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Factors Affecting Nitrogen Use Efficiency (NUE): Meta Analysis

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Abstract: Nitrogen (N) is an essential and limiting nutrient for crop production, as it is a structural part of plants and is involved in various processes. Worldwide, agricultural soils lack one or more essential nutrients, and nitrogen is one of them. Adding a sufficient amount of N will increase production. However, the overuse of N and loss of N from the soil-plant system is detrimental to the environment and results in economic losses. Nitrogen has reactive forms like ammonia, ammonium, nitrate, nitrite, nitric oxide, and nitrous oxide. Some reactive forms of N are harmful to humans, animals, plants, and microbial ecology. Nitrate can cause the eutrophication of surface water and contamination of groundwater. Drinking nitrate-contaminated water can cause methemoglobinemia and other health issues. Nitrous oxide emission depletes the ozone layer and contributes to climate change. Ammonia emissions contribute to acid rain and are also responsible for nitrous oxide emissions. This review addresses different factors/pathways/circumstances that contribute to the loss of N from the soil-plant system and reduce nitrogen use efficiency (NUE). Different factors influence NUE like ammonia volatilization, nitrification, denitrification, immobilization, leaching, runoff, temperature, soil pH, soil texture, rainfall and irrigation, soil salinity, tillage, weeds, pests, diseases, N loss from plants, fires, crop rotation, crop nutrition, crop varieties, and nitrogen management (right time, right source, right place, and right rate/amount).

Keywords: Nitrogen, nitrogen use efficiency, pathways of nitrogen loss, nitrogen losses

1. Introduction

Nitrogen (N) is an essential macronutrient, essential for the existence of life on earth as it is an integral part of genetic material (nucleic acid including DNA and RNA), amino acids, chlorophyll, and proteins (Davis, 2007; Anas et al., 2020; Azimi et al., 2021), and involved in the photosynthesis, enzymes production, carbon (C) metabolism, and N metabolism (Anas et al., 2020; Ma et al., 2022). Nitrogen is a limiting nutrient (Rütting et al., 2018; Anas et al., 2020; Azimi et al., 2021) and essential for crop production (Thorburn et al., 2017). Nitrogen is present in the atmosphere in the dinitrogen (N_2) form in bulk, but it cannot be used by plants directly (Bell, 2014; Raza et al., 2018; Aziz et al., 2022); it needs to be in plants available forms like ammonium (NH_4^+) and nitrate (NO_3^-) (Jones et al., 2013; Bell, 2014). It has a few other reactive forms also, like nitrite (NO_2^-), ammonia (NH_3), nitrogen oxides (NO_x), and nitrous oxide (N_2O) (Jones et al., 2013; Walsh and Belmont, 2015; Aziz et al., 2022).

In recent decades, N fertilizer consumption in agriculture increased many times to fulfill the demand for food to feed the increasing world population (Shahzad et al., 2019). According to an estimate, the seven-fold increase in synthetic nitrogen fertilizer consumption in the past four decades doubled food production (Hirel et al., 2007). In 2002, worldwide, 84 million metric tons of N fertilizer were consumed (Raun and Schepers, 2008); for ten years (2000-2009), 60% of the global increase in N consumption was consumed only in China (Gao et al., 2012). According to Shahzad et al. (2019), Asia (mainly Pakistan, China, and India) is responsible for 67% of surplus N (difference between N input and output) against 54% of global N input.

By the end of 2050, the world population will touch nine billion; for this level of population, we have to prepare ourselves in advance to feed this number of people by increasing food production (Raun and Schepers, 2008; Walsh and Belmont, 2015). "World Agriculture: Towards 2015/2030," a direction from the Food and Agriculture Organization of the United Nations, made researchers think about food security, hunger, efficient use of nitrogen, and the impact of excess nitrogen on the environment (Eickhout et al., 2006).

To understand these gains and losses of N fertilizer further from the soil-plant system, we have to understand the term Nitrogen Use Efficiency (NUE). NUE is an indicator to keep an eye on better crop production without compromising environmental quality (Shahzad et al., 2019; Aziz et al., 2022). In simple words, NUE is the ratio of the amount of N harvested through the crop or taken up by the plant to the N inputs (Brauer and Shelp, 2010; Benincasa et al., 2011; Abdullah Faraj, 2013; Thorburn et al., 2017; An et al., 2018; Demir et al., 2021; Aziz et al., 2022). NUE comprises two components, uptake efficiency (NUpE) (the ability of plants to uptake nutrients or N) and use efficiency (NUtE) (ability of plants to use nutrients or N) (Hirel et al., 2007; Benincasa et al., 2011; Abdullah Faraj, 2013; Han et al., 2015a; Huang et al., 2017; Williams et al., 2021). Every medium that will affect the N uptake and N use will be a reason for the decline in NUE.

Excess N affects plants as well as the environment. NUE is crucial for getting a good yield without causing pollution, without losing product quality, and by reducing the cost of production (Rawal et al., 2022). For the sake of efficiency, we cannot ruin crop productivity and quality; balanced use is significant when talking about nutrients, especially N (Roberts, 2008; Koffi et al., 2016). Deficiency of N in plants causes the dwarfness, root and shoot length reduction, change in leaf color (chlorosis), reduction in the number of leaves and leaf area, reduced rate of photosynthesis and transpiration, and ultimately yield reduction (Argyropoulou et al., 2015; Azimi et al., 2021; Demir et al., 2021). On the other hand, excess N can increase the period of vegetative growth, reduce growth and development, reduce the sugar content, and attracts insects, pests, and diseases (Anas et al., 2020).

The release of reactive forms of N from the soil-plant system can cause environmental damage and can affect microbial ecology, plants, animals, and humans (Cameron et al., 2013). All the nitrogen applied cannot be taken up by the plants; plants uptake around 40% of the N applied, and the rest is either stored in the soil or lost to the environment. Higher the application of N fertilizer higher the risk of loss (Thorburn et al., 2017). Urea is being used as the source of N worldwide (Fageria, 2014) and is susceptible to losses (Jones et al., 2013; Tao et al., 2018). The nitrate (a reactive form of N) leaching can be the reason for surface water eutrophication and groundwater contamination, which pose serious health issues to underwater life and humans (Gao et al., 2012; Cameron et al., 2013; Hu et al., 2018). Moreover, ammonia volatilization causes acid rain and is an indirect source of nitrous oxide that will lead to ozone depletion and ultimately promote global warming and climate change (Davis, 2007; Cameron et al., 2013; Rütting et al., 2018). Drinking water with a high rate of nitrate can cause serious health issues like cancer, heart disease, and methemoglobinemia, especially in kids/infants; that is why it is also known as blue baby syndrome (Mahler et al., 1990; Knobeloch et al., 2000; Cameron et al., 2013).

This study aims to project light on all the factors that are responsible for the loss of N, lower NUE, and pose a threat to the environment and sustainability in agriculture.

2. Nitrogen Cycle

2.1. Ammonia volatilization

Ammonia volatilization is one of the N loss pathways more dominant than others. It is the gaseous loss of ammonia into the atmosphere. About 40% of applied N is lost because of ammonia volatilization (Raun and Schepers, 2008; Raza et al., 2022). Ammonia can cause eutrophication and acidification directly or indirectly (Cameron et al., 2013; Fageria, 2014; Walsh and Belmont, 2015). Worldwide, agriculture is the largest source of volatilized ammonia, having a share of 50% (Cameron et al., 2013); ammonia's emission was reported to increase by up to 90% between 1970 to 2005 (Raza et al., 2022).

When urea is applied in the presence of water, urea is hydrolyzed and produces ammonium carbonate, which further produces ammonium, ammonia, and hydroxide ions with the assistance of the urease enzyme (Equation 1) (Cameron et al., 2013; Fageria, 2014; Walsh and Belmont, 2015).

$$CO(NH_2)_2 + 2H_2O \rightarrow (NH_4^+)_2CO_3 \rightarrow NH_4^+ + NH_3\uparrow + CO^2 + OH^- \quad (1)$$

The increase of OH^- increases the pH around the reaction site/around the urea. This increase in pH or alkaline condition will increase the conversion of ammonium to ammonia (Equation 2), leading to ammonia volatilization (Abdullah Faraj, 2013; Cameron et al., 2013; Fageria, 2014).

$$NH_4^+ + OH^- \leftrightarrow NH_3 + H_2O \quad (2)$$

Ammonia volatilization depends on the ammonium concentration, pH, temperature, moisture content of the soil, and soil type/texture (Cameron et al., 2013; Fageria, 2014; Shen et al., 2022).

2.2. Nitrification

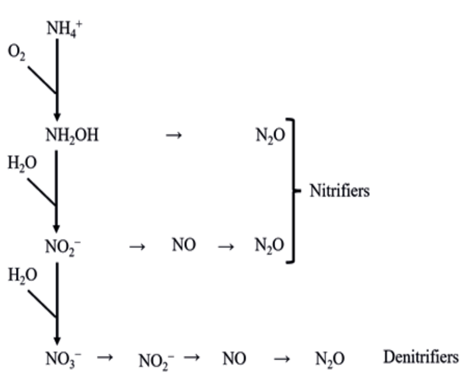
Nitrification is the conversion of ammonia to nitrite (Equation 3) and then to nitrate (Equation 4) that is available for the plant to uptake (Anonymous, 2002; Cameron et al., 2013; Han et al., 2015b).

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 2H_2O + 4H^+ + \text{energy} \quad (3)$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^- + \text{energy} \quad (4)$$

The conversion of ammonia to nitrite is assisted by *Nitrosomonas* and *Nitrosospira* bacteria. Moreover, nitrite to nitrate is assisted by *Nitrobacter*. Nitrification depends on ammonia concentration, pH, temperature, moisture content, oxygen availability (as bacteria are involved), and microbial population composition (Anonymous, 2002; Cameron et al., 2013). If the nitrification rate is higher in the early growth stage of the plant, plant cannot uptake all available nitrate, exchange sites in the soil cannot host nitrate, and in the end, nitrate will end up leaching (Cameron et al., 2013; Han et al., 2015b).

Interestingly, nitrification is responsible for the gaseous loss of N in the form of nitrous oxide (N_2O). *Nitrosomonas* and *Nitrosospira* can produce nitrous oxide from NH_4^+ and NH_2OH (Equation 5). "It is thought that the intermediate compound nitroxyl (HNO) may dismutate chemically under low O_2 concentrations to N_2O, or that the nitrate reductase enzyme may produce N_2O when O_2 concentrations are low and NO_2^- replaces O_2 as the terminal electron acceptor during metabolic processes" (Cameron et al., 2013).



(5)

2.3. Denitrification

Denitrification is the conversion of nitrate to nitrous oxide or dinitrogen with the help of denitrifying bacteria and the enzymes associated with them (Cameron et al., 2013; Fageria, 2014; Walsh and Belmont, 2015). Denitrification occurs in saturated soils where insufficient oxygen is available for the microbes for respiration. Instead of oxygen, microbes use nitrate as the electron acceptor, and in return, they produce nitric oxide, nitrous oxide, and dinitrogen (Equation 6) (Robertson, 1997; Cameron et al., 2013; Fageria, 2014; Walsh and Belmont, 2015).

$$2NO_3^- \text{ (nitrate)} \rightarrow 2NO_2^- \text{ (nitrite)} \rightarrow 2NO \text{ (nitric oxide)}$$

$$\rightarrow N_2O \text{ (nitrous oxide)} \rightarrow N_2 \text{ (dinitrogen)} \quad (6)$$

Different enzymes assist in this reduction like nitrate reductase is responsible for nitrate reduction, nitrite reductase is responsible for nitrite reduction, NO reductase is responsible for NO reduction, and N_2O reductase is responsible for nitrous oxide reduction (Cameron et al., 2013). Denitrification depends on pH, soil texture, temperature, microbial population, aeration, soil moisture content, and nitrate concentration (Cameron et al., 2013; Fageria, 2014; Ihara et al., 2014; Walsh and Belmont, 2015).

2.4. Immobilization

Inorganic N (nitrate, nitrite, and ammonium) is assimilated by the microorganisms, and temporarily that N is not available to plants (Equation 7) (Walsh and Belmont, 2015; Poffenbarger et al., 2018). Immobilization is only possible when the C:N ratio is higher than 35, and on the other hand, a low C:N ratio results in mineralization. C:N ratio of 20-30 is an equilibrium state between mineralization and immobilization (Brust, 2019).

$$NO_3^- \text{ or } NO_2^- \rightarrow NH_4^+ \rightarrow \text{Organic N} \quad (7)$$

After the death of microorganisms, decomposers assimilate and return N after decomposing dead microbes. During this process of death and decay, ammonia is released due to mineralization, and the rest of the N is released as a stable organic N that will be part of soil organic matter. The net effect of immobilization-mineralization is a decrease in N availability since the stable organic N is unavailable for the plant's uptake (Walsh and Belmont, 2015). It has been reported that in reduced tillage, where the microbial population is abundant immobilization rate is higher; because of this, most N will end up as an organic N. And to meet the crop demand, an increase in N input rates has been observed (Raun and Schepers, 2008).

3. Factors Affecting Nitrogen Use Efficiency

3.1. Environmental factors

3.1.1. Temperature

Temperature fluctuation not only affects the N cycle but also affects the plants. The temperature rise affects root growth, stresses the nutrients, and water uptake by the plants, and reduces crop production (Giri et al., 2017). An increase in temperature not only increases the urea hydrolysis rate but also increases the pH; the rise will boost the rate of ammonium conversion to ammonia; therefore, ammonia volatilization will occur. Warm soil water cannot hold much ammonia gas. As the temperature cools down, volatilization will not stop, but we can see a clear difference between the volatilization rate at low and high temperatures (Fagi and De Datta, 1981; Cameron et al., 2013; Jones et al., 2013; Fageria, 2014).

Temperature affects both nitrification and denitrification. With the increase in temperature, nitrification also increases, like denitrification (Cameron et al., 2013; Fageria, 2014). Stanford et al. (1975) reported that the temperature increase from 5 ºC to 10 ºC will increase the denitrification rate ten times. Similarly, De Klein and Van Logtestijn (1996) said denitrification would increase ten times with the temperature shift from 10 ºC to 20 ºC. Ihara et al. (2014) reported that the nitrification rate increases at high temperatures from 45 ºC to 50 ºC but only when the soil receives high temperatures for a more extended period, like seven days, compared to 1 day. Elevated temperature affects the microbial community that is involved in nitrification and denitrification. Microorganisms behave differently at high temperatures. Elevated temperature affects the microbial community by the soil drying (Fageria, 2014).

3.1.2. Rainfall and irrigation

Rainfall and irrigation affect nutrient leaching, runoff, and denitrification (Davis, 2007; Thorburn et al., 2017; Walsh and Belmont, 2015). When we apply irrigation or unwanted rainfall event that occurs after urea application increases the urea dissolution and hydrolysis rate, this will increase the ammonia concentration in the soil solution, making it susceptible to leaching, runoff, and volatilization. Volatilization loss can be reduced if ammonia leaches down within the root zone, as the surface concentration is reduced to be available for volatilization (Cameron et al., 2013). When the moisture content is low in the soil, the nitrification rate is high; when it is high, this will reduce nitrification (Davis, 2007; Abdullah Faraj, 2013; Fageria, 2014). Excessive rainfall and irrigation are the primary reasons for nitrate leaching and denitrification, and the leaching rate is high in high-rainfall areas (humid and subhumid areas) (Shumway et al., 2012; Fageria, 2014).

The direct impact of heavy rainfall can detach the soil particles, reduce aggregation, and be responsible for the transportation of sediments; in other words, heavy rainfall favors erosion. Eroded sediments move from one place to another (although they move a short distance) with the water, but they are not alone; they have the positively charged ammonium ions attached to the soil particles. If nitrate is also prey to runoff, the value of N losses increases compared to the eroded sediments with ammonium attached (Davis, 2007; Fageria, 2014; Meng et al., 2021).

Poor irrigation management is another reason for the lower NUE. Shortage of irrigation water at the critical stage of the crop and poor quality water also reduce NUE (Shahzad et al., 2019). Continuous use of brackish/poor-quality water can induce salinization in the soil, suppressing nutrient uptake and reducing the NUE (Balasubramanian et al., 2004). Optimized irrigation is also necessary to increase plant growth and improve N uptake, to prevent N losses through leaching and volatilization (Raun and Johnson, 1999; Cameron et al., 2013). It is also necessary for the sake of the environment, to reduce pollution due to N losses, and saving water.

3.1.3. Fires

Forest fires, prescribed fires, and crop residue burning affect soil's chemical, physical, biological, and mineralogical properties (DeBano, 1991; Robertson, 1997; Certini, 2005; Osman, 2008; Agbeshie et al., 2022). Annually, 800 to 1200 million tons of plant residues are disposed of by burning (Osman, 2008). Low-intensity fires are beneficial due to the deposition of nutrients into the soil and increase nutrient availability and pH (Certini, 2005; Agbeshie et al., 2022). However, low fire intensity also has disadvantages; it develops hydrophobicity in the soil because it soaks less water (Certini, 2005). Fonseca et al. (2017) reported that even in low-intensity fires, thirty-six months are not enough to cancel out the effects of fire; it will still affect the chemical properties of soil.

On the other hand, severe fires cause many irreversible changes like nutrients volatilization, increased bulk density, increased hydrophobicity, altered mineralization rate, erosion, leaching, and disturbing the above and below-ground life communities like soil-dwelling insects and microbial ecology (Certini, 2005; Osman, 2008; Agbeshie et al., 2022). The direct release of nutrients [like N, phosphorus (P), calcium (Ca), potassium (K), and magnesium (Mg)] to the atmosphere is temperature-dependent. Nitrogen volatilizes at a much lower temperature than other nutrients because of its low-temperature threshold of 200 ºC (DeBano, 1991; Osman, 2008). While other nutrients like phosphorous volatilize at >774 ºC, K at >760 ºC, Mg at >1107 ºC, sodium (Na) at >880 ºC, and Ca volatilize at >1240 ºC (Osman, 2008).

3.2. Managemental factors

3.2.1. Nitrogen management

When we talk about nitrogen management in crops and NUE, both includes the time of application, application rate, source of N, and method/place of application (Shumway et al., 2012; Tao et al., 2018; De Laporte et al., 2021).

When we talk about the time of application of N, we have to consider that we have to apply N close to the rapid growth stage of plant life when N uptake is maximum; otherwise, if we will apply N when uptake is minimum, this will increase the N losses (Fageria and Baligar, 2005; Walsh and Belmont, 2015). Instead of a one-time application split application of N fertilizer is recommended to reduce N losses (Fageria and Baligar, 2005; Jan et al., 2007; Raun and Schepers, 2008; Kubota et al., 2018; Demir et al., 2021). Application of N at the heading stage is more beneficial because it will improve N uptake and increase yield (Hu et al., 2018). “Recovery of N applied at planting ranged from 30 to 55% while that applied at anthesis ranged from 55% to 80%” (Raun and Johnson, 1999). We must apply N by considering the plant growth stage and climate conditions. Nitrogen application when soil is moist will increase the chances of N leaching down. Before applying N, we must monitor rain and irrigation or soil moisture (Cameron et al., 2013; Flis, 2017). In sandy soils, the application of N at the sowing time will face N leaching due to rainfall and irrigation (Fageria and Baligar, 2005; Cameron et al., 2013; Fageria, 2014).

The source of N is as vital as the time of N application. Ammonium and nitrate are both important sources of N for the plant. Ammonium-based N fertilizer can be absorbed by the soil particles and is less susceptible to leaching, denitrification, and volatilization (Raun and Johnson, 1999; Raun and Schepers, 2008; Walsh and Belmont, 2015). On the other hand, nitrate cannot be absorbed by soil particles. Instead of using one source of N, we should use both; one-quarter of ammonium-based N sources can increase NUE by 35% (Raun and Johnson, 1999; Raun and Schepers, 2008; Flis, 2017). Nitrate assimilation requires 20 ATP mol^{-1} NO^{3}, and ammonium assimilation requires 5 ATP mol^{-1} NH^{4+} (Raun and Johnson, 1999; Raun and Schepers, 2008). Organic sources of N can reduce the N loss and requirement because of net mineralization and uptake simultaneously (Gao et al., 2012).

Finding the exact amount of N required for crop soil testing and mid-season crop testing can help calculate the amount of N required (Walsh and Belmont, 2015). When we apply N according to the recommended rates, we can increase NUE and yield also (Fageria and Baligar, 2005). With the increase in N fertilizer application, ammonia volatilization, nitrate leaching, and N_2O emissions are observed (Fageria and Baligar, 2005; Flis, 2017; Demir et al., 2021).

Inappropriate methods of N application can reduce NUE (Sanaullah et al., 2022). Deep placement, injection, and side dress are more efficient than broadcasting (Fageria and Baligar, 2005; De Laporte et al., 2021; Sanaullah et al., 2022). Deep placement is more efficient than broadcasting, with 62% more N uptake and; a reduction in leaching, immobilization, and volatilization observed (Raun and Johnson, 1999; Flis, 2017; Sanaullah et al., 2022). Nitrogen application through foliar and fertigation are better than broadcasting and increase NUE, and fertigation can also improve water use efficiency (Raun and Johnson, 1999; Demir et al., 2021). When urea is applied on the surface and not incorporated, this can lead to a 40% N loss in the form of ammonia volatilization; this percentage can increase with the influence of temperature and pH (Raun and Johnson, 1999).

3.2.2. Leaching

Leaching is the downflow of the water and nutrients from the root zone. From the active forms of N, nitrate is more susceptible to leaching, one of the main pathways of nitrogen loss from the soil solution (Yi et al., 2008; Cameron et al., 2013; Cui et al., 2014; Pan et al., 2020). Leaching losses range from 10% to 20% of the amount of N applied (Davis, 2007). The negative charge on it makes it susceptible to leaching because the soil also has a negative charge; that is why soil cannot adsorb nitrate and ultimately leach down (Davis, 2007; Fageria, 2014; Huang et al., 2017; Shen et al., 2022). Besides this, nitrate loss also depends on the rainfall and irrigation, nitrification, soil texture, and the amount of nitrogen fertilizer applied (Fageria and Baligar, 2005; Lü et al., 2009; Cameron et al., 2013; Fageria, 2014).

Leaching losses are higher in course-textured soils and lower in fine-textured soils because drainage is easy in course-textured soils due to the excess of macropores (Fageria and Baligar, 2005; Cameron et al., 2013; Fageria, 2014; Walsh and Belmont, 2015). The higher the application rate of N, the higher the chances of leaching because not all N is uptaken by the plants which lower the nitrogen use efficiency (Lü et al., 2009). Higher the rate of nitrification, the higher the rate of nitrate production; this level of abundant nitrate in the soil solution is an easy prey to leaching (Cameron et al., 2013); Higher rainfall and extreme irrigation frequency can make it faster to leach (Cui et al., 2014; Fageria, 2014; Walsh and Belmont, 2015; Shen et al., 2022). This type of N loss reduces nitrogen use efficiency.

3.2.3. Runoff

Runoff is the water loss from the land's surface over an area. It is not only water; it has dissolved nutrients within it as it flows over the soil's surface (Davis, 2007). Nitrogen loss through surface runoff is an important pathway of N loss (Davis, 2007; Cui et al., 2014; Pan et al., 2020); still, it does not account for a significant fraction of N loss as compared to the other pathways (Raun and Schepers, 2008; Walsh and Belmont, 2015). Ammonium NH_4^+ is the main form of N that is lost through the runoff (Shen et al., 2022). Nitrogen loss through the surface runoff is 13% of the applied N fertilizer (Raun and Schepers, 2008). Nitrogen loss through the runoff depends on the application rates of the N, the place where N is applied as if it is surface applied or not, soil surface conditions, and frequency of rain events (Davis, 2007; Raun and Schepers, 2008; Walsh and Belmont, 2015; Shen et al., 2022).

3.2.4. Tillage

Tillage influences the NUE by affecting crop N uptake (Brennan et al., 2014). The manner in which soil is tilled can have a direct impact on several soil properties, including soil aeration, decomposition rate of residues, soil temperature, structure, microbial activity, N mineralization, and moisture. These properties are responsible for the increased production of N_2O. There are varying responses in N_2O emissions to reduced tillage (RT)/no-till (NT) methods based on the soil type, region, and management of crop residue, as evidenced in the literature (Sanaullah et al., 2022).

In conventional tillage, excessive N application can cause leaching losses (Shah et al., 2017). Soil quality can be improved by conservation tillage which can improve N uptake and utilization, and water use efficiency (Baligar et al., 2001; Fageria and Baligar, 2005). In sandy soil, nitrate leaching losses are significant in the no-tillage system compared to conventional tillage because of higher moisture content and continuous macropores, as nitrate leaching preferentially uses macropores (Fageria and Baligar, 2005). Minimum tillage can increase nutrient and water efficiency (Baligar et al., 2001). Denitrification rates are high in compacted soils compared to non-compacted soil because of no aeration in compacted soils which increases the denitrification rate. Denitrification losses are 10% in conventional tillage and 21% in zero tillage (Hilton et al., 1994). These denitrification losses can be doubled by incorporating straw because straw increases the energy supply to denitrifiers (Aulakh et al., 1984).

3.2.5. Weeds, pests, and diseases

Weeds, pests, and diseases not only influence the product quality but also affect the NUE by affecting the demand for N (Balasubramanian et al., 2004; Fageria and Baligar, 2005; Abdullah Faraj, 2013; Anas et al., 2020). Excessive N affects the plant's resistance to insects and diseases (Altieri et al., 2005). Pests rely on plants with sufficient N supply instead of low nitrogen (Rijsdijk, 1986); this will reduce N recovery efficiency. Weeds compete with plants for space, air, light, and nutrients, especially N. Some weeds are more responsive to N than crops, and the result of this competition is yield loss (Gholamshahi et al., 2016); ultimately, NUE drops down.

3.3. Soil-based factors

3.3.1. Soil pH

When discussing crop production and N losses, soil pH plays an important role. As the pH drops, soil acidification will occur; this will reduce the uptake of N by the plant and decrease the nitrogen use efficiency (Pan et al., 2020). Soil pH is also responsible for ammonia volatilization (Fagi and De Datta, 1981; Davis, 2007; Shen et al., 2022); when urea is applied, it causes an increase in pH; although it is temporary, this increase in soil pH increases the rate of conversion of ammonium to ammonia, this will increase the concentration of ammonia available for volatilization. However, this change is temporary; as the nitrification rate increases, the rate of ammonia volatilization will reduce as the pH is reduced because of nitrification, and the optimum pH for nitrification is in the range of 4.5-7.5 (Cameron et al., 2013; Jones et al., 2013). Soils with high buffering capacity (capacity of soil to resist pH change) will decrease volatilization losses (Jones et al., 2013). Soil pH also influences both nitrification and denitrification; as a result, it can influence the emission of N_2O and N_2. Denitrification and soil pH has a direct relationship with each other. When the pH is acidic, the denitrification rate is low; it will increase with the increase of soil pH. This behavior will influence the emission of N_2O and N_2 (Cameron et al., 2013; Fageria, 2014).

3.3.2. Soil texture

Nitrogen use efficiency is also influenced by soil texture, whether the soil is fine-textured or coarse-textured. Low water and nutrient holding capacity, poor soil texture, high bulk density, soil surface sealing and crusting, poor aeration, and water lodging will reduce the NUE (Baligar et al., 2001). If we talk about the N loss through leaching, it depends explicitly on soil texture that is higher in coarse-textured soils as compared to fine-textured soils because the drainage is easy in coarse-textured soils due to the presence of macropores (Abdullah Faraj, 2013; Cameron et al., 2013; Fageria, 2014). On the other hand, denitrification losses are significant in fine-textured soils compared to coarse-textured soils because fine-textured soils have fewer macropores and a higher number of micropores (Raun and Johnson, 1999; Cameron et al., 2013; Fageria, 2014; Tao et al., 2018). These micropores get clogged with the high irrigation and rainfall; ultimately, the aeration rate drops, increasing denitrification and ceasing nitrification (Davis, 2007; Abdullah Faraj, 2013; Fageria, 2014). That is why denitrification and N_2O emissions depend on soil texture also (Shumway et al., 2012; Zechmeister-Boltenstern et al., 2015).

If we talk about crop production, it will be high in fine-textured soils as compared to coarse-textured soils because fine-textured soils have high water and nutrient holding capacity. Fine textured soil/clay, along with organic matter, not only provides N and other macronutrients to the plants, this will help to increase the NUE (Thorburn et al., 2017; Tsujimoto et al., 2019). A balanced diet containing potassium, phosphorous, and other nutrients has been reported to increase the NUE (Aulakh and Malhi, 2004; Fageria and Baligar, 2005; Koffi et al., 2016).

3.3.3. Soil salinity

Soil salinity is a threat to food security. Soil salinity inhibits vegetative and reproductive growth, making plants suffer from ionic and osmotic stress, reducing the nitrogen and water use efficiency by reducing the uptake of N and water, suppressing the photosynthetic activity due to the toxicity because of salts accumulation in plants, and influence the stomata opening and shoot growth (Lea-Cox and Syvertsen, 1993; Nandy (Datta) et al., 2007; Chen et al., 2010; Zhang et al., 2012; Murtaza et al., 2013; Zeng et al., 2015; Ma et al., 2022).

Ma et al. (2022) reported that an increase in soil salinity reduces the N uptake. It has been reported that in low and moderate salinity increase in the N fertilizer application rate not only increases the N uptake but also improves the uptake of P and K (Zhang et al., 2012). However, in high soil salinities, N uptake is independent of the N application rate (Chen et al., 2010; Zhang et al., 2012). However, the low N input rate performed very well in low and high salinity (Zhang et al., 2012).

Akhtar et al. (2012) reported that salinity inhibits the second step of nitrification; as a result, soil solution faces the accumulation of nitrite (NO_2^-). If the salinity is severed, it will inhibit the first step of nitrification; consequently, the soil solution will face ammonium accumulation, ultimately leading to an increase in ammonia volatilization.

In the early stage of plant growth, which is a sensitive stage of growth also, excessive N application contributes to the increase in salinity and soil acidity and reduces yield (Zhang et al., 2012; Min et al., 2014; Han et al., 2015b; Zeng et al., 2015). During the nitrification process, H^+ ions are released (Equation 3); this will induce soil acidity (H^+ reduces the soil pH). In the calcareous soils, an excess amount of H+ ions will replace the Ca^{2+} and Mg^{2+} (Equation 8), and carbonate dissolution will release Ca^{2+} and Mg^{2+} (Equation 9). Nitrate production as a result of nitrification, plants do not uptake all the nitrate in their early growth stage; as a result, nitrate ends up in the soil solution. This accumulation of NO_3^-, Ca^{2+}, Mg^{2+} and other salts will increase the total dissolved solids (TDS), and an increase in soil salinity is evident (Han et al., 2015b).

$$\text{Soil-}Ca_2{}^+ + 2H^+ \leftrightarrow \text{Soil-}2H^+ + Ca_2{}^+ \tag{8}$$

$$2Ca_{(1-x)}Mg_xCO_3 + 2H^+ \leftrightarrow 2HCO_3{}^- + (2-x)Ca_2{}^+ + xMg \tag{9}$$

3.4. Plant-based factors

3.4.1. Plant nitrogen losses

Plants are also responsible for the loss of N from the soil-plant system to the atmosphere, mostly in the form of ammonia, mainly during the reproductive stage or after anthesis (Pearson et al., 1998; Raun and Johnson, 1999; Raun and Schepers, 2008; Walsh and Belmont, 2015). This N loss varies from crop to crop or from one variety to another (Walsh and Belmont, 2015). “Gaseous plant N loss in excess of 45 kg N ha^{-1} yr^{-1} has also been documented in soybean" (Raun and Johnson, 1999; Raun and Schepers, 2008).

A considerable amount of N is lost from the soil because of the harvested parts of the plant; other than the economically beneficial portion is crop residue, which is a massive pile of N. Moreover, this type of N loss in multipurpose crops is higher (Walsh and Belmont, 2015). Ammonia loss from crop residue cannot be prevented, but it can be reduced if we incorporate it back into the soil (De Ruijter and Huijsmans, 2019).

3.4.2. Crop rotation

Crop rotation is the sequence in which crops are grown in an area (Sanaullah et al., 2022; Wakeel et al., 2022). Effective utilization of soil N through crop rotation can significantly decrease the possibility of nitrate leaching. In addition, crop rotation can also have an impact on the rate of N mineralization by altering factors such as soil moisture, temperature, pH, plant residue, and tillage practices (Sanaullah et al., 2022).

Rice-wheat rotation (this rotation is popular in Asia) requires a massive amount of N fertilizer but has low NUE due to significant loss of N in the form of nitrate leaching because of wet-dry conditions (Sanaullah et al., 2022; Shahzad et al., 2019). NUE is also reduced in cotton-wheat rotation (this rotation is popular in Pakistan) (Shahzad et al., 2019). Like rice-wheat rotation, wheat-wheat rotation also depends on a high N rate but low NUE (Raun and Johnson, 1999; Abdullah Faraj, 2013). Corn-corn rotation requires more N than corn-legume rotation, reducing nitrate leaching (Tao et al., 2018; Sanaullah et al., 2022).

The inclusion of legumes and cover crops not only reduces the rate of N application but also adds N, reduces the leaching losses, and ultimately increases the NUE (Hirel et al., 2011; Abdullah Faraj, 2013; Kubota et al., 2018; Sanaullah et al., 2022). Misselbrook et al. (2022) reported that in China, crop rotation improved nutrient use efficiency between 27% to 44%.

3.4.3. Crop nutrition/balance diet

Another reason for the low NUE is the imbalance of crop nutrition (Shahzad et al., 2019). Various studies prove that the deficiencies of micronutrients and macronutrients can reduce the NUE (Tsujimoto et al., 2019). Nitrogen uptake increases with the increasing phosphorous level (Fageria, 2014). Studies have shown that the nitrogen-phosphorous combination of fertilizer application has a 14% higher NUE than the nitrogen application alone (Duan et al., 2014; Fageria, 2014; Koffi et al., 2016).

Potassium deficiency can affect the N utilization and uptake efficiency (Fageria and Baligar, 2005; Fageria, 2014). Potassium increases the absorption of nitrate by the plant instead of ammonium. And plants that absorb nitrate accumulate more cations than ammonium (Fageria, 2014). Adding K along with N and P can increase the NUE and yield (Fageria and Baligar, 2005; Duan et al., 2014; Koffi et al., 2016; Rawal et al., 2022). Lime (calcium carbonate) application in acidic soils, along with sufficient N application, not only increase the pH (reduce soil acidity) but also increases the NUE (Fageria, 2014). Sulfur (S) is also important because it affects the photosynthesis rate. The addition of sulfur in fertilizer management increases the NUE compared to non-sulfur managemental practices (Fageria, 2014; Tsujimoto et al., 2019).

Micronutrients are also equally crucial for plants. Like zinc (Zn) application can increase NUE, $ZnSO_4$ application increase the response of plants to urea. Nitrogen concentration in plants can influence copper, iron, and manganese uptake. Iron (Fe) is responsible for nodule formation, increase in yield, and NUE in legumes. Boron (B) is responsible for N fixation and utilization (Fageria, 2014). By managing deficiencies of the nutrients like P, Zn, S, silicon (Si), and Fe toxicity, we can improve NUE (Tsujimoto et al., 2019). We all know that a balanced diet (micronutrients and macronutrients) is vital for plants; all of them somehow play a role in NUE.

3.4.4. Crop varieties

Crop varieties/cultivars influence the NUE because every genotype affects the uptake and utilization of N. Based on their morphological and functional characteristics, every genotype differs from the other (Benincasa et al., 2011). Williams et al. (2021) reported that hybrid canola has high NUE and productivity compared to parent/traditional canola even under low N input because hybrid canola can remobilize N for seed production and N accumulation in the plant (Williams et al., 2021). Similarly, hybrid corn performed very well compared to standard corn varieties, and this difference is based on the use of accumulated N before anthesis under low N input (Raun and Johnson, 1999; Raun and Schepers, 2008).

Koffi et al. (2016) tested five different varieties of rice (Pusa Basmati, Sahel 329, Sahel 177, Sahel 328, and Sahel 108) against five different rates of nitrogen (0, 60, 90, 120, and 150 kg ha^{-1}) along with phosphorous (26 kg P ha^{-1}) and potassium P-K (26 kg P ha^{-1} and 50 kg K ha^{-1}). He found that Sahel 108 and Sahel 177 have higher NUE than other varieties. A balanced diet and good crop variety can improve NUE.

4. Conclusions

Several reasons reduce NUE as stated above in this study, considering all of them, it is not that simple to improve NUE without leaving environmental footprints, without increasing N inputs, reducing N surplus, increasing yield, and preventing N loss to prevent the environment and soils from degradation. And one of the primary goals is to produce enough to feed the world. Every pathway responsible for the N loss from the soil-plant system or, in other words, every way that will suppress N uptake and utilization will reduce NUE. According to the study stated above, now it’s clear how different factors influence the NUE and N losses. Now it’s important to make strategies and amendments to our traditional cropping system considering these losses.

NUE depends on several factors; it's not that easy to maintain all of them. All of these factors cannot be handled by farmers, like rainfall, environmental changes/climate change, and N fertilizer price fluctuations. But a few steps can be taken that can be easily handled by the farmers like the use of slow-released fertilizers, improving irrigation, balanced crop nutrition, selection of efficient crop variety, use of nitrification inhibitors, and application of 4Rs of nutrient management (right source, right time, right amount/rate, and right placement). Soil testing before cropping and mid-season crop testing to estimate crop nutrient requirements can help to improve NUE and reduce N losses. To understand and adopt new technologies, farmers' training is crucial; this will not only improve NUE but also help them produce a good quality crop, and increase yield and income.

Keeping in view the growing population and limited resources, it's the researcher's responsibility to work on the improvement of NUE and better yield. Development of genetically modified and N efficient crop varieties. Although it's challenging, it is not like developing resistance against disease in plants; it is way more complex because it involves multiple efficiencies from uptake to its use. Fertilizer companies should focus on the production of cost-friendly slow-released N fertilizers, fertilizers optimal use, and proper guidelines for the farmers with appropriate recommendations.

World (developed countries) is moving towards new strategies and new technologies for a better world and for the sake of sustainable agriculture like China where a new term is introduced named "integrated soil-crop management approach/system" and is being practiced on a very large scale. It is an approach perusing the legacy of sustainable agriculture by choosing the pathway of safe use of fertilizers eliminating the environmental risks, reducing the cost of production, increasing productivity, and improving nutrient use efficiency. It involves soil quality improvement by using all possible means, integrated utilization of different sources of fertilizers matching the crop requirement, and integrated soil and nutrient management with high-yielding cultivation systems. Research and extension services should work side by side; this will make the easy spreading of research and innovative technologies and timely adoption by the farmers. A combined effort is required by plant geneticists and breeders, soil scientists, agronomists, physiologists, biologists, and chemists to develop a system to overcome this issue for the sake of a better world for our upcoming generations.

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