Review on Improving Nitrogen Use Efficiency for Cereal Crop Production

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Abstract: Nitrogen (N) is an essential macronutrient and a major structural and physiological component of basically all processes related to plant development, growth and reproduction. For sustainable agriculture and food production, N is indispensable and it therefore has to be re-supplied to agricultural soils to prevent nutrient depletion and soil degradation. Nitrogen is the most critical externally added input for any crop production system. The half of the global population directly or indirectly depends on nitrogenous fertilizers for food supply. Efficient use of nitrogen is essential to decrease negative impacts of agriculture on the environment. Improvement in nitrogen use efficiency (NUE) is important to reduce input costs and the negative impact of excessive N on the environment. Therefore, response to applied nitrogen and its use efficiency have to be monitored properly for obtaining the maximum potential and sustainable yield. Efficiency of applied nitrogenous fertilizers is very low due to its various losses i.e. volatilization, leaching, surface runoff and denitrification from soil-plant system. Therefore, the proper understanding of advanced soil and plant management practices which helps in enhancement of nitrogen recovery efficiency is one of the key factors to enhance crop output, decreasing cost of cultivation, and to maintain environmental quality which ultimately adds towards the goal of achieving long term sustainable production system. In this review, an attempt has been made to summarize the locally as well as scientific soil and crop management technologies used for improving use efficiency of applied N. This paper also discusses nitrogen cycling in soil-plant systems, various N losses pathways, present status and most possible management options at the farm level for enhancing nitrogen use in crop production system. Therefore, use of efficient rates of nitrogen fertilizer application is important with regard to increasing crop productivity and maintaining environmental sustainability.

Keywords: Essential; macronutrient; nitrogen use efficiency; sustainable agriculture.

1. INTRODUCTION

Nitrogen (N) is the most important plant nutrient determining the crop production. N is the most limiting nutrient required for food productivity worldwide (Giller et al., 2004). Over the past four decades, the doubling of global agricultural food production has been reached in part with a seven fold increase in the use of N fertilizers, where approximately 90-100 million metric tons are used for agricultural production (London et al., 2005). Global population growth has led to a significant increase in demand of cereal crops and other agriculture products. World population growth is expected to reach 8 billion people by 2025 further increasing the demand for food and greater efficiency in productivity. However, a great challenge will be to do this in an environmentally sustainable manner. One direction which will have an influence is the development of novel plant genotypes which have a greater capacity to produce harvestable yields using less external inputs such as nitrogen fertilizers. These genotypes should have the capacity to accumulate and or assimilate N more efficiently than that of previously selected crops while still maintaining the required harvested production levels demand of farmers and consumers (Hirel et al., 2007).

Nitrogen can only be used by plants in its reduced form. Unfortunately, the majority of N in the environment is in the form of di-nitrogen (N₂) which comprises ~78% v/v of the air on the planet. Available forms of N (NH₄⁺ &NO₃⁻) can occur through the activity of lighting, biological nitrogen fixation and via the energy intensive Haber-Bosch process. Plants such as legumes can form an effective N₂-fixing symbiosis with soil bacteria, where they obtain the necessary levels of N from the atmosphere to adequately balance the demands required for growth and successful seed production. However in non-legume crops, N must be acquired in a reduced form where demand can vary widely depending on
the targeted yield and final protein content of the harvested product. Furthermore, differences in plant genotypes, environmental interactions and management systems will influence the supply and demand by the plant for N (Angus et al., 2001).

1.1. Nitrogen Use Efficiency

Nitrogen use efficiency (NUE) of a crop plant refers to the relative balance between the amount of fertilizer taken up and then used by the crop versus the amount of fertilizer supplied directly or indirectly (Nielsen et al., 2006). In other words, NUE looks at fertilizer input recovery in a production system to classify which plants do this better or worse when compared equally based on production (yield). NUE is defined by many authors in the context of crop production and the literature contains a number of different definitions depending on whether authors are dealing with agronomic, genetic, or physiological studies (Good et al., 2004; Fageria et al., 2008). According to Moll et al. (1982) N uptake efficiency (NupE) is the primary component determining NUE when soil N supply increases. This is explained by N uptake exceeding the critical value of N content in crop dry matter (Lawlor et al., 2001; Lemaire and Millard, 1999). On the other hand, Ortiz-Monasterio et al. (1997) reported that N uptake is also an important component of NUE under low condition. Both (Ortiz-Monasterio et al., 1997 and Le Gouis et al., 2000) stated that NupE in wheat accounts for most of the variation in NUE at low N availability. Ortiz-Monasterio et al. (1997) further defined NupE to include harvest index (HI) and biomass production efficiency (BPE) affirming that HI is best associated with NupE. Reductions in NUE as N supply increases could result from reductions in any of the components, including NupE, NutE and N retention efficiency (NRE). Different studies on wheat and perennial grasses have shown various limitations in each of these components (Huggins and Pan, 2003; Jiang et al., 2000; Ortiz-Monasterio et al., 1997). For example, Ortiz-Monasterio et al. (1997) found that in all wheat varieties evaluated, both NupE and NutE were reduced at higher N supplies, causing an overall reduction in NUE. Morris and Paulsen (1985) and Cox et al. (1985) showed a reduction in N-translocation efficiency at high versus low N supply (Dhugga and Waines, 1989).

Nutrient Use Efficiency can be partitioned into the individual components of NupE and NutE (Moll et al., 1982; Ortiz-Monasterio et al., 1997). NupE can be calculated as the total above-ground N per unit of N supplied, including available N from soil or not. Therefore, organic matter N mineralization plays an important role in the calculation of N uptake from the soil (Le Gouis et al., 2000). However, Youngquist et al. (1992) suggested that when initial soil N contents are equal, genotypic differences in NupE can be determined by measuring only plant N.

Feil et al. (1992) indicated that cultivars producing large amounts of biomass seemed to have a more efficient nutrient uptake, which could decrease the total NUE of modern cultivars. Since N concentration is higher in leaves than in stems and sheaths, N uptake may be more closely related to leafiness than to total shoot biomass (Feil et al., 1997). Moreover, genetic differences in N recovery in the grain were mostly attributed to the net N uptake after anthesis rather than of remobilized N (Suprayogi et al., 2011). Post anthesis N uptake was found to be exponentially related to grain mass (Pan et al., 2006) but may vary with environmental conditions, such as N and water availability (Baresel et al., 2008).

1.1.1. Nitrogen-use efficiency and expression

Nitrogen-use efficiency may be defined in various terms and their approximate value over region and crop basis is shown in Table1.

Terms Used in Describing N-Use Efficiency (Doberman, 2005)

- Agronomic efficiency (AEN): It may be defined as increase in grain yield kg grain kg⁻¹ N applied. Its value ranges from 18 to 24 kg grain kg⁻¹ N applied and was the smallest in maize and largest in rice.
- Apparent nitrogen recovery (ANR): It may be defined as per cent increase in the uptake of N in fertilized crop as compared to control where no N was applied. Its value ranges from 10 to 70 % across region and various crops.
- Physiological efficiency (PEN): It is defined as increase in grain yield Kg grain kg⁻¹ N absorbed. Its value ranges from 20 to 52 across various regions and crops.
Agronomic efficiency (AE\(_N\)), physiological efficiency index of N (PE\(_N\)), recovery efficiency (RE\(_{N15}\)), Partial Factor Productivity of N (PFP\(_N\)). It is the gain in grain yield per kg N applied to the crop. Its value ranges between 39 and 72, which means by application of one kg of N, 39–72 kg grain yield can be gained across various continents and crops.

1.2. Enhancing Nitrogen Use Efficiency

The utilization by crops of N applied through fertilizers varies from 30 to 50% depending upon nature of the crop, climate, soil and management practices. It can be 50-60% for wheat grown in temperate climates and around 30% for lowland rice grown in coarse textured soils. The energy required to produce fertilizer N to be applied per unit area is about one-third of the total energy requirement for raising the crop. More efficient use of N fertilizers therefore, means a net saving in energy (IFA, 2016). According to IFA, (2016) three types of processes affect excess N not utilized by the crop. Their relative impact on the supply of N to crops depends upon weather, soil conditions, and other factors. These processes are: - microbial e.g. nitrification, denitrification, immobilization; chemical e.g. exchange, fixation, precipitation and hydrolysis; physical e.g. leaching, run-off, volatilization.

Fertilizer best management practices for the application of plant nutrients attempt to increase nutrient use efficiency and minimize unfavorable effects on the environment. The root system of most arable crops only explores 20-25% of the available soil volume in any one year. So the utilization of nutrients by plants will not only depend on the stage of growth and nutrient demand, but also on the rate of delivery of plant nutrients to the root by mass flow and diffusion in the soil solution.

1.2.1. Split Application

Application of N fertilizers at multiple times during the growing season–can help improve N use efficiency and reduce losses. Applying N fertilizer as close as possible to the time of uptake requirement by the crop is a good management strategy to maximize efficiency. Similarly, site-specific fertilizer management leads to application of fertilizer N after taking into account the N supplying capacity of the soil and thus ensures high fertilizer N use efficiency. Any surplus mineral N remaining in soil at harvest is likely to be lost by leaching and denitrification. Use of cover crops and crop residue management can help keep the N in organic compounds in the soil and make it less susceptible to leaching and denitrification losses.

1.3. Strategies to Improve NUE

Cereals require N-fertilizers to produce maximum yields and high protein content (Barraclough et al., 2010). However, NUE in cereals is generally poor, where it is estimated 30-40% of the total of N-fertilizers applied is actually harvested in the grain. The reminder of the applied N is lost to the soil, where often-excessive application can affect natural ecosystems through N pollution. Loss of N also contributes to significant direct economic losses to the grower particularly when N fertilizer costs are high (Glass et al., 2003; Gruber and Gilloway, 2008). It has been estimated that an increase in NUE by one percent is worth as much as USD $234 million (Magen and Nosov, 2008). Therefore, initiatives to improve NUE will be important in order to minimize both N- fertilizer losses and the direct production costs of the crop. On the basis of field experiments, (Cassman et al., 2002) reported N recovery in wheat varied from as low as 18 percent under unfavorable weather to 49 percent under favorable weather conditions. One of the main causes of low NUE in actual N management practices is the limited
synchrony between N soil availability and crop demand (Cassman et al., 2002; Fageria and Baligar, 2005). Consequently, many different agronomic avenues are pursued to improve NUE in cereal crops which includes: 1) Application of the correct dose of N-fertilizer and/or application during growth stages when N is required; 2) Directed delivery of N to minimize losses or maximize utilization, for example, banding or point placement close to the root; 3) Use of cover crops, to retain organic matter and soil N in the soil; 4) Increased use of crop rotations (shallow and deep rooted crops), such as wheat following legumes, and avoiding wheat- fallow or wheat-wheat scenarios; 5) Use of modern farming techniques such as conservation tillage to control weed, soil moisture, erosion, operation costs and environment; 6) Identifying the best sowing rate, spacing and depth for best use of soil water and fertilizers and 7) The selection of wheat germ plasm that produce larger seeds to ensure quick plant establishment and access to available N at the young seedling stage.

1.4. Plant and Soil Factors Influencing NUE

As mentioned previously, cereal NUE can be as low as 30-40% due to a range of biotic and agronomic-based factors. These include the primary growing conditions that influence overall photosynthesis and plant respiration such as day/night temperatures (Yoshida et al., 1982) and the amount and timing of precipitation (Kravchevckov et al., 2003). High-yielding varieties will often demand larger amounts of N fertilizer to meet expected yields or to improve grain quality (higher protein content). While pest and disease pressure will often affect demand for N, this can consequently reduce yield and NUE. Furthermore, the type of plant also has a dramatic impact on NUE. In general, cereal crops have higher N recovery efficiency (RE_N) than root crops, which in turn have a higher RE_N than leafy vegetables (Balasubramanian et al., 2004).

The impact of N fertilization on crop plants is very much influenced by the cycling of N between inorganic and organic forms and the relationship between the N present in the air, water and soil fractions. This transition of N activity is referred to as the N cycle, which describes the different forms and stages that N exists in the air, soil, water and the biological continuum. N is never lost completely in the cycle, but merely changes its form and availability (Mosier et al., 2004 and Smil et al., 1999). The predominant changes include: (1) Ammonification which is the process where organic forms of N are converted to ammonium (NH_4^+). Soil organisms (bacteria and fungi) carry out the majority of ammonification. The organisms receive carbon, N and energy from the breakdown of organic matter, while excess N is released; (2) Nitrification is the process involving the conversion of NH_4^+ to nitrite (NO_2^-) and then to nitrate (NO_3^-). Soil organisms involved in nitrification processes get energy from the chemical transformation of NH_4^+ to NO_2^-; (3) Denitrification is the process where NO_3^- and NO_2^- are converted into gaseous N (N_2, N_2O) by microorganisms. Denitrification occurs mainly when there is little or no oxygen in the soil (e.g. soil is waterlogged). However, denitrification process stops when soil dries; (4) N_2 fixation is the conversion of N gas (N_2) to NH_4^+, either by free living bacteria in soil or water, or by bacteria in symbiotic association with plants (e.g. legume symbiosis); (5) N immobilization is the process whereby N is incorporated into microbial cells and effectively tied-up’ in the ‘microbial pool’ of N. Immobilization occurs in parallel with ammonification.

Figure 1. The global N balance in crop production (adapted from Mosier et al., (2004), and Smil et al. (1999). The figures are in Tg (10^{12} g) per year. Leaching (37 Tg) includes runoff and erosion losses; ammonia volatilization (21 Tg) includes volatilization from soil and vegetation.
Thus N cycling has a significant impact on the quantity and supply of N to the plant. A significant component of the N cycle involves soil-based microbial activity. This process is strongly influenced by the availability of organic C in the soil, which is used as a primary microbial energy source (Stevenson et al., 1994). Application of organic material or crop residues with high C: N ratios to the soil can stimulate microbial N immobilization, a process where available NH$_4^+$ and NO$_3^-$ is competitively used by microbes. This process can reduce crop yield unless N is supplemented with applied fertilizers (Van Lauwe et al., 2002). Soil based constraints can also promote or decrease microbial based N cycling activities including denitrification, ammonia volatilization (Mosier et al., 2001a; Schlesinger et al., 1997).

1.5. Managing Nitrogen use

Nitrogen is a dynamic and highly mobile element in agricultural soils causing environmental problems through increased N pollution that acts both locally and globally (Glass et al., 2003; Gruber and Galloway, 2008). The extensive use of N-fertilizers in agriculture has created major problems worldwide through N based pollution of surface and underground water supplies. Therefore, concentrations of NO$_3^-$ in agricultural products and drinking water should be minimized. Although the fact that the main source of NO$_3^-$ intake is food, not water, the World Health Organization (WHO, 1970, modified in 1993) set a recommended limit for drinking water of 50 mg NO$_3^-$ per liters. The main issue was the microbial conversion of NO$_3^-$ to nitrite (NO$_2^-$), which was associated with problems involving nitrosamines and methaemoglobin. The so-called “blue-baby syndrome” (methaemoglobinemia), for example, arises from bacteria contamination and not from ingesting too much NO$_3^-$ as originally supposed. Recent work even suggests that ingested NO$_3^-$ provides gastro-intestinal protection against food-borne pathogens and “epidemiological studies show a reduced rate of gastric and intestinal cancer in groups with a high vegetable based nitrate intake” (Leifert and Golden, 1997). Elevated concentrations of nitrate in streams or aquifers are mostly due to excessive or poorly used N applications in agriculture. High NO$_3^-$ concentrations in water also occurs in years following drought. High NO$_3^-$ concentrations in forage can cause sickness and death in livestock when grazing due to NO$_3^-$ accumulation in plant tissue. The accumulation occurs due to high temperature, drought, other nutrients deficiency and plant disease (IFA, 2007).

Urea is a common N fertilizer used in agricultural systems worldwide. It is estimated that more than half of all fertilizer used globally is in the form of urea (Gilbert et al., 2006). The benefit of using urea as a fertilizer is due to its high N content (≈ 46% N), high solubility, and low expense to manufacture, store, and transport (Prasad et al., 1998). However, urea is susceptible to hydrolysis followed by ammonia volatilization (Fenn and Hossner, 1985). During hydrolysis, urea N is converted into NH$_3^-$, which subsequently reacts with a proton to produce NH$_4^+$. Under alkaline conditions, the equilibrium of NH$_3$ + H$_2$O $\leftrightarrow$ NH$_4^+$ + OH$^-$ shifts more to the NH$_3$ ion, increasing volatilization losses that leads to lower efficiencies of fertilizer N used by plants. Soil texture and organic C content can also play an indirect role in N gaseous loss. For example, soils with high sand content generally have lower rates of N$_2$O production than do clay soils (Corre et al., 1996). Leaching intensity is controlled by soil texture. Lighter sandy soils are more prone to leaching losses than are soils with greater clay content (Hack-ten Broeke and de Groot, 1998).

1.6. Nitrogen Sustainability

Globally farmers often apply an excess of N as insurance against low yields. This approach can lead to increased losses of N from agricultural systems and poor NUE in plant production systems (Dobermann and Cassman, 2004; Goulding et al., 2004). One of the challenges for plant breeders will be to increase NUE in a manner that will reduce production costs and minimize environmental pollution while at the same time meeting both yield and quality measures (Daberkow et al., 2000).

More sustainable agricultural practices that manage N-delivery and its use across a crop production cycle are currently highly sought. For example, the use of split N application procedures, where delivery occurs at a time when plants need N during their life cycle will help to achieve improved NUE that reduces N loss while sustaining or improving yield and quality (Matson et al., 1998). In light of the growing concern about N fertilizer use and its direct economic costs and impacts on the environment, most nations are investigating alternative strategies to make agriculture more sustainable. A reduction in the amount of N fertilizers applied to the field will help to achieve this but at the same time there is a requirement to maintain and or increase yield to meet future food demand. Sustainable agricultural
practices, such as N-fertilization based on demand, effective use of crop rotations with N-fixing legumes and the establishment of ground covers and burial of N-rich crop residues are encouraged (Hirel et al., 2007). Others strategies to improve N efficient use are to use genetic modification and/or to breed for new varieties that take up more organic or inorganic N from the soil N and utilize the absorbed or metabolized N more efficiently without compromising yield (Hirel and Lemaire, 2006).

2. SUMMARY AND CONCLUSION

The use of nitrogen fertilizers has played an instrumental role in enhancing agricultural productions over the world. Currently, about 83 million tons N is used in agriculture globally. A large portion of applied N is lost through leaching, volatilization and runoff, and only 50 % of applied N is assimilated by the crop plant. Nitrogen is a key input for sustaining high crop yields, but the fertilizer N uptake efficiency in crops is relatively low with conventional production practices (<50%). Recently, there have been serious concerns about environmental footprints of N fertilizers, particularly greenhouse gas emissions from the rice fields and escalating costs of fertilizers beyond farmers’ reach. To meet the growing need for N fertilizers due to the rise in food requirement for ever multiplying population on the one hand and an increasing environmental and atmospheric pollution on the other, improving nitrogen-use efficiency (NUE) appears to be a viable solution. Use of nitrogen in agriculture is indispensable as it is an important constituent of plant material and human food, and its contribution in food production is the largest among all other plant nutrients. More than 50 % of applied N is lost through various processes, and nitrogen-use efficiency remains below 50 % in most crops. NUE includes N uptake, utilization or acquisition efficiency and expressed as a ratio of output (total plant N, grain N, biomass yield, grain yield) and input (total N, soil N or N-fertilizer applied). Nitrogen use efficiency (NUE) is the product of both nitrogen uptake efficiency which is a root-associated trait, and nitrogen utilization efficiency, which is a function of canopy activity. NUE is yield per unit of available N. Yield is mainly determined by C fixation in the canopy (which is dependent on N for growth and function); grain also requires N for protein, which is transported directly from the soil or from remobilization during canopy senescence (major contribution). Nitrogen fertilization provides essential benefits for food production but its optimal management is subject to a high level of complexity.

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