Scholars Journal of Agriculture and Veterinary Sciences
OPEN ACCESS
Abbreviated Key Title: Sch J Agric Vet Sci
ISSN 2348–8883 (Print) | ISSN 2348–1854 (Online)
Journal homepage: https://saspublishers.com

Climate Change and Agricultural Nitrogen Losses: A Review of Mitigating Strategies for Soil, Water, and Environmental Protection

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DOI: https://doi.org/10.36347/sjavs.2025.v12i01.007 | **Received:** 19.12.2024 | **Accepted:** 26.01.2025 | **Published:** 28.01.2025

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Abstract **Review Article**

Climate change presents considerable challenges to agricultural systems, particularly regarding nitrogen (N) dynamics within ecosystems. While nitrogen is crucial for plant growth, its overuse in agriculture results in environmental issues such as water pollution, soil degradation, and increased greenhouse gas emissions. This review summarizes current understanding of the interactions between climate change and agricultural nitrogen losses, emphasizing their implications for soil, water, and environmental quality. We explore various strategies to improve nitrogen use efficiency (NUE) while minimizing environmental losses. These strategies include adopting precision agriculture techniques, using cover crops and crop rotation, implementing controlled-release fertilizers, and integrating agro ecological practices. We also discuss the importance of policy frameworks and farmer education in promoting sustainable nitrogen management. By addressing the complex challenges posed by climate change, this review aims to provide a comprehensive overview of effective practices that can protect soil health, safeguard water resources, and contribute to a more resilient agricultural future. Through coordinated efforts among researchers, practitioners, and policymakers, we can reduce nitrogen losses and enhance the sustainability of agricultural systems in a changing climate.

Keywords: Nitrogen losses, Agricultural production, Soil erosion, Climate change, Organic amendments.

INTRODUCTION

The word "climate change" describes a significant and prolonged variation in climate variables like temperature, precipitation, wind, or snow patterns (Pope *et al.*, 2022). The degree of climate change is thought to be severely accelerated by Greenhouse gas emissions and global warming (Sovacool *et al.*, 2021). In the world, one of the serious issues that occurs is climate change. It refers to substantial changes in the average values of meteorological elements, such as precipitation and temperature, calculated over an extended period. Increased human activity has altered the global atmosphere's composition in recent decades, resulting in significant global climate changes (Malhi *et al.*, 2021).

Since 1750, the concentration of greenhouse gases has risen by 150%, including NO_2, CO, and CH_4 with increases of 40% and 20% gases respectively (Abeydeera *et al.*, 2019). In 2014, carbon dioxide accounted for 36.14 billion metric tons of greenhouse gas emissions, up from 22.15 billion metric tons in 1990. During the last decade, the average global surface temperature has risen by 0.15 to 0.20 0C every ten years, and by 2021, it is expected to rise by 1.4 to 5.8 0C (Mohanty). Global warming is caused by the release of greenhouse gases, especially CO_2 and other GHGs, such as CH_4, N_2O and CFCs.

The atmospheric CO_2 concentration rose from 315.98 ppm in 1959 to 411.43 ppm in 2019 (Druckenmiller *et al.*, 2021). With 11% resulting from forestry and other land uses and 65% coming from industrial operations and fossil fuels, CO_2 is the basis source of greenhouse gasses in the atmosphere. Fossil fuels produced very little CO_2 before 1750, but as the industry grew, emissions rose quickly (Malhi *et al.*, 2021). Agriculture is the industry most susceptible to climate change, which will have a major negative effect on the economy because of its size and weather dependence. Agricultural yields are significantly impacted by changes in climate variables like temperature and precipitation.

Variations in precipitation, CO_2 fertilization, and rising temperatures have diverse impacts depending on the region, crop, and level of parameter change. Rises in precipitation are predicted to counteract or mitigate the effects of temperature increase, however, it has been demonstrated that temperature rises to reduce yield (Malhi *et al.*, 2021). It has been demonstrated that a decrease in precipitation or an increase in temperature in Cameroon significantly reduces farmers' net income. Due to this reason and poor policymaking, Cameroon's agricultural exports have low demand, which has led to revenue volatility in the country's economy (Karimi *et al.*, 2018).

Crop yields are affected significantly by climate change based on the region and irrigation method. Increasing the area under irrigation can increase crop production, but this might have detrimental environmental effects. Due to shorter growing seasons, various crops are expected to yield less when temperatures rise (Malhi *et al.*, 2021). In both the temperate and tropical regions, a 2 °C increase is predicted to lower the total production of wheat, rice, and maize. The total effect of climate change is greater in tropical locations because tropical crops experience high-temperature stress during high temperatures because they remain nearer to their high-temperature optima (Malhi *et al.*, 2021).

One of the most essential plant nutrients that is present in soil and also the most limiting nutrient for crops is nitrogen. The constant use of nitrogen fertilizers has caused substantial changes in the worldwide nitrogen cycle over last five years. The five main processes of nitrogen cycling are ammonification, nitrification, BNF, nitrogen assimilation, denitrification, and microbial biomass pool (Malhi *et al.*, 2021). However, excessive applications of both chemical and biological N fertilizers to soil for crop development requirements result in N loss. Only 45–50% of the N provided for crop growth is utilized in agricultural products, and the remaining portion is lost significantly (Xu *et al.*, 2020). Soil contains a significant amount of nitrogen that can be released into the environment as N_2O, NO_3, or NH_3. Furthermore, nitrate may remain to recycle in the soil-water-air system, denitrify, and ultimately return to the atmosphere as nitrous oxide and nitrogen (Houlton *et al.*, 2019).

The role of agriculture to worldwide nitrogen pollution necessitates ongoing observation and implementation of important steps at regional, national, and farm levels to prevent and control the degradation of the environment (Mahmud *et al.*, 2021). In the agricultural context, nitrogen footprint refers to the quantity of nitrogen released by the usage of resources in production of agriculture at each stage of the manufacture line, regardless of whether it is upstream or downstream. In an ecosystem service, the nitrogen footprint can be used to measure how much nitrogen is used and lost during the production and consumption of food and energy (Mahmud *et al.*, 2021).

Nitrogen application improves crop quality and production, plant greenness, CO_2 absorption rate, and vulnerability to environmental stressors such as saline soil and water scarcity. Nitrogen application is more important than the other main required fertilizer components for optimal yields of crops. However, if nitrogen is applied earlier, soil nitrogen mineralization is enhanced, and a portion of the nitrogen shares with the mineralized nitrogen (Anas *et al.*, 2020b). The conversion of nitrogenous compounds, which stored nitrogen during earlier growth phases, increased nitrogen levels in the plants at an thesis stage.

Nitrogen loss would result in odor pollution, equipment corrosion, acid rain, and atmospheric nitrogen deposition, as well as a reduction in the end product's agronomic quality. Due to the change of nitrogen during composting, huge amounts of total nitrogen are lost as gaseous emissions (mostly NH_3 and N_2O). As a result, nitrogen loss from NH_3 emissions is the primary cause of decreased compost quality and odor pollution during the composting process (Han *et al.*, 2019). In this review article, we will discuss climate change, agricultural nitrogen losses, and its mitigating strategies.

2: Effects of climate change on soil properties and agriculture

The frequency of great actions leading to flood and drought disasters in the agricultural sector has grown-up due to climate changes, including global rainfall, the continuous rise in carbon dioxide, and the average temperature shown in Fig 1. These changes pose a danger to the productivity of crops and cereals worldwide (Duchenne-Moutien and Neetoo, 2021). Crops are adversely exposed to a variety of biotic and abiotic stresses as a result of temperature and precipitation variations, which directly impact crop growth and maturity. A recent study found that 30–50% of global agricultural output losses are caused by these biotic and abiotic stressors (Chaudhry and Sidhu, 2022). Along with this productivity loss, climate change poses a hazard since it may result in a major rise in the variety of pests and diseases, which might increase the severity and frequency of plant diseases (Yang *et al.*, 2023).

Climate change harms soil systems in addition to directly affecting plants. The soil-plant system is changing as a result of changes in atmospheric carbon dioxide concentrations, rate, pattern, and precipitation amounts, as well as rising temperatures, which influence SOC levels and the rate of decomposition (Pathak, 2023). The amount of organic carbon in the soil directly affects the microbial population, fertility, soil structure, and processes. Current research has demonstrated that the mechanism by which minerals are transformed into soil compounds is determined by the combinatorial effects of temperature and moisture (Li *et al.*, 2023a). Seasonal temperature, precipitation, fluctuation rates, and changes in the soil water regime all have an impact on the hydro-physical characteristics of the soil (Fatima *et al.*, 2024). The hydrological characteristics of soil are greatly influenced by the physical characteristics of the soil, including bulk density, porosity, size distribution of pores, mechanical composition or texture, and structure, including form and stability (Yu *et al.*, 2018a). All of these characteristics work together to help control the soil's air, water, and heat. Soil fertility and crop yields are significantly impacted by these physical characteristics, which also have a substantial influence on the chemical and biological activities of the soil (Bibi and Rahman, 2023).

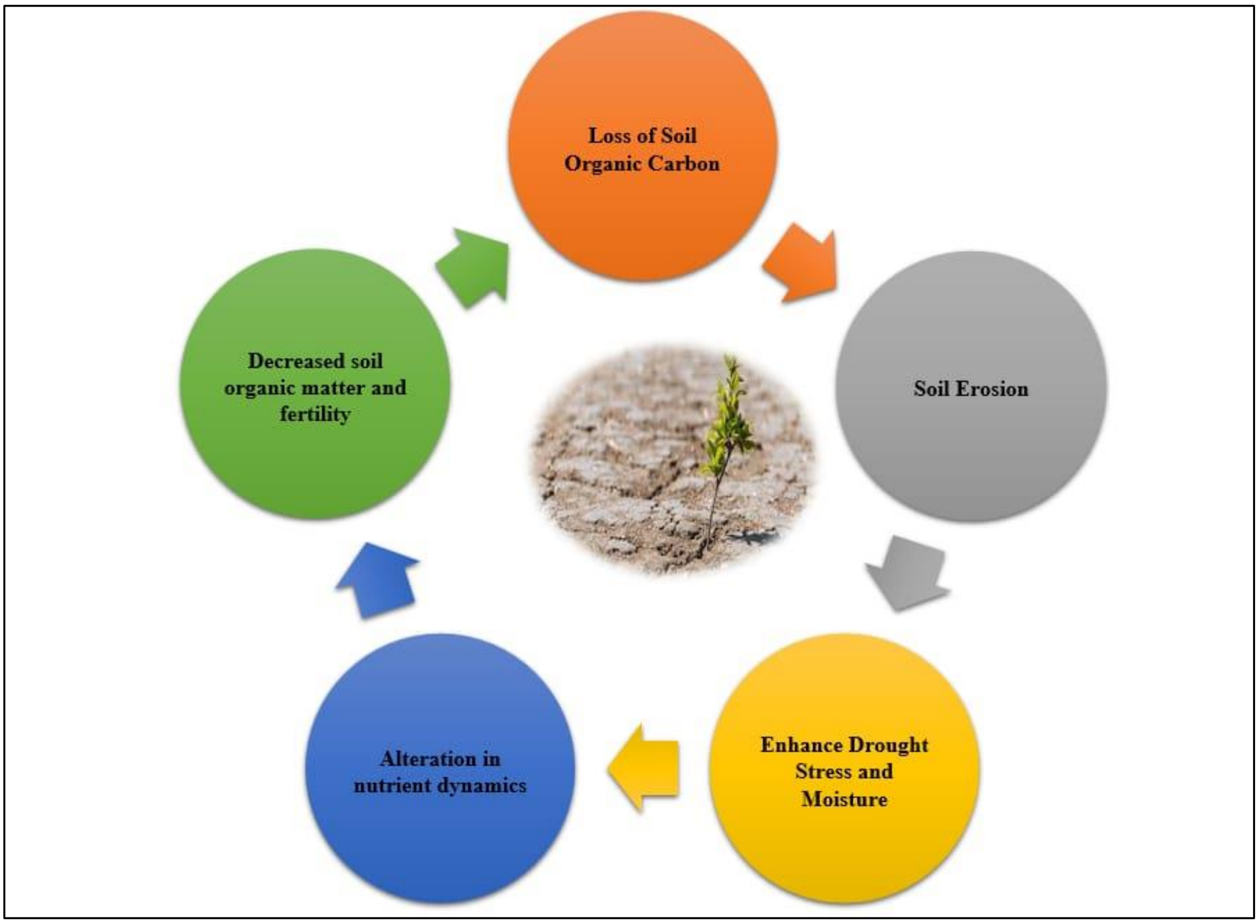

Figure 1: Impact of Climate Change on Agriculture

Determining how much climate change affects the physical properties of soil is a challenging task. The most common and significant direct consequences of climate change on disturbing soil structure are the detrimental potential of precipitation, surface runoff and water filtering, and raindrops (Liu *et al.*, 2023). In contrast, variations in vegetation patterns and soil biological characteristics, such as termites', earthworms', and the soil micro biome's sensitivity to these climate shifts, led to the indirect consequences.

Soil bulk density, organic matter content, and texture are directly influenced by climate (Wessolek *et al.*, 2023). According to recent research, higher atmospheric carbon dioxide levels significantly decrease soil organic matter by boosting soil microbial activity. As the global temperature rises, it accelerates the positive feedback in the global carbon cycle, which leads to increased carbon turnover in the atmosphere (Wessolek *et al.*, 2023). Furthermore, soil microbial activity and soil erosion cause organic matter to be lost, increasing the bulk density of the soil and, consequently, the compaction of the soil. Compaction and bulk density of soil prevent plant roots from growing, which together lead to low agricultural yields.

The chemical characteristics of soil, nutrients, carbonates, CEC, base saturation value, pH, and soluble salt concentration are also effected by extreme climate events (Nel *et al.,* 2022). These processes accelerate leaching and cause soil acidity by increasing precipitation and weathering rates. When the soil has an acidic pH, harmful heavy metals can move more easily, depleting the soil of basic cations (Corami, 2023). According to recent research, soil from warmer and drier locations has fewer amounts of organic carbon, nitrogen, and phosphorus. The amount of organic matter in the soil is one of the most crucial indicators of soil efficiency. A higher temperature accelerates the rate at which microorganisms decompose, and biological decomposition helps to increase the amount of organic matter in the soil (Whalen *et al.,* 2022). Nevertheless, the process is not constant, and beyond a certain point, additional temperature increases alter microbial physiology by decreasing the efficiency of carbon utilization.

3: Nitrogen losses in terms of climate change

Climate change is a worldwide overall occurrence of climate alteration that involves changes in the planet's regular climate (temperature, precipitation, and wind) induced mainly by human efforts. The stability of the world economy and the rest of humanity as well as the sustainability of the world's ecosystems, are all challenged as a result of excessive weather on Earth. Climate change (both temperature and precipitation) would have an impact on agriculture and runoff, as well as the risk of nitrogen loss (Meng *et al.,* 2021).

A good understanding of how changes in hydrology due to climate change may influence nitrogen losses is important for optimizing production methods and minimizing environmental effects (El Bilali, 2021). While it is evident that increasing runoff conditions would have a major impact on N losses, less is well-known almost the influence of climate change on agricultural management strategies (for example cropping system) and the influence on N losses such as NO_3 leaching, NH_3 volatilization, denitrification losses etc. (Angulo *et al.,* 2013).

3.1: Influence of climate change on the nitrogen cycle

The nitrogen cycle is one of the utmost affected biogeochemical cycles on a worldwide scale, with significant impacts on water and air quality, biodiversity, and the health of humans. Although reactive nitrogen is certainly carried through the atmosphere, from air to water, soil, also back to plants, it plays a significant part in every aspect of climate change effects, including impacts, adaptation and mitigation, etc. (Aryal *et al.,* 2022). In terms of recent radioactive forcing, nitrogen cycling influences the atmospheric attention of the three greatest significant anthropogenic greenhouse gases such as nitrous oxide, methane, and Carbon oxide (Greaver *et al.,* 2016).

Nitrogen influences primary productivity in terrestrial ecosystems as a limiting nutrient. Soil fertility, plant development, and ecosystem dynamics are all directly impacted by nitrogen availability (Yi *et al.,* 2023). Climate change would have a significant influence on nitrogen cycle mechanisms, influencing both human health as well as marine and terrestrial ecosystems (Ullah, Munir, *et al.,* 2024). Climate change affects the nitrogen cycle and soil availability through mechanisms like rising temperatures and altered precipitation patterns. Both an excess and a shortage of nitrogen can affect organisms' ability to survive in terrestrial environments (Viancelli and Michelon, 2024). The type of vegetation has an impact on the nitrogen cycle in forest ecosystems because the soil temperature, nitrogen leaching, little composition, substrate availability, microbial diversity, and gaseous loss are all impacted by the cover structure and root distribution (Abbott *et al.,* 2021).

The little nitrogen released by depolymerization and mineralization processes is contested by organisms in a forest. Mature trees, naturally renewing plants, different woody and herbaceous understory species, mycorrhizal fungus, and free-living bacteria and fungi, both close to and distant from the rhizosphere, are all examples of these organisms (Pellegrini *et al.,* 2018). Spatial and temporal separation in N acquisition can reduce direct competition between these organisms. This includes occupying different soil compartments, selectively absorbing N over time, and having diverse preferences for N sources, such as inorganic versus organic N molecules (Viancelli and Michelon, 2024).

3.2: Influence of erosion and runoff on nitrogen losses

As an essential component that is replenished in soil, nitrogen helps crops produce more protein and photosynthesis, accelerates the addition of elements and nutrient metabolism, and contributes significantly to crop growth (Li *et al.,* 2023b). Nitrogen is lost in a variety of ways as a result of climate change. The primary factor causing the movement of dissolved materials in the soil is surface runoff, however, other mechanisms also influence nitrogen loss (Uwizeye *et al.,* 2016). The impact of nitrogen loss in soil erosion brought on by rainfall runoff was thoroughly examined in this study, and each runoff area's nitrogen loss trended upward as precipitation increased (Wang *et al.,* 2020). When comparing the properties of total nitrogen (TN), ammonium nitrogen, and soil nitrate nitrogen loss under various intensity rainfall settings, it can be shown that an increase in average rainfall intensity and increasing rainfall causes a progressive increase in soil nitrogen loss. Moreover, the consequences of soil nutrient loss varied considerably depending on the slope and tillage pattern (Li *et al.,* 2023b).

Surface soil contains dissolved nitrogen (N), which is readily carried in runoff when rainfall starts, resulting in relatively higher nitrogen concentrations in surface runoff. Consequently, when rainfall intensity increases, nitrogen loss in surface runoff increases continuously (Li *et al.*, 2023c). Continuous rainfall primarily releases and dissolves soil-soluble nitrogen (N), a very stable process that contributes to N in surface runoff. Consequently, surface runoff's N loss tends to stabilize. Because of the comparatively slow nature of this process, stabilization time is longer under light rain (Wang *et al.*, 2024). Slope has an impact on soil loss, particularly erosion, and the amount of water retained in the soil. N is transported by both soil and water. Thus, slope influences N loss, which in turn influences how plant control affects N loss in slope farms (Haidri *et al.*, 2024). The land with the 10° slope had the highest loss of total nitrogen, nitrate nitrogen, and ammonium nitrogen (10° > 15° > 5°) (Wang *et al.*, 2023). This could be because the area covered by rainfall shrinks at higher gradients, and the resulting quick runoff makes it harder for raindrops to erode the soil, which lowers the amount of N lost in surface runoff.

3.3: Changes in precipitation pattern and losses of N in agriculture

Changes in precipitation pattern and intensity are likely to increase N losses by condensing them into less, larger pluses or what have been called hot moments for nitrogen (Bowles *et al.*, 2018). Denitrification and nitrate leaching may be accelerated by much more frequent substantial precipitation actions in early summer and spring (Chen *et al.*, 2016). Additionally, less however but additional extreme rain occurrences would have complex and interconnected impacts on soil, plant, and microbial processes that control nitrogen losses. The soil N cycle is directly impacted by precipitation through changes in soil water availability and leaching, and it is indirectly impacted by precipitation through changes in plant productivity and N intake (Lv *et al.*, 2023). Although soil moisture modifies the N mineralization process, which impacts soil inorganic N availability, it is unclear how soil N transformation in a semiarid ecosystem responds to changing precipitation regimes.

Low soil moisture has various impacts on plants and microorganisms causing during dry periods, inorganic nitrogen will build up in the soil and then be released during rainy seasons (Harding and Snyder, 2014). If this accumulation is followed by heavy rains that result in major nitrogen losses through denitrification and leaching, aerobic bacteria and plants will be unable to out-compete denitrifying microorganisms and physical processes that transport nitrogen away (Butterbach-Bahl and Dannenmann, 2011). Soil moisture, growth of plants, and evapotranspiration impacts on agricultural nitrogen losses are influenced by interactions among several overall alterations drivers like warming, modified patterns of precipitation, and better CO_2 concentrations in the atmosphere (Lv *et al.*, 2023). Heat and drought, especially combined, will have a greater negative effect on agricultural production than either event alone (Jin *et al.*, 2017) increasing the potential of N losses. Stomatal conductance is also decreased as CO_2 levels rise.

3.4: Rise in temperature

Temperature changes can also affect mechanisms related to N loss in runoff. Increased temperature has caused greater nitrogen losses to drainage due to improved mineralization of organic material (Peltonen-Sainio *et al.*, 2009) winter mineralization rates and high autumn, alongside decreased high percolation and uptake of the crop, would rise the risks of nitrate leaching. Additionally, changes in the dissolved oxygen concentration brought about by greater soil water content may have an impact on nitrification and nitrogen mineralization (Hutchins *et al.*, 2020). Temperature influences nitrogen conversion, which in turn controls the pace of chemical reactions as well as microbial and biological activity (Li *et al.*, 2019). The rates of nitrogen mineralization and nitrification rise with temperature, and plants absorb more inorganic nitrogen, producing more complicated results. According to studies that more precipitation even throughout winter and autumn months enhances nitrogen leaching and rates of percolation (Wang *et al.*, 2015).

Due to the huge variation of its sources, the mechanism of ammonia volatilization from the rice ecosystem is intricate (Zhou *et al.*, 2016a). Major local differences in ammonia emissions are however, based on regional heterogeneities in basic surface conditions (such as soil types), climatic conditions (relative air humidity, temperature, and wind speed), and agricultural management techniques (type of fertilizer, application rate and timing of fertilizer) (Lian *et al.*, 2021). In the last five decades, the most significant environmental variable for ammonia volatilization is temperature which has grown by 1.2 ^{0}C (Piao *et al.*, 2010). Therefore, calculating the loss of ammonia volatilization is essential in the context of global warming (Soares *et al.*, 2012).

4: Forms and Available Sources of Nitrogen

The competence of nitrogen usage is significantly effected by the transformation of nitrogen into other forms. Nitrogen in the NO_3 form is crucial in the early stages of growth, but it is not frequently utilized as fertilizer on its own; instead, the other forms enter the atmosphere through nitrification shown in Fig 2. Nevertheless, urea, the most used nitrogen fertilizer, is quickly nitrified after being converted to ammonium (Anas *et al.*, 2020a). Even though urea can turn into nitrate and ammonium after being applied to soil, little is known about how urea is absorbed by plants and how this affects their metabolism. Due to its higher nitrogen content and low production costs in South Africa, urea is likewise a preferred and main source of nitrogen (Anas *et al.*, 2020a). Under low N conditions, plants can store surplus NO3-nitrogen in unassimilated pools, such as the vacuoles of leaves, and use it when needed. According to (Hajari *et al.*, 2015), dry roots had more NO3--N per gram than shoots across all growing media. (Hajari *et al.*,

2015) asserted that the sugarcane plant's inability to effectively transfer nitrate nitrogen from root to shoot results in reduced transport and absorption of nitrogen instead of assimilation, which could impact the nutrient use efficiency in sugarcane.

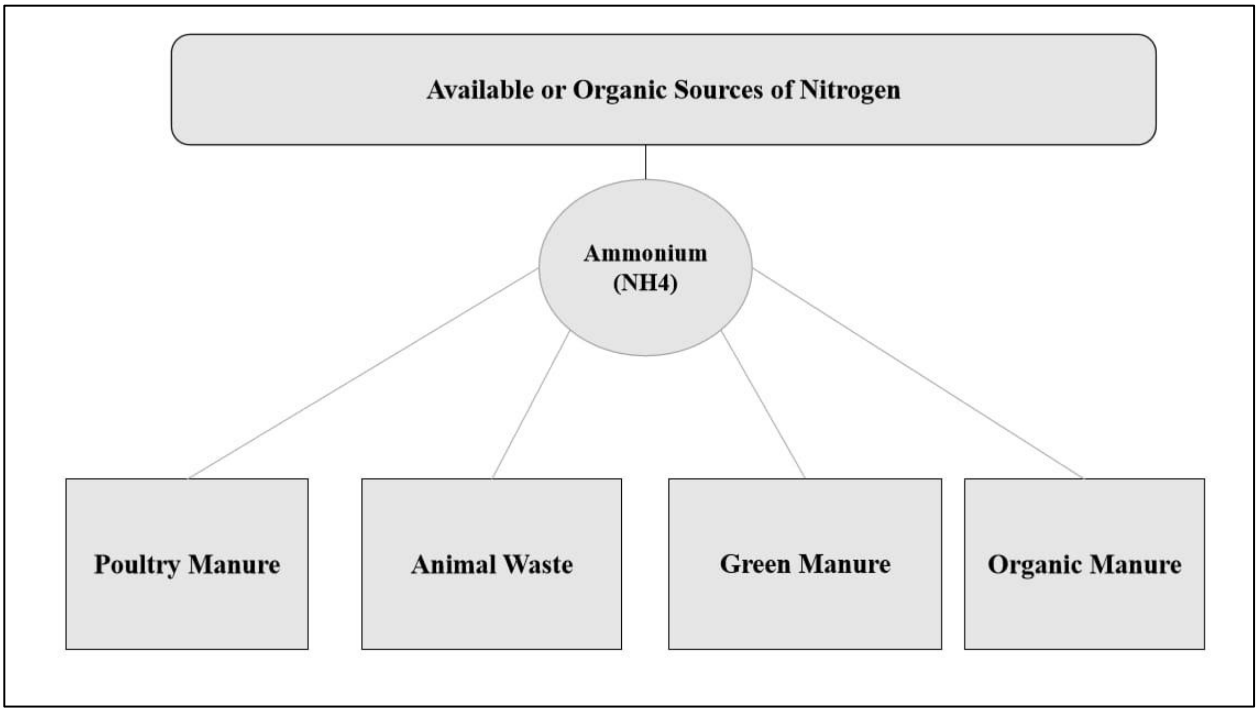

Figure 2: Available and organic sources of nitrogen

4.1 Forms of Nitrogen losses

The process of removing nitrogen compounds from soil or water is known as "nitrogen loss," and it frequently results in lower fertility or environmental issues. These are some common forms of nitrogen loss.

4.1.1: Ammonia volatilization

Ammonia volatilization is one of the main problems of nitrogen loss from arable crops around the world. The rate of NH_3 volatilization from the soil is influenced by many soil conditions shown in Table 1 (Mahmud *et al.*, 2021). However, soils with a higher pH are now more liable to lose substantial quantities of ammonia, NH_3 can be removed in neutral or acid soils, particularly considering the application of fertilizers like urea or organic fertilizers like urine (Waseem *et al.*, 2023). Furthermore, low soil moisture promotes high soil solution concentrations, leading to increased NH_3 loss (Cameron *et al.*, 2013; Mundepi *et al.*, 2019).

When applied to the soil throughout various stages of crop growth, NH_4^+-containing fertilizers like urea (CH_4N_2O), ammonium sulphate (NH_4SO_4) and ammonium nitrate (NH_4NO_3) are typically susceptible to rapid NH_3 volatilization. Due to its ability to react with acidic environmental components, volatilization poses a major risk to both human health and the environment like nitrate (NO_3), sulphate (SO_4^{-2}) form a toxic inorganic aerosol. Additionally, ammonia emissions contribute considerably to acid rain precipitation in the atmosphere, could be an secondary source of nitrous oxide emission, and facilitate eutrophication of surface water bodies (Carlson *et al.*, 2019). The economic consequences of NH_3 emissions are specifically severe in many countries, where recent simulations research revealed that approximately a third of applied nitrogen fertilizers or manure is lost to the atmosphere as ammonia (Mahmud *et al.*, 2021).

4.1.2: Nitrate leaching

Leaching is the major source of nitrogen loss from field soils that are not accounted for. The loss is essentially all in form of nitrate because movement is strongly linked to those of water shown in Table 1 (Islam *et al.*, 2014). The amount of leaching loss varied from nutrient to nutrient and from soil to soil. In general, nitrogen fertilizers are water soluble and a large amount is lost by leaching. Even though water moves NO_3 down through the soil profile much of the nitrate in well-drained sandy soils can be lost through leaching (Camberato *et al.*, 2008; Mahmud *et al.*, 2021). Nitrogen was lost by leaching during the ammoniacal form in a decreased soil zone. Nitrate leaching is one of the most substantial variables that affect groundwater quality. Natural (pedology, climate) and manmade (cultivation) influences both have an impact on it (Martinez-Feria *et al.*, 2019).

Nitrate is one of the main nutrients that is washed out from the soil profile. Below the root zone distribution, the amount of irrigation and rain affects nitrate loss in the soil profile (Olesen *et al.,* 2019). The structure and texture of the soil can also impact nitrate levels (Teixeira *et al.,* 2021). Clay soil has to have the slowest structure and is the slowest to decompose Moreover, plant movement and soil macro fauna. Rapid nitrate uptake in the soil is usually facilitated by vegetative growth. The amount of surface and ground water quality has declined as a result of nitrate leaching, causing in algal bloom and eutrophication (Mahmud *et al.,* 2021).

The intensification of biogeochemical processes in the soil is caused by a rise in temperature associated with climate change (Dirnböck *et al.,* 2016). As a consequence, the microbial nitrogen cycle is enhanced, potentially leading to increased nitrogen availability due to excessive nitrogen may be leached down with water. Groundwater replenishment is affected by seasonal changes in precipitation**.** This is related to nitrate leaching (Reichenau *et al.,* 2016). Humans have a tremendous effect on the nitrogen balance as a result of their land use and agriculture techniques (e.g. fertilization). Additionally, crop management factors like fertilizer quantities and sowing, harvest, and fertilization dates have an impact on the soil nitrogen budget (Mahmud *et al.,* 2021; Stuart *et al.,* 2011)

4.1.3: Nitrous oxide emission

N_2O has a much lower concentration in the atmosphere than carbon dioxide, however, it is still a significant GHG because climate change is around 300 times that of CO_2 shown in Table 1 (Del Grosso *et al.,* 2008; Sarabia *et al.,* 2020). Almost two-thirds of N_2O emissions are formed through soil processes such as nitrification and denitrification. Reactive nitrogen released into the plant-soil system has improved considerably with the increased usage of nitrogen fertilizers and nitrogen-fixing crops (Mohanty *et al.,* 2020). Anthropogenic climate change could influence carbon and nitrogen cycle amounts in non-managed systems, producing reinforcing (positive) or reducing (negative) feedback (Smith *et al.,* 2012).

Considerable quantities of carbon and nitrogen are cycled between terrestrial systems and the atmosphere and even little changes in cycling amounts can result in significant changes in the atmospheric pool of CH_4, CO_2, and NO_2 are the main long-lived biogenic GHGs (Mohanty *et al.,* 2020). Furthermore, as both input and output amounts are altered, estimating the net effect of global warming on GHG flow rates is problematic. Climate change can affect the amount of nitrogen in the soil by influencing nitrogen cycle rates as well as plant nitrogen requirements by affecting growth rates in the example of N_2O (Mohanty *et al.,* 2020; Reay *et al.,* 2012).

In analyzing anthropogenic emissions from different sources such as nitrous oxide emissions, indirect emissions should be considered (Kanter *et al.,* 2016). The indirect emission of nitrogen is that which left the pasture or farm in a form other than N_2O and was altered into N_2O offsite. Those emissions are most often considered agricultural emissions. As a consequence, differentiating the excess N_2O from no-managed systems from improved nitrogen deposition which is previously counted as agricultural N_2O is favorable (Shrestha and Wang, 2018).

4.1.4: Denitrification losses

Denitrification happens when there is enough nitrate nitrogen in the soil but not adequate oxygen to fulfill the demand of microorganisms and bacteria. Microorganisms strip oxygen from nitrate while oxygen levels are low, generating nitrogen gas or nitrous oxide which volatilizes from the soil (Li *et al.,* 2022). Wet soils, compaction, and warm temperatures all lead to a favorable environment for denitrification. Denitrification is the primary loss mechanism in fine-textured soils with little or no artificial drainage or in low sections of the field where water tends to accumulate (Wang *et al.,* 2018).

Denitrification happens 24 to 48 hours after saturation conditions have already been established (Li *et al.,* 2022; Pinay *et al.,* 2007). Although the microorganisms that reduce nitrate to gaseous forms that are lost to the atmosphere operate in oxygen-depleted soils, this is the situation. When soil temperatures are warm (over 65°F), an estimated 4-5% of N in the nitrate form is lost for each day that soils are saturated (Wang *et al.,* 2018).

Table 1: Main sources, amounts, and pathways of reactive nitrogen emission (Mahmud *et al.,* 2021)

Reactive Nitrogen	Amount (Tg)	Source	Pathway
Ammonia (NH_3)	45	Agriculture	Volatilized
NO_x	35	Transportation and emission	Gaseous emission
Nitrate	161	Agriculture and Industries	Leaching and surface runoff
Nitrous Oxide (N_2O)	6.2	Agriculture	Gaseous emission
Potential nitrogen emissions to water, primarily as NO_3^-	28	Consumer	Mainly Sewage

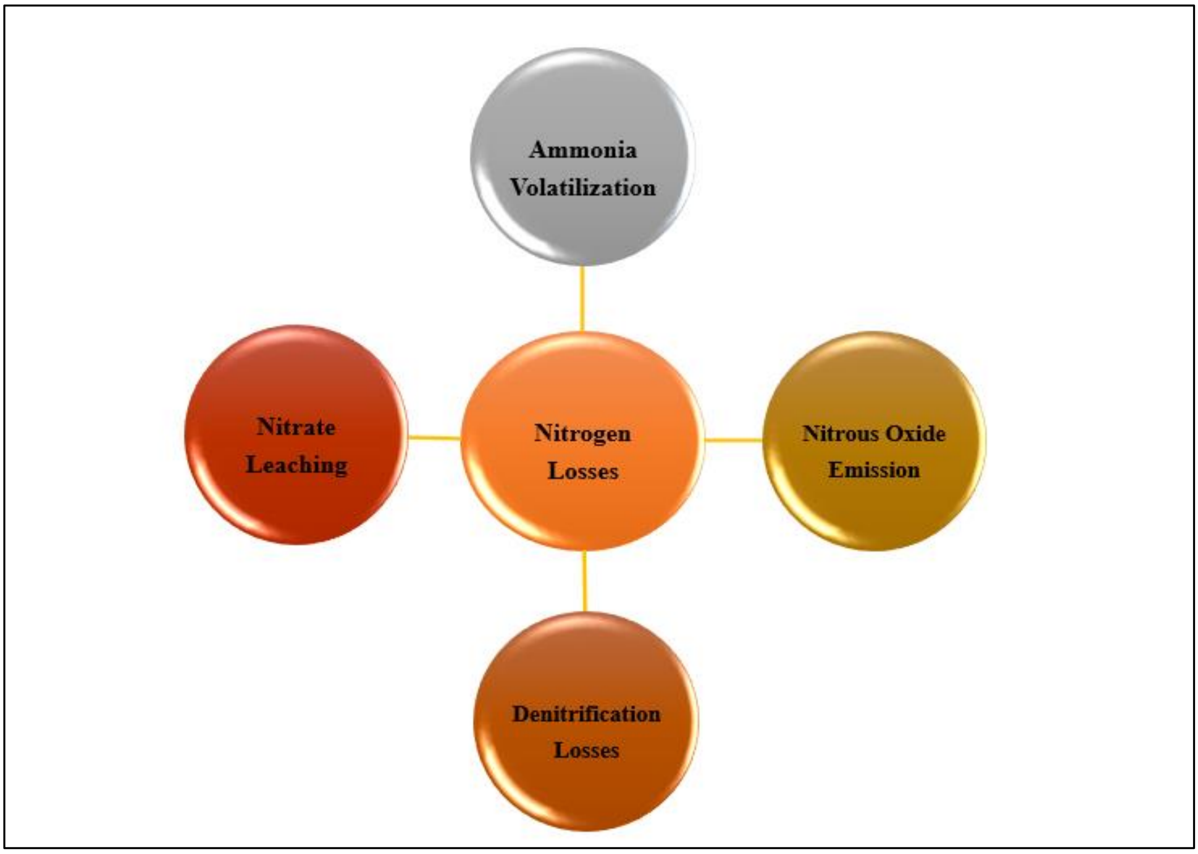

Figure 3: Forms of Nitrogen Losses

5: Factors affecting losses of nitrogen

5.1 Soil texture:

Soil texture plays a significant part in determining diversity in N loss through volatilization, with sandy soils having higher losses. This was most likely owing to the decreased cation exchange capacity of sandy soils as previously stated (Tao *et al.*, 2018). The applied fertilizer was more likely to dissolve in wet soils than in dry ones, but when the soil dries out, dissolved ammonia gas concentrates in the residual soil water solution, raising the possibility of loss (Schwenke, 2014). Approximately half of nitrogen fertilizer widely used in agriculture is lost to the ecosystem as a consequence of volatilization, run-off, or leaching (Billen *et al.*, 2013). These losses result in environmental issues like soil acidification, greenhouse gas emissions, biodiversity loss, and water pollution.

5.2: Excessive inputs

Approximately 40% of the total nitrogen intake is used by GVP, where excessive nitrogen fertilizer application is particularly prevalent. Losses of nitrogen are becoming more severe as a result of its excessive nitrogen input (Sun *et al.*, 2019). In comparison to other locations, in northern China, the nitrate content of groundwater near vegetable greenhouses is substantially greater (Zhou *et al.*, 2016b). Even though it makes only a modest portion of greenhouse gases, nitrous oxide is a significant component. The use of nitrogen fertilizer in agriculture ultimately boosts agricultural products above reproach, or, to put that another way, agricultural products have grown considerably higher demand in recent years (Zhao *et al.*, 2019).

Excessive nitrogen in the environment is a worldwide problem that requires global attention. Excess nitrogen is ingested into the environment in the form of N_2O, NH_3, and NO_3 (Bashir *et al.*, 2013). The discharge of this waste into the soils, aquatic systems, and air causes a barrage of problems, along with eutrophication of surface and ground waters, soil acidification, air quality degradation, and the acceleration of global warming, all of which are detrimental to the environment and human health (Cameron *et al.*, 2013). Numerous early research have focused on the connection between nitrogen losses and nitrogen application rate (Liu *et al.*, 2017). Further data, however, indicated that the connection between nitrogen input and losses is nonlinear. Numerous earlier investigations have demonstrated that the environment does not react smoothly to a single, steady change (Zhao *et al.*, 2019).

5.3: Excessive Irrigation

Although fertilization and irrigation are intimately connected, excessive fertilization combined with high irrigation greatly increases the loss of nutrients. When growing rice, nitrogen fertilizers are essential. However, crops can only consume 30%–40% of nitrogen fertilizers due to over-irrigation, which might result in low fertilizer usage efficiency (Zhang *et al.*, 2017). Ammonia volatilization, denitrification, runoff, and leaching all contribute to the environmental loss of around half of the nitrogen that is applied. Numerous significant environmental issues have been brought on by this circumstance, including air pollution, water eutrophication, groundwater contamination, and soil acidification (Cheng *et al.,* 2021). Farmland irrigation water control can save water and increase the quality of crops and output since crops have varying water needs throughout their growth periods (Ullah *et al.,* 2024). The yield of grains, nitrogen use efficiency, and nitrous oxide gas emissions from water regimes and fertilizers have all been examined in the growing body of research on water-saving irrigation strategies (Islam *et al.,* 2018).

Excessive irrigation and fertilizer cause the root zone to lose a significant level of nitrogen (Song *et al.,* 2009). Drip irrigation mixed with improved fertilization allows for effective control of irrigation and fertilization duration and amount. This substantially actually reduces irrigation and fertilizer use (Tanaskovik *et al.,* 2011). Excessive use of N in soils beyond plant absorption and sustainability consequences in higher nitrate rates in ground water due to leaching. Furthermore, nitrogen loss to surface water can be caused by direct runoff, intrusion through the root zone, and discharge to surface water through a tile drainage system or seepage (Bashir *et al.,* 2013). In the first scenario, the majority of the nitrogen is in the form of ammonium, and nitrogen loss is exacerbated by decreased steeper topography, soil infiltration capacity as a result of fertilizer and manure application as well as limited fluvial zone (Baram *et al.,* 2016).

5.4: Tillage and conservation practices:

Nitrogen leaching, which is the primary source of nitrate addition in ground water is influenced by tillage, irrigation, and soil structure. These two systems, which are influenced by agronomic management approaches, particularly tillage, influence the quantity of nitrogen lost from agricultural systems and, as a consequence, the intensity of pollution from non-point sources in agriculture shown in Fig 4. Since tillage affects soil structure (Bowles *et al.,* 2018), soil moisture migration, affects soil aggregate turnover, tillage practices affect nitrogen losses in agriculture output, and non-point source pollution (Alliaume *et al.,* 2014). Even though the amount of force depends on the type of tillage practice used, tillage is thought to be a primary factor underlying agricultural nitrogen losses and non-point source pollution.

Conservation tillage is a broad concept that covers mulch till systems, strip-till, ridge-till, minimum till, and no-till, etc. On the other hand, the implications of these conservation tillage techniques on nitrogen losses in agriculture have been infrequently seen. (Zhang *et al.,* 2020) So far, conflicting research has limited our efforts to properly comprehend the influence of conservation tillage on subsurface and surface nitrogen losses in agriculture. Subsurface nitrogen losses may be more susceptible to tillage practices than surface nitrogen losses according to conservation tillage theory (Blanco-Canqui *et al.,* 2015).

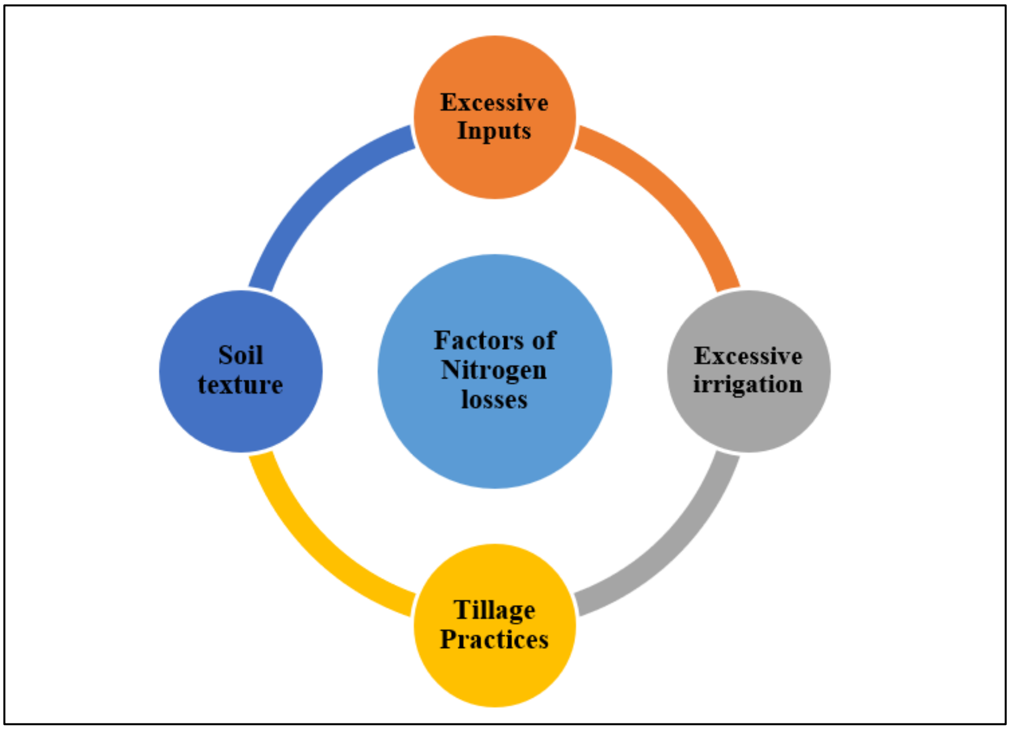

Figure 4: Different factors affecting losses of nitrogen

6: Mitigating strategies for minimizing nitrogen losses

Only nitrogen fertilizer is mentioned in the utmost generally recommended best management solutions for decreasing nitrogen losses. They hope to increase the synchronization between nitrogen fertilizer supply and plant nitrogen demand by using machine learning. Nitrogen fertilizer at the correct rate, at the correct time, in the correct form, and at the correct location (also known as "4Rs") (Cassman *et al.,* 2002). By enhancing nitrogen utilization efficiency, the assumption is that nitrogen losses are minimized at the same time. Rate and timing are the two most essential of these strategies, but they should be based on reasonable yield estimates, nitrogen mineralization, precision application, and soil nitrogen analysis (Rodriguez *et al.*, 2019)

6.1: Management of nitrogen fertilizer

Strategies for managing nitrogen to improve agricultural resistance to future global warming and crop productivity. Climate change and nitrogen management are intimately linked since nitrogen is involved in many environmental processes. In agricultural crop production systems, it is frequently a limiting component and a necessary nutrient for plant growth(Chatterjee *et al.,* 2023). Synthetic nitrogen fertilizers are frequently used by farmers to fulfill the increasing demand, which raises the extent of reactive nitrogen in the environment. This may result in several environmental problems (Pathak *et al.,* 2019). Nitrogen cycles are impacted by climate change itself. Agriculture continues to be the most important task in sustaining our world's expanding population as we face the harsh effects of global climate change. When nitrogen fertilizers are applied improperly, reactive forms of nitrogen such as NH_3, NO_3, N_20 are lost (Chatterjee *et al.,* 2018).

The crop management strategies that increase the efficiency of nitrogen usage and diminish reactive nitrogen loss may be the primary source of climate change resilience. According to (Pathak *et al.*, 2019), for example, nitrification inhibitors can reduce N2O emissions by 10–42%. Likewise, compared to manual settlement and prilled urea broadcasting, deep placement of urea briquettes decreased N2O emission by 6–13% (Chatterjee *et al.,* 2018) Effective nitrogen management enhances agro-ecosystem performance and, over time, increases climate change resilience. The overall amount of nitrogen in manure is greater than the amount of nitrogen available to the crop in manure. As a result, more total manure N must be applied to obtain the same results as utilizing fertilizer to fulfill the same net crop demand (Ata-Ul-Karim *et al.,* 2014). Manure N availability, however, improves with the appropriate application of manure management.

Variable-rate N application, which is based on crop growth state and its interpretation for varying N rate application the standard whole-field uniform-application-rate technique, has the potential to increase crop yields while minimizing nitrogen environmental losses (Cui *et al.,* 2010). Wang *et al.,* (2016) studied that optimum fertilizer nitrogen rates, enhanced application and placement timings, and method, particularly formulated forms of fertilization, including urease inhibitors and nitrification, organic manure, organic residues, and integrated use of mineral fertilizers to achieve more synchronization between crop requirements and nitrogen supply particularly in the case of cereals are some of these. These strategies are thought to improve the quality of soil as well as crop productivity sustainably. This type of management strategy might improve soil quality by boosting soil biological health and decreasing soil and environmental pollution if nitrogen fertilizer could be saved without lowering productivity (Zebarth *et al.,* 2009).

6.2: Use of organic amendments

Organic manure promotes soil fertility by increasing organic carbon in the soil, soil physical properties, and nutrient availability. As a result, the benefits of organic amendments are largely determined by the type of organic fertilizer used and the quantity at which it is applied (Jones and Healey, 2010). Organic manure is typically made up of farmyard manure and vermicomposting generated from biomass waste. It acts as a habitat for the beneficial microorganisms intricate in nitrogen retention (Prasad *et al.,* 2018) as well as a soil improver for keeping nitrogen and supplying carbon sources (Yu *et al.,* 2018b). The absorption and retention of nitrate nitrogen, ammonium nitrogen, and phosphate by the biochar amendment minimizes phosphorus and nitrogen losses in soil (Thangarajan *et al.,* 2018). It keeps the energy flowing for soil fertility, which serves to maintain C in the soil and reduces greenhouse gas emissions (CH_4 and N_2O).

Synthetic fertilizers, however, play a vital part in enhancing agricultural productivity and are extensively used. Furthermore, the production and usage of these fertilizers have major environmental consequences, such as GHG emission, eutrophication, and the use of limited resources like phosphate rocks and fossil fuels. (Liu *et al.,* 2021) Fertilizers based on nitrogen fed nearly 48% of the worldwide people. On the other hand, the loss of nitrogen applied to agricultural land adds greatly to global nitrogen pollution (De Notaris *et al.,* 2018). Soil denitrification releases a significant amount of N_2O and NH_3 into the atmosphere (Khalil *et al.,* 2009). The mineralization of nitrogen results in the development of highly water-soluble nitrate nitrogen which is available to plants. It can simply flow below the root zone, polluting groundwater and risking human health.

6.3: Soil Health Improvement

Healthy soil and the ability to produce high yields with minimal external nutrient inputs can be the results of a sustainable agricultural production system that combines ecosystem processes and fertilizer application (Pangaribuan and Hendarto, 2018). The use of optimal amounts of all nutrients is essential, but also because of the basic connection of the nitrogen and carbon cycles nitrogen fertilizer management cycle is further closely linked with the formation of soil health and soil organic carbon (Poffenbarger *et al.,* 2017). When nitrogen inputs are below the optimum rate for high productivity, applied nitrogen enhances agricultural growth and increases crop residue inputs to the soil enhancing soil organic carbon.

Furthermore, when fertilizer nitrogen inputs reach the optimum level, extra nitrogen does not affect crop residue output but enhances residual inorganic nitrogen, boosting soil organic carbon mineralization and diminishing microbial nitrogen limitation one critical strategy to enhance nitrogen use efficiency is to synchronize nitrogen N transfer from fertilizers and soils with nitrogen uptake by plants. When nitrogen application is not matched with crop demand, nitrogen losses from the soil-plant system are more causing low nitrogen fertilizer use efficiency (Ozlu *et al.,* 2019). The requirement to synchronize nitrogen fertilizer supply to crop needs in space and time to optimum performance is well understood (Khan *et al.,* 2008). Some effective nitrogen management policies have been established to enhance fertilizer nitrogen use efficiency in crops, mainly cereals.

6.4: Irrigation water management

To establish sustainable irrigation, both economically and environmentally, society will need to enhance agricultural output, change infrastructure, change water laws, boost the efficiency and on-farm systems, increase management of degraded soils, improve water reuse, improve agricultural water management, and identify increasing power prices (De Oliveira *et al.,* 2009). As a consequence, better water management in irrigated agriculture is required to enhance crop yield even while maintaining water and soil quality. Irrigation management should emphasize the development of practices to improve water use efficiency so that other divisions can obtain extra water for economic purposes (Molden and de Fraiture, 2010).

Natural precipitation's contribution to the whole quantity of water mandatory for irrigation varies by climate. Crop growth and output are difficult in arid regions (precipitation 200 mm yr^{-1}) without irrigation (Schaible and Aillery, 2006). The continuous shortage of fresh water in semiarid and arid regions has promoted the implementation of water-saving methods that do not decrease crop yields. Deficit irrigation is currently being investigated widely as an agronomic practice within this concept (Fereres and Soriano, 2007). Deficit irrigation may also be beneficial to enhance water efficiency for different yields without producing significant return losses, according to a few findings (Yang *et al.,* 2015b).

Deficit irrigation is an irrigation approach that is used during the drought-sensitive stages of crop growth. Outside of these seasons, when rainfall provides enough water, irrigation is limited or perhaps unneeded (Geerts and Raes, 2009). To achieve good yields with deficit irrigation water limitation should be limited to drought tolerant agronomic phase, such as late ripening period and vegetative stages (Chai *et al.,* 2016). Although drought tolerance differs greatly by genotype and phonological stage, Deficit Irrigation requires a detailed understanding of crop response to drought stress for each of the growth stages. Any reduction in production is expected to be modest when associated with the benefits of redirecting the diverted water to irrigate other crops. The grower will need a prior understanding of crop output reactions to deficit irrigation.

6.5: Combined application of organic and inorganic fertilizer

The environmental impacts of nitrogen losses from agricultural soils will vary depending on the underlying affecting variables like climate and soil, livestock density as well as socioeconomics and governance structures that manage N inputs at the farm scale (including farm geographical distribution) (Chadwick *et al.,* 2011). Consequently, nitrogen losses from runoff and leaching will have a catchment, local, and potentially regional effect on water quality, depending on the flow channel, nitrogen transformation, and reduction activities along this pathway shown in Fig 5. A full understanding of source receptor matrices, as well as appropriate time and geographical distributions, is necessary for these reactive N species (Yang *et al.,* 2015a).

In other parts of the world, inadequate fertilization and excess nitrogen fertilizer have resulted in substantial nitrogen losses due to ammonia volatilization and leaching (Peng *et al.,* 2011). As a consequence, nitrogen utilization efficiencies are as low as 35% (Cao *et al.,* 2013). Among the most difficult aspects of field management is decreasing the number of nitrogen fertilizers applied in the field while minimizing soil nitrogen deficit Mugwe *et al.,* (2009) determined that the use of organic matter, like manures, may only mitigate short-term losses of soil organic matter.

When used alone, organic manures may have a restricted nutrient content, making them uncertain to meet the needs of high-yielding rice cultivars. The combined application of organic and inorganic fertilizers enhances nutrient availability and decreases losses by changing inorganic nitrogen to organic forms (Mahmud *et al.,* 2016), resulting in prolonged yield. Farmyard manure, as established by (Zadeh, 2014), not only provides a source of nitrogen and other nutrients but also enhances the effectiveness of applied nitrogen. Cow dung is high in nitrogen and potassium, as well as fiber elements that serve to maintain soil temperature and moisture, as well as inhibit weed growth on soil surfaces (Ojobor *et al*., 2014).

Figure 5: Mitigating strategies for minimizing nitrogen losses

CONCLUSION AND FUTURE PERSPECTIVES

Climate change and excessive nitrogen inputs are the main causes of agricultural nitrogen losses, which present serious problems for the quality of soil, water, and the ecosystem. Nitrogen losses through leaching, runoff, volatilization, and denitrification are made worse by increasing temperatures and changing precipitation patterns, affecting biodiversity, water quality, and atmospheric equilibrium. Effective mitigation techniques are necessary to protect ecosystem health and guarantee sustainable agricultural yield given the ecological and economic consequences. Nitrogen losses through agriculture soils are mainly driven by anthropogenic sources and due to climate change agricultural management strategies such as conventional tillage, excessive use of chemical fertilizers, fungicides, and runoff conditions, lead to nutrient losses from agricultural fields to the environment. Due to climate change rises in temperature favor the vigorous change in the biogeochemical processes in the soil which results in increased nitrogen mineralization, as well as increased precipitation, which is likely to lead to higher runoff and losses of nitrogen. Losses of nitrogen occur in different forms such as nitrate leaching, ammonia volatilization nitrous oxide emission, etc. Soils with a high pH, on the other hand, are now more likely to lose considerable amounts of NH_3, while NH_3 can be removed in neutral or acid soils, specifically where fertilizers like urea are also used. Low soil moisture also stimulates high soil solution concentrations, therefore resulting in increased NH_3 losses. Wind speed, air relative humidity, temperature, as well as humidity, temperature, nitrification potential, cation exchange capacity, pH, nitrogen concentration in solution, and amount of organic matter can all effect nitrogen loss by ammonia volatilization. Several climatic factors, like temperature, wind speed, air relative humidity, and rainfall, as well as soil properties, such as humidity, temperature, cation exchange capacity, amount of organic matter, nitrification potential, pH, and nitrogen concentration in soil solution, may influence nitrogen loss by ammonia volatilization. Due to increased temperature higher rate of net nitrogen mineralization results in rapid microbial nitrogen turnover and, as a consequence, a potentially higher nitrogen availability. The loss of NO_3 from the soil beneath the root zone is influenced by the amount and distribution of rainfall and irrigation. Soil acidification, eutrophication of aquatic environments, and perturbations in nutrient-poor ecosystems are all related to ammonia volatilization and subsequent deposition. Appropriate fertilization management (modifying fertilization times) can compensate for the effects of climate change in terms of water protection. Cover cropping could also be used as adaptive management to preserve crops and reduce nitrogen losses as the climate change and mitigation potential are comparable to other practices such as no-till. We suggested a study of agricultural management strategies for runoff and nutrient losses, the use of organic amendments, improved soil health, irrigation water management, and comparative application of organic and inorganic fertilizers to regulate the influence of climate change on nutrient losses and demand for mitigation. Use of organic amendment to minimize nitrate leaching and ammonia volatilization losses in soil. A combination of agronomic and molecular techniques can increase nitrogen use efficiency. Precision agriculture, reducing nitrogen doses, intercropping legume and no-legume crops, introducing nitrogen-efficient genotypes, and enhancing plants can all help decrease nitrogen losses.

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