International Journal of Forestry and Horticulture
Volume 6, Issue 3, 2020, PP 12-19
ISSN No.: 2454-9487
DOI: https:// doi.org/10.20431/2454-9487.0603002
www.arcjournals.org

Review on Improving Nitrogen Use Efficiency for Cereal Crop Production

Obsa Atnafu*

Jimma Agricultural Research Center, Jimma, Ethiopia

Corresponding Author:** ***Obsa Atnafu, *Jimma Agricultural Research Center, Jimma, Ethiopia*

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 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. This 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 (N_2) which comprises~78%v/v of the air on the planet. Available forms of N (NH_4^+ &NO_3^-) 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 N_2-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.

Table1. *Descriptive statistics of various NUE terms for cereals in various continents*

Region/Crop	AE_N	RE_{N15}	PE_N	PFP_N
Africa	13.9	0.37	22.9	39.3
Australia	8.0	0.41	-	54.0
Europe	21.3	0.61	27.7	50.4
America	19.6	0.36	28.4	49.6
Asia	21.5	0.44	46.6	53.5
Average/Total	19.6	0.44	40.6	51.6
Maize	24.2	0.40	36.7	72.0
Rice	22.0	0.44	52.8	62.4
Wheat	18.1	0.45	28.9	44.5
Average/Total	20.6	0.44	40.6	51.6

Source: Anchal et al. (2014)

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 (Kravcheckov *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 (NO_2, N_2) 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.

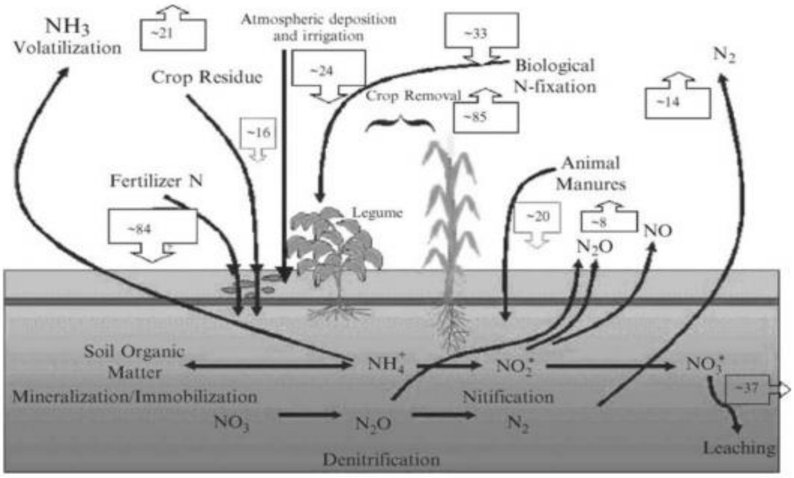

Figure1. *The global N balance in crop production (adapted from Mosier et al, (2004), and Smil et al, (1999). The figures are in Tg (10^{12} g) per year. Leaching (37 Tg) includes runoff and erosion losses; ammonia volatilization (21 Tg) includes volatilization from soil and vegetation*

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’’ (methaemoglobinaemia), 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 $NH_3 + H_2O \leftarrow \rightarrow NH_4^+ + OH^-$ shifts more to the NH_3 ion, increasing volatilization losses that leads to lower the 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_2O 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.

References

[1] Angus J. F. 2001. Nitrogen supply and demand in Australian agriculture. Australian journal of Experimental Agriculture. 41: 277-288.

[2] Balasubramanian V., Alves B., Aulakh MS., Bekunda M., Cai Zc., Drinkwater L., Mugendi Van Kessel D.C., and Oenema O., 2004. Crop, environmental and management factors affecting N use efficiency.

[3] Baresel J. P., Zimmermann G., Reents H. J., 2008. Effects of genotype and environment on N uptake and N partition in organically grown winter wheat (Triticum aestivum L.) in Germany. Euphytica. 163, 345-347

[4] Barraclough P. B., Howarth J.R., Jones J., 2010. Nitrogen efficiency of wheat: genotypic and environmental variation and prospects for improvement. European Journal of Agronomy 33, 1-11.

[5] Cassman K.G., Dobermann A. and Walters D., 2002. Agro ecosystems, Nitrogen Use Efficiency and Nitrogen Management. Ambio 31:132-140.

[6] Corre M. D., Van Kessel C., and Pennock, D. J., 1996. Landscape and seasonal patterns of nitrous oxide emissions in a semiarid region. Soil Sci. Soc. Am. J. 60, 1806–1815.

[7] Daberkow S., K.F. Isherwood, J. Poulisse, and H. Vroomen., 2000. Fertilizer Requirements in 2015 and 2030. In Proc. IFA Agricultural Conference on Managing Plant Nutrition, 29 June-2 July 1999. Barcelona Spain.

[8] Diaz, C., Lemaitre, T., and Christ C. 2008. Nitrogen recycling and remobilization are differentially controlled by leaf senescence and development stage in Arabidopsis under low nitrogen nutrition. Plant Physiology.147:1437–1449.

[9] Dobermann A., and Cassman, K. G., 2004. Environmental dimensions of fertilizer nitrogen: What can be done to increase nitrogen use efficiency and ensure global food security? In Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment.

[10] Fageria N.K., Baligar V.C., Li, Y., 2008. The role of nutrient efficient plants in improving crop yields in the twenty first century. Journal of Plant Nutrition 31, 1121–1151.

[11] Feil B. 1997. The inverse yield-protein relationship in cereals: Possibilities and limitations for genetically improving the grain protein yield. Trends in Agronomy 1, 103-119.

[12] Feil B., Hanson, K.A., and Martin J.M., 1992. Breeding progress in small grain cereals- a comparison of old and modern cultivars. Plant Breed. 108: 1-11.

[13] Gallais, A., Coque, M., Quillere, I., Prioul, J. L., and Hirel, B. 2006. Modelling post silking nitrogen fluxes in maize (Zea mays) using N labeling field experiments. The New Phytologist.172:696–707.

[14] Gilbert P.M., Harrison J., Heil C., and Seitzinger S., 2006. Escalating worldwide use of urea – a global change contributing to coastal eutrophication. 77:441-463.

[15] Giller K.E., Chalk P.M., Dobermann A., Hammond L.C., Heffer P., Ladha J.K., Nyamudeza P., Maene L.M., Ssali H., and Freney J.R., 2004. Emerging technologies to increase the efficiency of use of fertilizer nitrogen. p. 35-52.

[16] Good A.G., Shrawat A.K. & Muench D.G., 2004. Can less yield more? Is reducing nutrient input into the environment compatible with maintaining crop production? Trends in Plant Science 9, 597–605.

[17] Goulding K.,2004. Pathways and losses of fertilizer nitrogen at divergent scales. In Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment.

[18] Gruber N. and Galloway, 2008. An Earth-system perspective of the global nitrogen cycle. Nature 451, 293-296.

[19] Hack-Ten Broeke M.J.D. & W.J.M. De Groot, (1998). Evaluation of nitrate leaching risk at site and farm level. Nutrient Cycling in Agro ecosystems 50:271-276.

[20] Hirel B., G. Lemaire, 2006. From Agronomy and Ecophysiology to Molecular Genetics for Improving Nitrogen Use Efficiency in Crops.

[21] Huggins D.R., Pan W.L., 2003. Key indicators for assessing nitrogen use efficiency in cereal-based agro ecosystems. Journal of Crop Production 8, 157–185.

[22] IFA, 2007. International Fertilizer Association. Fertilizer-Use Statistics. www.fertilizer.org/ifa/statistics.asp, May 2007.

[23] Jiang Z., Sullivan W.M., Hull R.J., 2000. Nitrate uptake and nitrogen use efficiency by Kentucky bluegrass cultivars. Horticulture Science 35 (7), 1350–1354.

[24] Kravcheckov A. N., Thelen K. D., Bullock D. G., and Miller N. R., 2003. Relationship among crop grain yield, topography, and soil electrical conductivity studied with cross correlograms. Agron. J. 95, 1132–1139.

[25] Lawlor D.W., Lemaire G., Gastal F., 2001. Nitrogen, plant growth and crop yield. In Plant nitrogen, P.J. Lea, J.F. Morot Gaudry, (eds.). Berlin: Springer-Verlag. P.343-367.

[26] Le Gouis J., Béghin D., Heumez E. and Pluchard P., 2000. Genetic differences for nitrogen uptake and nitrogen utilization efficiency in winter wheat. Eur. J. Agron. 12:163– 173.

[27] Leifert C, Golden M, Duncan C. L. H., Dykhuizen R., Frazer R., Johnston P., MacKnight G., Smith L., Lamza K., McKenzie H., Batt L., Kelly D., Benjamin N., 1997. Protection against oral and gastrointestinal diseases: importance of dietary nitrate intake, oral nitrate reduction and enter salivary nitrate circulation. Department of Plant & Soil Science, University of Aberdeen, Scotland, U.K.; 118(4):939-48.

[28] Lemaire G., Millard P., 1999. An Ecophysiological approach to modelling resource fluxes in competing plants. Journal of Experimental Botany 50: 15-28.

[29] Lemaitre, T., Gaufichon, L., Boutet Mercey, S., Christ, A., and Masclaux Daubresse C., 2008. Enzymatic and metabolic diagnostic of nitrogen deficiency in Arabidopsis thaliana Wassileskija accession. Plant and Cell Physiology.49:1056–1065.

[30] London J.G., 2005. Nitrogen study fertilizes fears of pollution. Nature 433:791.

[31] Magen H., and V. Nosov, 2008. Putting Potassium in the Picture: Achieving Improved Nitrogen Use Efficiency. In: IPI-BFA-BRRI International Workshop on Balanced Fertilization for Increasing and Sustaining Productivity. 30 March -1 April 2008, Dhaka, Bangladesh.

[32] Matson P. A., Naylor R.L. & Ortiz-Monasterio,1998. Integration of Environmental, Agronomic, and Economic Aspects of Fertilizer Management Environment. Science 280, 112–115.

[33] Moll R.H., 1982. Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. Agronomy Journal 74, 562–564.

[34] Mosier A.R., 2001a. Exchange of gaseous nitrogen compounds between terrestrial systems and the atmosphere. In Nitrogen in the Environment: Sources, Problem, and Management, ed. R.F. Follett and J.L. Hatfield, 291-309. Amsterdam: Elsevier.

[35] Mosier A.R., Syers J.K., Freney J.R., 2004. Agriculture and Nitrogen Cycle. Island Press, Washington, D.C., p. 296.

[36] Nielsen R. L., 2006. Nitrogen loss mechanisms and nitrogen use efficiency. Purdue Nitrogen Management Workshops.

[37] Pan J., Zhu Y., Jiang D., Dai T., Li Y.and Cao W., 2006. Modeling plant nitrogen uptake and grain nitrogen accumulation in wheat. Field Crop Res., 97: 322-336.

[38] Prasad R.,1998. Fertilizer urea, food security, health and the environment. Current Science 75:677-683.

[39] Schlesinger W. H., 1997. Biogeochemistry: An Analysis of Global Change‘‘, 2nd edn, Academic Press, San Diego, CA.

[40] Smil V., 1999. Nitrogen in crop production: An account of global flows. Global Biogeochem. Cycles 13:647-662.

[41] Stevenson F.J. John Wiley & Sons,1994. Humus chemistry: Genesis, Composition, Reactions. 2nd ed., New York.

[42] Suprayogi Y., Clarke J. M., Bueckert R., Clarke F. R., Pozniak C. J., 2011. Nitrogen remobilization and post-anthesis nitrogen uptake in relation to elevated grain protein concentration in durum wheat. Canadian Journal of Plant Science, 2011, 91(2): 273-282, 10.4141/CJPS10185.

[43] Van Lauwe B., Palm C. A., Murwira H. K., and Merckx R., 2002. Organic resource management in sub-Saharan Africa: validation of a residue quality-driven decision support system. Agronomy Journal Vol 22 pp839-846.

[44] Wang X. & Below F.E., 1992. Root growth, nitrogen uptake, and tillering of wheat induced by mixed-nitrogen source. Crop Science 32, 997-1002.

[45] World Health Organization (WHO), 2003. Diet, Nutrition and the Prevention of Chronic Diseases: Report of a Joint WHO/FAO Expert Consultation, WHO Technical Report Series 916, World Health Organization, Geneva.

[46] Youngquist J.B., Bramel-Cox P., Maranville J.W., 1992. Evaluation of alternative criteria for selecting nitrogen use efficient genotypes in sorghum. Crop Science 32: 130-133.

Citation: *Obsa Atnafu, ‘‘Review on Improving Nitrogen Use Efficiency for Cereal Crop Production,’’, International Journal of Forestry and Horticulture, 6(3), pp. 12-19. DOI: https:// doi.org/10.20431/2454-9487.0603002*