prone to leaching loss. [4] On the other end, Ammonium (NH_4^+) and NO_3 are major plant available forms of N in soil. Owing to its positive charge, NH_4^+ has very poor mobility in negative charged soils of the subtropical climate [5].

The use of any form of fertilization, whether it is inorganic or organic, can have a detrimental effect on the environment if not properly managed. In the past, large quantities of nitrogenous (N) fertilizers were utilized worldwide. However, the rate of recovery or effectiveness of nitrogenous fertilizers in the cultivation of crops on arable land is low, with an estimated recovery rate of 25-50% of the fertilized N [6]. The increasing utilization and expense of nitrogen fertilizers in agricultural production is cause for concern. By increasing N use efficiency, yields and profits can be increased by an average of $18.75 per acre when cultivating grain crops with minimal environmental impact [7].

In agriculture, nitrogen (N) is added to fields to increase crop yields. However, nitrogen is also a critical nutrient for plants to grow and develop, but it is also a limiting nutrient for aquatic ecosystems. As a result, nitrification of excess nitrous oxide (N and/or phosphorus, P) from consuming contaminated groundwater has been associated with a number of downstream consequences, such as accelerated surface water erosion, blooms of algae and hypoxia and public health problems. Nitrogen loss to the environment occurs when it leaches to the groundwater and is transported to the surrounding surface waters by surface run off, or directly to the surface waters by tile drainage by bypassing stream buffers [8, 9].

In this review, I discuss various factors controlling N use efficiency and the methods which can improve N use efficiency in agriculture minimizing environmental losses. This review is the first of its kind to look at all the research that's been done on how to use both inorganic and organic sources of N to make it better. N use efficiency in different crops in a single work. We specify possible ways to improve N use efficiency for future research.

Nitrogen sources and how they interact with plants and soil

Nitrogen is a naturally occurring element that can be found almost everywhere. It's mostly nitrogen gas (N_2) in the atmosphere, making up about 78% of the total amount of nitrogen gas (4000 trillion tons). Dinitrogen is broken down into different forms like ammonium and nitrite by bacteria and other organisms [10]. About 95% nitrogen is naturally occurring organic matter in the soil. [10]. However, when looking at nitrogen from an agricultural perspective, it is clear that certain sources of nitrogen are responsible for the majority of nitrogen available to plants and crops. These nitrogen sources can be either natural or organic, and can also be generated through artificial processes. Natural nitrogen is found in soils through the mineralization of minerals and the fixation of bacteria [11]. In soil, nitrogen is available in the form of ammonium or nitrate [12]. In soil, nitrogen is also present in the form of nitrites, nitrous oxides, and atmospheric nitrogen. However, these forms of nitrogen are not naturally available to plants unless they are transformed into ammonium or nitrates through bacterial or lightning fixation [12]. Another source of nitrogen is stored in living cells. When cells die, they decompose and release nitrogen back into the soil. Legumes and animal carcasses typically contain more nitrogen than other living things, making them excellent natural nitrogen fertilizers [13, 14]. The use of leguminous crops in crop rotations is a method of fixing atmospheric nitrogen and subsequently depositing it into the upper levels of agricultural soils. The high nitrogen content of animal bone or bone meal is utilized as an effective substitute for chemical fertilizers [15, 16]. Nitrogen is sourced primarily from the atmosphere, where it constitutes about 78% of the air. It's often obtained through a process called nitrogen fixation, where certain bacteria convert atmospheric nitrogen into forms that plants can absorb. Additionally, nitrogen is found in organic matter, like decaying plants and animal waste.

In terms of interactions, nitrogen is crucial for various biological processes. It's key component of amino acids, which are building blocks of proteins. Plants use nitrogen to grow and develop and its availability can impact crop yield. However, excessive nitrogen in soil and water can lead to environmental issues like water pollution and eutrophication. Balancing nitrogen levels is essential for sustainable agriculture and ecosystem health.

Nitrogen in the Environment

Nitrogen is a crucial element in the environment, existing in various forms like nitrate, nitrite, and ammonia. It's essential for plant growth and is often a component of fertilizers. However, excess nitrogen from agriculture and industrial processes can lead to environmental issues like water pollution, algal blooms, and soil degradation. The acquisition and disposal of nitrogen in the agri-ecological system is linked to a variety of intricate and interconnected processes. The primary causes of nitrogen loss in agricultural systems include: (a) gaseous emissions in the form of volatilization or denitrification of ammonia; (b) leaching (i.e., removal of nitrogen below the root zone by percolating water); (c) plant uptake; and (d) surface run-off. To understand the nitrogen cycle, a simple mathematical equation can be used.

$$N_{net} = N[e + bf + c + om + min.] - N[pl + g + i + l + r]$$

The positive sign shows that N has been added to the soil and the negative sign shows that the soil has been depleted of N. N net is the net amount of N added to the soil. e is electrical discharge, bf is biological fixation, c is chemical fertilizer, om is organic manure, min is mineralization, pl is plant uptake, g is emissions (volatilization , denitrification) i is immobilization, l is Leaching and r is surface runoff. The losses associated with plant uptake and surface runoff are relatively low. However, the losses due to volatilization are significant at a pH level typically higher than 8.0, in soils with a high temperature and low cation exchange capacity. Anoxic soil conditions are conducive to denitrification. The leaching of NO_3^- into groundwater is more hazardous to human health than other chemical elements [17].

Problems Associated with excessive Nitrogen in the Environment

Nitrogen fuels and facilitates good growth of plants. However, plant species have different nitrogen-response values because of their inherent growth rate dichotomy and their response to other related changes such as acidification or nutrient imbalances. As a result, it seems that every farmer needs to be seriously trained in the art of fertilizer application. Most importantly, the rate of fertilizer that plants need relative to their normal functioning must be determined, without causing damage to the environment.

The traditional method of fixing nitrogen biologically is beneficial to the environment; however, it is not sufficient to meet the current growing demand for food. As a result, the addition of nitrogen fertilizer to agricultural ecosystems in order to improve the yield of crops has been adopted, which has seen a dramatic rise in the past 50 years [18]. The long-term consequences of over-application of N often lead to surface water being eutrophicated, a phenomenon commonly referred to as highly toxic to water bodies. Drainage canals have long been a means of transporting nitrate and phosphate effluents out of paddy fields and into rivers or lakes. This is most commonly observed when paddling releases pond water. Percolation tends to purify soil layers, but leaching works its way out of the soil and acts as a powerful deterrent to the system.

Rain and irrigation are two of the best ways to spread fertilizer further into the soil than it can reach from the root zone. Over time, this can lead to groundwater contamination. Rain and irrigation are great harbingers of contamination because they cause nitrate fertilizers to react on the soil surface, which in turn causes nitrogen to be lost to the atmosphere [19, 20] also concedes the fact that natural processes, such as intensive watering and large amounts of rainfall, also remove excess surface nitrogen fertilizer, contaminating waterways. Hypoxia, which is a low level of dissolved oxygen in comparison to algal blooms, is caused by high nitrate levels in waterways, which can be toxic to warm blooded animals at 10 mg/L or higher if left unchecked [21, 22]. Excessive nitrogen in the environment can lead to various problems, such as water pollution, air pollution, and ecosystem disruptions. It can cause nutrient imbalances, harmful algal blooms, and contribute to greenhouse gas emissions. Additionally, excessive nitrogen can negatively impact human health, aquatic life, and biodiversity.

Atmosphere Pollution

Nitrogen pollution from agriculture primarily stems from the excessive use of synthetic fertilizers and poor management of livestock waste. When these sources release nitrogen compounds into the atmosphere, they can contribute to the formation of airborne pollutants like ammonia (NH3) and nitrous oxide (N2O). Ammonia can affect air quality, and nitrous oxide is a potent greenhouse gas that contributes to climate change. There are direct health effects of air pollution. In 2017, 5 million people died due to air pollution-related diseases. The United States and China have the highest mortality rates among the top 10 countries [23]. Agricultural activities account for nearly 15% of global greenhouse gas emissions each year [24, 25]. Human activity is responsible for between 60% and 80% of global (N2O) emissions. [26,27]. N2O is a greenhouse gas that remains 298 times more powerful than carbon dioxide in the atmosphere due to the growing use of N fertilizer in food production around the world [28].

However, some recent research on corn cropping systems shows an exponential correlation between them [29, 30]. According to the latest estimates made by the Intergovernmental Panel on Climate Change (IPCC), the current global average N2O emitted by nitrogen fertilizers is just under 0.9 % of the N used in the cropland [31]. This means that, every 100 kg of nitrogen fertilizer used in agriculture releases 1.0 kg nitrogen dioxide (N2O) into the atmosphere [29]. Agricultural nitrous oxide (N2O) emissions to the atmosphere reached 7.718 Gg in 2018 [32]. Sustainable practices such as precision farming, proper fertilizer application, and efficient manure management are crucial. These measures can help minimize nitrogen emissions, reduce environmental impact, and promote healthier air quality.

Aquatic Ecosystems Pollution

Aquatic ecosystems can be adversely impacted by pollution from agricultural nitrogen. Excessive use of nitrogen-based fertilizers can lead to runoff off nitrogen compounds into nearby water bodies, causing problems such as nutrient enrichment, algal blooms, oxygen depletion, and harm to aquatic life. This phenomenon, known as eutrophication, disrupts the balance of the ecosystem and can have cascading effects throughout the food chain. It’s important for agricultural practices to be managed sustainably to mitigate these pollution effects and protect aquatic ecosystems. Nitrate concentrations are a fundamental factor in assessing the level of contamination in aquatic systems, as they are the most consistent form of N and their high concentration disturbs the essential equilibrium of aquatic organisms [33, 34].

Agriculture is one of the main contributors to nitrate leaching [35–38]. Nitrogen leaching depends not only on the amount of fertilizer used, but also on other factors such as the time and location of fertilizer application in relation to the growing cycle of the crop, irrigation techniques, fertilizer types, agronomic techniques, crop rotations, soil properties, soil cover, climatic conditions, etc. [39–45]. A sustainable population is incompatible with the depletion of groundwater aquifers. Groundwater is being used more and more to meet increasing water demands. Today, 43% of all irrigation water and 50% of all domestic water consumption worldwide are sourced from groundwater [46]. Contamination of this resource is therefore a serious threat to the health of those who rely on it. Numerous studies have shown that long-term use of water with a nitrate content above 50 (mg/L) increases the risk of some types of cancer [47–49]. In the 1990s, the first research was conducted on the production of toxins by cyanobacteria in polluted aquatic environments [50, 51]. Cyanobacteria colonize the surface of the body of water where the highest concentration of solar radiation occurs, causing the water to turn green and blocking light from reaching the deeper layers of the water [52]. When vegetation and many floating algae reach the new limit of photosynthesis, they die due to a reduction in nutrients, which are then broken down by bacteria that, during their activity, absorb oxygen and create toxins. As a result, native aquatic species die due to a lack of oxygen and are replaced by species more suitable for anaerobic conditions. At a deeper level, the cold temperatures and lack of oxygen and light create an unviable habitat for vernacular living organisms [53]. Eutrophication affects many inland and coastal bodies of water around the world [54] and life in some of the world's oceans is threatened. Carpenter and Bennett [55] mention that the maximum acceptable nutrient intake limit for wetland, lakes and freshwater has already been reached.

Sustainable Nitrogen management policies

It's been shown that all of these strategies and methods are effective at increasing crop yields and reducing diffuse N pollution from the agriculture industry. But farmers don't seem to be very happy with the Best management Practices (BMPs) and they have a few obstacles to overcome when it comes to changing their farming methods [56, 57]. It is essential to comprehend how farmers make decisions in order to enhance fertilizer management [58].

It typically includes policies aimed at reducing nitrogen pollution, improving agricultural practices and improving ecosystem health. Examples include regulating industrial nitrogen emissions, increasing fertilizer use, promoting crop rotation and promoting wastewater treatment solutions. These policies need to be tailored to each region's unique needs and challenges. Public policies to reduce N pollution will only be effective if they match the incentives that drive farmers to switch management modes. The focus should be on reinforcing positive messages that emphasize the advantages of these BMPs [59].

Policies

Environmental policies, in general aims, are all about internalizing, stopping, and fixing the outside effects of economic activity. Regarding N use as fertilizer, we've already talked about the externalities in the previous posts, and these policies are all about changing farmers' management practices. Different countries have different levels of environmental regulations, and each has different farmer requirements.

Some specific policy approaches that can contribute to the sustainable management of nitrogen. Fertilizer management, introduce guidelines for responsible fertilizer use, including precision agriculture techniques, proper timing, and dosage to minimize excess nitrogen application. Nutrient trading programs, establish programs that allow farmers to trade nutrient credits, incentivizing those who adopt practices that reduce nitrogen runoff or emissions. Cover crops and crop rotation encourage the use of cover crop rotation to improve soil health, reduce nitrogen leaching, and increase nutrient efficiency. Regenerative agriculture it support practices like agroforestry, agroecology, and organic farming that emphasize holistic approaches to reduce nitrogen runoff and enhance soil health. Wastewater treatment upgrades, sewage treatment plants to effectively remove nitrogen from wastewater before it's released into water bodies.

Kanter et al. [58] propose the concept of a complete food chain NUE as a new framework for analyzing policies to reduce N pollution. In their study, the authors argue that, due to the close interdependence between all the players in the food supply chain, reducing N losses at the farm level can only be achieved by implementing non-farmer-oriented policies. In the US, there are a few rules about how to use fertilizer, like how to plan it and what it should contain. But there's not much federal regulation about how to use it. Most of the time, it's just a bunch of free programs. And the amount of nitrogen oxide in the air is up for grabs [60]. Currently, there is very little regulation on N pollution in China. However, due to the high levels of pollution in air and water in many Chinese regions, the China Ministry of Agriculture initiated an ecological-based reform of the subsidy system [61]. The effectiveness of these policies varies depending on local circumstances, socio-economic considerations, and stakeholder engagement. Combining these strategies in a context-specific way can lead to a more sustainable approach to nitrogen management.

A social intervention related to nitrogen use could focus on raising awareness and encouraging responsible nitrogen management practices among farmers and the broader agricultural community. To educate farmers about the importance of responsible nitrogen use and promote practices that reduces nitrogen pollution while maintaining agricultural productivity. To organize workshops and training sessions for farmers to inform them about the impacts of nitrogen pollution, best practices for nitrogen application, and techniques to improve nutrient efficiency. Information dissemination, to develop educational materials such as pamphlets, videos, and infographics, explaining the effects of nitrogen runoff on water quality and ecosystem health. Distribute these materials at agricultural fairs, markets, and community centers. Peer-to-peer learning, facilitate peer learning networks where experienced farmers who have successfully adopted sustainable nitrogen practices can share their knowledge and experiences with their peers. Create mobile apps or websites that provide farmers with easy access to information about nitrogen management, including calculators for optimal fertilizer application based on soil type and crop. Collaborate with agricultural organizations and government agencies to provide incentives for farmers who adopt sustainable nitrogen practices. These incentives could include subsidies for financial support for equipment, or recognition for best practices. It would be difficult to compile a comprehensive list of current and potential policies around the world that could be implemented to enhance agricultural N management, as each nation has its own regulations with varying levels of rigidity. For instance, in the United States, agricultural policies are based on voluntary initiatives, as exemplified by the Environmental Quality Initiatives Program. As for China, the world's largest user of nitrogen fertilizers, there is a growing awareness of the need for improved environmental protection, which is reflected in high-level regulations such as the recently reintroduced National Environmental Protection Act, which provides for severe penalties for companies that do not adhere to environmental regulations [62].

Economic Instruments

As far as taxes are concerned, economists have suggested that the cost of fertilizer would need to double in order to produce fertilizer savings [63], the review of the European Union's fertilizer taxation system reveals that, on the whole, the efficiency of pricing remains limited [64]. Provide financial incentives, subsidies, or tax breaks to farmers adopting nitrogen-reducing practices. Alternative tools for improving pollution control under the EUN Directive have recently been studied by several authors, such as [65], manure application standards would be a more effective way to limit nutrient surplus to soils than a nutrient surplus tax, according to researchers alternatives for reducing N on dairy farms.

Technical Innovations

The use of precision irrigation and drip irrigation is also on the rise and has been supported by many governments [66]. Utilizing energy conservation technologies also makes fertilization (the use of fertilizer through irrigation water) easier. Chen et al. [61] show that innovation subsidies are an effective way to reduce agricultural emissions. While production subsidies are harmful to the environment (for example, in China) innovation subsidies reduce total emissions of pollutants while increasing the farmer's bottom line.

CONCLUSION

Nitrogen’s dual nature as a crucial agricultural asset and an environmental liability underscores the need for conscientious management practices. While nitrogen-based fertilizers have revolutionized food production, their unchecked use can lead to severe ecological consequences. Striking a balance between maximizing agricultural output and minimizing the negative impacts of nitrogen requires a collaborative effort involving farmers, policymakers, researchers, and consumers. By adopting precision techniques, embracing sustainable farming methods, and advocating for responsible nitrogen use, the agricultural sector can ensure its viability while safeguarding the environment for current and future generations.

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