Chapter 12

Management strategies for improving nitrogen use efficiency in rice based system under various rice ecologies

A.K. Shukla[1*], A.K. Nayak[2], R. Raja[2], Mohammad Shahid[2] and B.B. Panda[2]
[1]Indian Institute of Soil Science, Bhopal, Madhya Pradesh, India
[2]Central Rice Research Institute, Cuttack, Odisha, India
*e-mail: arvindshukla2k3@yahoo.co.in

The impact of modern agriculture on natural resources has become a major global concern. Aiming at improving resource-use efficiencies, in high-input systems the focus should be on more yield with less fertilizer nitrogen (N). In low-input systems additional use of N fertilizer may be required to increase yield level and yield stability. In order to achieve a higher agronomic nitrogen use efficiency (NUE), it is inevitable that N supply should match N demand in time and space, not only for single crops but for a crop rotation as an integrated system. Nitrogen is the most important mineral nutrient for cereal production, and an adequate supply is essential for high yields, especially with modern cultivars in many agro ecosystems including rainfed and irrigated rice-based systems (Spiertz, 2010). External N application is critical for intensive rice production as appropriate N inputs enhance soil fertility, sustainable agriculture, food security (enough calories) and nutrition security (appropriate supply of all essential nutrients, including protein). High grain yields can only be obtained when rice crop assimilates adequate amounts of N in the course of growing season (Shukla et al., 2004). Although di-nitrogen gas (N_2) is the most abundant component of the earth's atmosphere, it can not be used directly by plants, with the exception of some plant species (e.g. legumes) that have developed symbiotic systems with N_2-fixing bacteria. Owing to the strong bond between its two N atoms, N_2 is almost inert and thus non-reactive. It requires a high energy input to convert N_2 into plant available, reactive N forms. By contrast, reactive nitrogen (Nr) species, such as NH_3, NH_4^+, NO_x, HNO_3, NO_3^-, N_2O and organic N forms, exist only in small quantities under natural environmental conditions (Galloway et al., 2008). The growing complexity of managing N in sustainable agricultural systems calls for problem-oriented, interdisciplinary research. A major point of concern for many intensively managed agricultural systems with high external inputs is the low resource-use efficiency, especially for N. A high input combined with a low efficiency ultimately results in environmental problems such as soil degradation, eutrophication, pollution of groundwater, and emission of ammonia and greenhouse gases. Evidently, there is a need for a transition of current agricultural systems into highly resource-use efficient systems that are profitable, but at the same time ecologically safe and socially acceptable. Here, opportunities to improve NUE in various rice ecologies are analyzed and discussed.

Rice ecologies

The importance of rice in global concerns regarding food security, poverty alleviation, preserving cultural heritage, and sustainable development has been understood very well. More than 90% of the world's rice is grown and consumed in Asia. Between now and 2020, about 1.2 billion new rice consumers will be added in Asia. Feeding these people will require the greatest effort in the history of agriculture, especially rice production. In Asia, rice is grown in 135 m ha with an annual production of 516 m t. Rice area covered by rainfed lowland and flood prone ecosystem are the most unfavorable rice ecosystem is about 35%, which is next to irrigated ecosystem (55%). The average productivity in rainfed lowland and flood-prone ecosystem is very low (1.5 – 2.8 t ha^{-1}) as compared to the irrigated ecosystem (4.9 t ha^{-1}).

Of the total rice area in India, 43.8% is irrigated, 14.6% is upland, 30.1% is rainfed lowland and 11.4% is flood-prone. In general, rice yield is very low in rainfed lowland and flood-prone ecosystem as compared to irrigated ecosystem. Rice productivity in different ecosystems are 3.6, 0.8, 2.4 and 1.5 t ha^{-1}, respectively.

Each system is different from the other with respect to varieties grown, methods of cultivation and soil and water management practices followed**.** Irrigated rice is grown in bunded fields with ensured irrigation for one or more crops a year; so that 5–10 cm of water can be maintained in the field. Rainfed lowland rice is grown in bunded fields that are flooded with rainwater for at least part of the cropping season. Rainfed rice environments experience multiple abiotic stresses and high uncertainty in timing, duration, and intensity of rainfall. Because of the environment prevailed, the farmers rarely apply fertilizer to the rice crop. Rainfed upland rice is grown under dryland mostly under direct seeded conditions. Upland environments are highly variable with respect to climate, soils type, and topography. Since rice production systems vary widely in their macro and micro environment, each system has its unique effect on carbon nitrogen dynamics in soil-plant-atmosphere continuum and hence there is wide spread variation in N loss from the system. Irrigated rice consumes about 8 to 9 m t of fertilizer N annually, which is about 10% of total N production in the world. In general most of the N applied to rice crop is lost through various mechanisms like volatilization, denitrification and leaching. Hence, rice systems are a major contributor to the accumulation of Nr compounds in the environment.

The nitrogen cycle

The N cycle refers to the circulation of N compounds through the Earth's atmosphere, hydrosphere, biosphere and pedosphere. At various points in this cycle, Nr compounds become involved in processes that can affect human health and the environment in both positive and negative ways. Nitrogen moves from the soil to the plant, and back from the plant to the soil, often with animals or humans as intermediates. The real situation is however more complex as N compounds undergo a number of transformations in the soil (mineralization, immobilization, nitrification and denitrification) and are exchanged between soil and the atmosphere (through volatilization, denitrification, biological N fixation, atmospheric deposition) and between soil and the hydrosphere (through leaching, erosion/runoff, irrigation). These transformations and fluxes constitute the soil N cycle. In 1995-96, 10.8 Tg N was applied as nitrogenous fertilizers to agricultural soils in India; another 1.14-1.18 Tg N was added through biological nitrogen fixation. Velmurugan et al. (2008) estimated the soil N pool other than forest to be as large as 1046 to 2581 Tg N. The proportion of N contained in soil which is actively recycled in the soil-plant system is not known with certainty. Crude estimates show that Indian agricultural systems produce annual harvest that removes ~4.13 Tg N from the total crop N pool of ~12.47 Tg N. Further, ~1.9 Tg N is removed from the crop N pool and used for fuel, which in turn released N_2O into atmosphere. The nitrogen contained in plants was either recycled or was supplied to consumers such as animals (~5.81 Tg N) or people (~0.57 Tg N). India has the largest livestock population in the world and the livestock biomass N pool was estimated to be ~1.62 Tg of N. The animals in turn may return a portion of the N to the system as manure. Animals, such as birds or insects also harvest some N and may return it to the system as excreta and corpse which are difficult to estimate. Organic manure is one of the important sources of N used in crop production. It is produced from crop, animal and human wastes and added ~0.17 Tg N to the soil during 1995-96. The wet N deposition (NO_3^- and NH_4^+) in agricultural soils in India during 1995-96 as estimated by Velmurugan et al. (2008) worked out to be ~0.81 Tg N. Nitrate N leaching beneath agricultural soils and through runoff was estimated to be ~0.06 Tg N. This agricultural leaching and run-off result in nitrate pollution of ground water bodies or N enrichment of river systems. Since irrigation is one of the essential components of modern agricultural production systems, ground water is utilized to irrigate ~36.25 m ha in India. As a result, 0.11 Tg N in the form of NO_3^- contained in the ground water is brought back into the agricultural production system.

Nitrogen use efficiency: Terms and calculations

Partial factor productivity *(kg product/kg N applied)*: crop yield per unit N applied.

Agronomic efficiency *(kg grain increase/kg N applied)*: crop yield increase per unit N applied.

Recovery efficiency *[(fertilized crop N uptake-unfertilized crop N uptake)/N applied]*: increase in N uptake by the crop per unit N added, usually for the first crop following application and usually expressed as a percent or fraction.

Removal efficiency *(crop N removal/N applied)*: N removed by the harvested portion of the crop per unit N applied, usually expressed as a percent or fraction.

Physiological efficiency *(kg grain increase/kg fertilizer N uptake)*: crop yield increase per unit fertilizer N taken up.

Improving nitrogen use efficiency in rice

A recent review of worldwide data on NUE for cereal crops from researcher-managed experimental plots reported that single-year fertilizer N recovery efficiencies averaged 65% for corn, 57% for wheat, and 46% for rice (Ladha et al., 2005). However, experimental plots do not accurately reflect the efficiencies obtainable on-farm. Differences in the scale of farming operations and management practices (i.e. tillage, seeding, weed and pest control, irrigation, harvesting) usually result in lower nutrient use efficiency. Nitrogen recovery in crops grown by farmers rarely exceeds 50% and is often much lower. A review of best available information suggests average N recovery efficiency for fields managed by farmers' ranges from about 20% to 30% under rainfed conditions and 30% to 40% under irrigated conditions. Cassman et al. (2002) and Shukla et al. (2004) looked at N fertilizer recovery under different situations (Table 1) and found N recovery averaged 31% for irrigated rice grown by Asian farmers and 40% for rice under field specific management. Fertilizer nutrients applied, but not taken up by the crop, are vulnerable to losses from leaching, erosion, and denitrification or volatilization in the case of N, or they could be temporarily immobilized in soil organic matter to be released at a later time, all of which impact apparent use efficiency.

Fertilizer use efficiency can be optimized by fertilizer best management practices that apply nutrients at the right rate, time, and place. The highest nutrient use efficiency always occurs at the lower parts of the yield response curve, where fertilizer inputs are lowest, but effectiveness of fertilizers in increasing crop yields and optimizing farmer profitability should not be sacrificed for the sake of efficiency alone. There must be a balance between optimal nutrient use efficiency and farmer profitability.

TABLE 1. *Nitrogen fertilizer recovery by rice from on-farm measurements*

Region	Number of farms	Average N levels kg N ha^{-1} (± SD)	REN % (± SD)
Asia-field specific management	179	117 ± 39	31 ± 18
Asia-field specific management (LCC)	179	112 ± 28	40 ± 18
Uttar Pradesh- farmers practice	75	138 ± 32	32 ± 11
Uttar Pradesh-LCC based	75	105 ± 15	49 ± 8

Source: Cassman et al. (2002); Shukla et al. (2004)

Strategies to enhance nitrogen use efficiency

Nitrogen management is the key for sustainable and profitable rice production in India. The fertilizer N use efficiency depends upon potential of cultivars, time, method, rate and source of N fertilization and rice ecologies. Traditional cultivars generally grown in water logged lowlands are low fertilizer responsive and are therefore raised either without fertilization (NPK) or with low doses of applied N, which is the major cause for low rice yield and optimal crop productivity. Many strategies have been developed to increase the efficiency of urea-N through proper timing, rate, placement, modified forms of fertilizer, and use of nitrification and urease inhibitors (Ladha et al., 2005; Shukla et al., 2004, 2006; Bijay Singh et al., 2008). The response to added nutrients varies markedly due to differences in weather, genotype, soil, agronomic practices, water regime, pest management, and crop history. Despite these differences, it is necessary to develop strategies to improve fertilizer-use efficiency.

Right rate

Rice is grown in different ecologies depending on cultivar, management practices, climate, etc. So it is critical that realistic yield goals are established and that nutrients are applied to meet the target yield. Over- or under-application will result in reduced nutrient use efficiency or losses in yield and crop quality. Soil testing remains one of the most powerful tools available for determining the nutrient supplying capacity of the soil, but to be useful for making appropriate fertilizer recommendations good calibration data is also necessary. Unfortunately, soil testing is not available in all regions of India because laboratories are using different methodology which are inaccessible or calibration data relevant to current cropping systems and yields are lacking. Other techniques, such as omission plots, are proving useful in determining the amount of fertilizer required for attaining a yield target. In this method, N, P, and K are applied at sufficiently high rates to ensure that yield is not limited by an insufficient supply of the added nutrients. Target yield can be determined from plots with unlimited NPK. One nutrient is omitted from the plots to determine a nutrient-limited yield. For example, an N omission plot receives no N, but sufficient P and K fertilizer to ensure that those nutrients are not limiting yield. The difference in grain yield between a fully fertilized plot and an N omission plot is the deficit between the crop demand for N and indigenous supply of N, which must be met by fertilizers. Nutrients removed in crops are also an important consideration. Unless nutrients removed in harvested grain and crop residues are replaced, soil fertility will be depleted.

Right time/ Site specific nitrogen management

The most efficient management practice to maximize plant uptake and minimize losses is to synchronize the N supply with the plant demand. This general concept of balancing supply and demand implies maintaining low levels of mineral N in soil when there is little or no plant growth, and providing sufficient N to meet plant requirements during periods of rapid growth (Peoples et al., 1995, Balasubramanian et al., 1998, 2004). Blanket fertilizer N recommendations, developed for large tracts having similar climate and land forms in rice based systems in India cannot help to increase NUE beyond a limit. Nitrogen use efficiency can be improved by adopting fertilizer, soil, water, and crop management practices that will maximize crop N uptake, minimize N losses, and optimize indigenous soil N supply. Further improvement can be achieved only by planning strategies for fertilizer N management responsive to temporal variations in crop N demand and field-to-field variability in soil-N supply. Improvement in the synchrony between crop N demand and the N supply from soil or the applied N fertilizer is likely to be the most promising strategy to improve NUE. Site-specific N management requires quantitative knowledge of crop nutrient need and expected indigenous nutrient supply and can be aimed at improving the recovery efficiency of applied fertilizer. The basic objective is to optimize the congruence of supply and demand of N (Giller et al., 2004). Depending on when and what decisions are made, site-specific N management (SSNM) can be (1) prescriptive, (2) corrective, or (3) a combination of both (Dobermann et al., 2004). In prescriptive N management, the amount and timing of N applications are prescribed before seeding based on N supply from indigenous sources, expected crop N demand, which is calculated from the target yield, expected efficiency of fertilizer N, and the expected risk from weather and pests. While prescriptive N management relies on information generated before the planting of a crop, corrective N management methods employ diagnostic tools to assess soil or crop N status during the growing season. Management decisions that increase fertilizer N use by crops can focus on two approaches: (1) increase fertilizer N use during the growing season when the fertilizer is applied and (2) decrease fertilizer N losses, thereby increasing the potential recovery of residual fertilizer N by the subsequent crops. Removing plant growth limiting factors would increase crop demand for N, leading to a greater use of available N and, consequently, higher NUE (Balasubramanian et al., 2004).

Poor fertilizer N use efficiency for rice production in India is an accepted fact. The agronomic N use efficiency (AEN) of the farmers' N-fertilizer practice is 5.2±3.4 kg kg^{-1} for the irrigated rice crop (Shukla et al., 2004, Bijay Singh et al., 2008, Pathak et al., 2006). A well-managed rice crop should have an AEN of 15–25 kg kg^{-1} under irrigated conditions if the N input is optimal. Nitrate leaching subject to excessive N input was one of the major causes for poor fertilizer N use efficiency in Indo-Gangetic plains of India while gaseous N losses is dominant cause in traditional rice growing areas. Furthermore, excessive N is applied mostly in the vegetative stage during the early growing season i.e., 56–85% of total N in the first 10 days after transplanting (Shukla et al., 2006). The improper timing of N application also contributed to the poor fertilizer N use efficiency for rice production.

The International Rice Research Institute (IRRI) developed site-specific N management (SSNM) such as real-time N management (RTNM) and fixed-time adjustable-dose N management (FTNM) to increase the fertilizer N use efficiency of irrigated rice. In RTNM, a certain rate of N fertilizer is applied only when leaf N content is below a critical level. Therefore, the timing and number of N applications and total N rates vary across seasons and locations. Leaf N content can be estimated non-destructively with a soil plant analysis development (SPAD) chlorophyll meter or leaf color chart (LCC) (Balasubramanian et al., 1998; Shukla et al., 2004). In FTNM, yield response to N application is estimated based on the difference between grain yield with a zero-N control and the target yield. The target yield is usually set at 85% of climatic yield potential. Total N rate is estimated based on the yield response and the target AEN. Total N is applied split at basal, mid-tillering, panicle initiation and heading. The rates of N topdressing at the key growth stages are adjusted according to leaf N status measured with SPAD or LCC. In this approach, the timing and number of N applications are fixed while the rate of each N application varies across seasons and locations.

Evaluation of RTNM in many Asian rice growing countries has generally shown that the same rice yield could be achieved with about 20–30% less N fertilizer applied, but increases in yield were rare (Peng et al., 1996; Balasubramanian et al., 1998; Singh et al., 2002). However, across eight sites in Asia, average grain yield increased by 11% and average N recovery efficiency (REN) increased from 31 to 40% by using FTNM compared with farmers' N fertilizer management (Dobermann et al., 2002). Experiment conducted at farmers field showed increase in recovery efficiency from 32±11 to 49±8 kg grain kg^{-1} N in sandy loam soils of Upper-Gangetic plains of India (Shukla et al., 2006). It has also been shown that both RTNM and FTNM could improve fertilizer N use efficiency of rice production in India (Ladha et al., 2005).

Chlorophyll meter

The SPAD - chlorophyll meter offers relative measurements of leaf chlorophyll content. Chlorophyll meters have their greatest sensitivity in the deficient to adequate range of N nutrition and have the advantage of being self-calibrating for different soils, seasons and cultivars. Although the chlorophyll meter enables users to quickly and easily measure leaf greenness, which is affected by leaf chlorophyll content, several other factors affect SPAD values. Differences in leaf thickness reflected in specific leaf weight are largely responsible for variations in the relationship between N content and SPAD values (Peng et al., 1993). Moreover, the linear relationship of SPAD values and N status in crops varies, depending on growth stages and cultivars. Finally, environmental and stress factors caused by excess or limited water, deficiency of nutrients other than N, and pests and diseases can also confound the SPAD readings.

Leaf color chart

The LCC, a plant health indicator, has been found to be an ideal tool to optimize the N supply in rice cropping, irrespective of the source of N applied, either inorganic or organic. The LCC is an easy to use, inexpensive and accurate tool for determining N status in rice plants. Conceptually, the LCC is based on the close link between leaf chlorophyll content and leaf N content over divergent growth stages. The LCC depicts gradients of green hues that are based on the wavelength characteristics of rice leaves, from yellowish-green to dark green. Farmers have always used their eyes as a subjective indicator of the rice crop's N status. With the LCC, they can make informed decisions regarding the need for fertilizer applications. Leaf color charts have been used extensively in Asia (Balasubramanian et al., 1998). The use of LCC, relatively an inexpensive tool, has shown great promise in optimizing N use in rice based on colour of the leaf which in turn reflects total N supply in different countries of Asia (Yadvinder-Singh et al., 2007). Farmers can easily use the LCC to quantitatively assess foliar N status and adjust top dressing accordingly as it is proved that the current recommendation of three split application at specified growth stages is not adequate to synchronize N supply with crop N demand (Bijay Singh et al., 2002; Shukla et al., 2004; Alam et al., 2005, 2006). By using LCC farmers saved 11-25 and 18-37 kg N ha^{-1} as compared to recommended dose and their own practice of N fertilization (Shukla et al., 2004) without a loss of rice yield.

Nitrogen management in rainfed lowland ecology

In rainfed lowland rice, split application of fertilizer N is often not practical due to adverse soil–water situations. Hence, the entire required amount of N has to be applied in one single application when the water regime is favorable. A single broadcast application, however, increases N loss. Deep placement of urea super granules (USG) has been proven to improve N fertilizer efficiency. Deep-point placement of urea fertilizer is probably the most effective application method in reducing nitrogen loss except in soils with high percolation rates (Katyal et al., 1985).The placement technology is best suited to conditions where the predominant N loss mechanism is ammonia volatilization rather than leaching or denitrification. Deep placement of USG thus has greater benefit over surface split application on soils with moderate to heavy texture, low permeability and percolation rate and high cation exchange capacity and pH. Environments and management factors conducive to high ammonia volatilization potential would benefit most from deep placement technology. Improved N recovery and efficiency of USG has been well documented for lowland rice, but its market availability and methods to achieve placement pose problems. The technology has very limited adoption because USG is not commercially available or manufactured in most countries and labor requirement is high with hand placement. Manual application creates more difficulties in handling the granules, besides taking 36-42 more hours per hectare, than 2 split broadcast applications of prilled urea. Applicators developed so far have not worked satisfactorily under standing water conditions and in direct seeded rice conditions due to hardness of the soil. Hence, it is necessary to develop a suitable applicator to overcome these difficulties. Alternatively, for direct seeded rice, N fertilizers can be subsoil-banded near seed rows. The placement technology, if adopted by the farmers of the potential lowland areas in eastern India, is expected to give an additional production of 5.6 m t of rice.

Placement technologies

Deep-point placement of USG at 5-10 cm depth (reduced soil layer) is one of the most efficient N management techniques developed for rice. It is, however, labor-intensive and hence, recent research has focused on the development and evaluation of less labor-intensive methods for deep placement, such as pneumatic injection of urea or USG, mechanical deep placement of urea solution, injection as a mud slurry and use of a USG dispenser (De Datta & Buresh, 1989).

Depending on temperature, thickness of polymer coating and moisture permeability co-situs placement of 'control-release urea-N fertilizers (CRUNF)' provides an innovative way to improve NUE and reduce labor. Co-situs placement brings the fertilizer closer to the emerging roots, thus inducing more N uptake, fertilizer recovery and increased efficiency. Better recovery and higher efficiency can also be achieved by matching N release from CRUNF with plant N demand.

Band placement of urea solution

Band placement of urea solution into the anaerobic soil layer has been as effective as deep placement of USG in reducing volatilization losses and improving grain yield (Buresh et al., 2008). The technology, however, has not been tested at farm-level due to its site-specificity, problems in maintaining the peristaltic pump to deliver N solution in subsoil at uniform rates, and greater labor demand than conventional urea application.

Deep-point placement of urea super granules

Agronomic, economic and environmental advantages of deep-point placement of USG have been well established along with the saving of 20-40% of the urea-N for the same grain yield, compared with conventional urea applications. Deep-point placement (5-10 cm depth) in anaerobic soil layer, (i) limits the concentration of N in floodwater and in the surface oxidized layer; (ii) decreases N losses through runoff, ammonia volatilization and denitrification; (iii) minimizes weed use of the applied fertilizer; (iv) minimizes NH_4^+ and P fixation and immobilization; (v) ensures prolonged N availability up to flowering; and (vi) stimulates biological N fixation (BNF) because floodwater concentration remains low.

In using USG, consideration of the following factors should help to ensure agronomic efficiency of deep-placed USG and increase the chances of obtaining additional yield:

1. *Soil factors:* Only use in soils having low water percolation rate and CEC of 10 meq 100 g^{-1} soil.
2. *Plant factors:* Give preference to short- to medium-duration dwarf rice varieties. For the long duration variety, basal deep-placed USG with a suitable topdressing of N as prilled urea at panicle initiation stage would be helpful.
3. *Management factors:* Apply basally 30 to 60 kg USG-N ha^{-1} using only USG of the right weight (1-2 g urea $granule^{-1}$). Place one super granule for each four hills at 7-10 cm soil depth using the right plant population and modified spacing. Use modified 20 × 15 cm or 20 × 20 cm spacing to facilitate efficient placement of USG by hand or machine. Workers should always use the so called traffic lane of the modified spacing for performing all post-transplanting field operations. When deep placement of USG is delayed after transplanting, extra care is necessary to close the holes left at the placement sites. When puddling is inadequate or improper and deep placement is done during transplanting, some care may be required to close the holes.

Slow release fertilizers

Appropriate modification in fertilizer source or management practices can lead to reduced losses of N and increased fertilizer N use efficiency. For example, slow-release N fertilizer developed by coating urea granules with sulphur has been tested *vis-a'-vis* ordinary urea in rice and this material out performed ordinary urea in almost all types of soils (Meelu et al., 1983; Bijay-Singh & Katyal, 1987). Oil derived from seeds of neem (*Azadirachta indica*) contains melicians (generally known as neem bitters) of which Epinimbin, Deacetyl, Salanin and Azadirachtin are the active fractions, which showed dose-dependent nitrification inhibition action (Devakumar & Goswami, 1992). Although it has been established that neem products when applied along with urea are capable of enhancing NUE in rice (Singh & Singh, 1986), large scale use of neem products along with urea could not become possible as process for large-scale coating of urea with neem products was not available. Also, large quantity of neem products required for coating and coated products were not available as per specifications laid down in the Indian Fertilizer Control Order. The form of added N plays a role in regulating N losses and influencing NUE. Nitrogen fertilizers predominantly contain N in the form of ammonia, nitrate or urea. Among these forms, nitrate is the most susceptible to leaching, ammonia the least and urea moderately susceptible. Ammonia and urea are more susceptible to volatilization loss of N than fertilizers containing nitrate. Controlled release compounds have the potential to improve NUE and many different forms are now available. Controlled release N fertilizers offer a good option to reduce N losses from the system because their delayed N release pattern may improve the match with crop demand.

Use of inhibitors

Fertilizer N use efficiency could be greatly increased if the hydrolysis of urea to ammonium by soil urease could be retarded by the use of urease inhibitors, or if nitrate accumulation during the cropping phase could be regulated by nitrification inhibitors.

Urease inhibitors

Several studies using PPD and NBPT as urease inhibitors have been conducted in flooded rice fields (Simpson et al., 1985, Buresh et al., 1988, Cai et al., 1989), but little reduction in NH_3 loss has been achieved by using these compounds as PPD is rapidly hydrolyses under the alkaline conditions or it decomposed due to the high temperatures reached in the floodwater (Chai & Bremner, 1987). Studies with another thiophosphorictriamide, thiophosphoryl triamide, showed that it too was a relatively weak inhibitor of urease activity. Appreciable inhibition was only achieved after it had been converted to its oxon analogue (McCarty & Bremner, 1989; Bremner et al., 1991). These studies indicate that the thiophosphorictriamides do not inhibit urease activity, but that the phosphorictriamides are potent inhibitors of urease activity.

Nitrification inhibitors

Since ammonia or ammonium-producing compounds are the main sources of fertilizer N, maintenance of the applied N in the ammonium form should mean that less N is lost by denitrification. One mechanism of maintaining added N as ammonium is to add a nitrification inhibitor with the fertilizer (Sahrawat et al., 1987). Numerous substances have been tested for their ability to inhibit nitrification, and several of these have been patented. Only a limited number of chemicals are available commercially for use in agriculture. These include 2-chloro-6 (trichloromethyl) pyridine (nitrapyrin), sulfathiazole, dicyandiamide, 2-amino-4-chloro-6-methyl pyrimidine, 2-mercapto-benzothiazole, thiourea and 5-ethoxy-3-trichloromethyl-1,2,4-thiadiazole (terrazole). Unfortunately, most of these compounds have limited usefulness (Keeney, 1983). For example, the most commonly used nitrification inhibitor, nitrapyrin, is seldom effective because of sorption on soil colloids, hydrolysis to 6-chloropicolinic acid and loss by volatilization. Positively charged ammonium N is retained by negatively charged soil colloids and is less subject to leaching and denitrification losses. One method of maintaining N in the soil as ammonium is to add a nitrification inhibitor with the fertilizer. Nitrification inhibitors, which slow the conversion of NH_4^+-N into NO_3^-- N, have been reported to increase NUE and crop yield (Prasad & Power, 1995). Application of these inhibitors could also have considerable influence on emissions of N_2O and methane from soil (Malla et al., 2005; Pathak & Nedwell, 2001). Most of nitrification inhibitors remain unpopular with farmers in South Asia because of their high cost and poor availability. Further research and development are needed to identify cheap locally available materials such as neem cake and neem oil, which can inhibit nitrification and increase NUE.

Conclusions

Since the agricultural N cycle cannot be separated from the global N cycle, hence for improving N use efficiency and to minimize N losses in rice based system, it is required a better understanding of the N cycle at regional level. There is always N flows between the agricultural system and the wider environment. The N supply through indigenous sources should be taken in to account properly for assessing the N need, inevitable losses and NUE for sustainable agricultural production. Nitrogen management should make possible to partly fill the gap between current relatively low NUE levels observed in farmers' fields and results achieved in well-managed research plots. Because more than half of world N consumption takes place in Asia, where farms are predominantly small-scale, the main challenge remains the transfer of improved practices to hundreds of millions of farmers. At the same time, financial support provided to governmental extension services is rapidly declining throughout the world. Partnerships involving governments, the industry and other stakeholders will be required to fill this gap. Considering that N is an essential part of our developmental paradigm, options to minimize N loss from agriculture to wider environment will have to be addressed at many different levels, such as establishing/updating national N information systems, improvements in fertilizer/biofertilizer formulations, enhancement of the N-use efficiency of our crops and farming systems/practices, reduced dependence on non-renewable energy sources, improvements in fossil-fuel quality, fuel-use efficiency and reduction of fossil-fuel use/abuse, reduction in NO*x* emissions from farming, industrial and vehicular sources, minimizing anthropogenic (including agri-industrial) reactive N load in naturally overloaded areas (e.g. geodeposits) and fragile ecosystems, better management of wetland ecosystems, etc.

References

Alam, M.M., Ladha, J.K., Khan, S.R., Foyjunnessa, Rashid, H., Khan, A.H., & Buresh, R.J. (2005). Leaf color chart for managing nitrogen fertilizer in lowland rice in Bangladesh. *Agronomy Journal,* 97, 949-959.

Alam, M.M, Ladha, J.K., Khan, S.R., Foyjunnessa, Rashid, H., Khan, A.H., & Buresh, R.J. (2006). Nutrient management for increased productivity of rice-wheat cropping system in Bangladesh. *Field Crops Research,* 96, 374-386.

Balasubramanian, V., Alves, B., Aulakh, M.S., Bekunda, M., Cai, Z.C., Drinkwater, L., Mugendi, D., Van Kessel, C., & Oenema, O. (2004). Crop, environmental, and management factors affecting N use efficiency. In A.R. Mosier, J.K. Syers, J.R. Freney (Eds.), *Agriculture and the N cycle: Assessing the impacts of fertilizer use on food production and the environment.* (pp. 19-33). Paris, France : SCOPE 65.

Balasubramanian, V., Morales, A.C., Cruz, R.T., & Abdulrachman, S. (1998). On farm adaptation of knowledge intensive N management technologies for rice systems. *Nutrient Cycling in Agroecosystem,* 53, 59-69.

Bijay-Singh, Yadvinder-Singh, Ladha, J.K., Bronson, K.F., Balasubramanian, V., Jagdeep-Singh, Khind, C.S. (2002). Chlorophyll meter and leaf color chart based nitrogen management for rice and wheat in northern India. *Agronomy Journal*, 94, 821-829.

Bijay-Singh & Katyal, J.C. (1987). Relative efficacy of some new urea-based nitrogen fertilizers for growing wetland rice on a permeable alluvial soil. *Journal of Agricultural Science (Cambridge),* 109, 27-31.

Bijay-Singh, Shan, Y.H., Johnson-Beebout S.E., Yadvinder-Singh and Buresh, R.J. (2008). Crop residue management for lowland rice-based cropping systems in Asia. *Advances in Agronomy,* 98, 201-270.

Bremner, J.M., McCarty, G.W., & Higuchi, T. (1991). Persistence of the inhibitory effects of phosphoroamides on urea hydrolysis in soils. *Communications in Soil Science and Plant Analysis,* 22, 1519-1526.

Buresh, R.J., De Datta, S.K., Padilla, J.L., & Chua, T.T. (1988). Potential of inhibitors for increasing response of lowland rice to urea fertilization. *Agronomy Journal,* 80, 947-952.

Buresh R.J., Reddy K.R., & van Kessel, C. (2008). Nitrogen transformations in submerged soils. In J.S. Schepers, W.R. Raun (Eds.), *Nitrogen in agricultural systems.* Agronomy Monograph 49. (pp. 401-436). Madison, Wisconsin, USA: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Cai, G.X., Freney, J.R., Muirhead, W.A., Simpson, J.R., Chen, D.L., & Trevitt, A.C.F. (1989). The evaluation of urease inhibitors to improve the efficiency of urea as a N-source for flooded rice. *Soil Biology and Biochemistry*, 21, 137-145.

Cassman, K.G., Dobermann, A., & Walters, D. (2002). Agroecosystems, nitrogen use efficiency, and nitrogen management. *Ambio*, 31, 132-140.

Chai, H.S., & Bremner, J.M. (1987). Evaluation of some phosphoroamides as soil urease inhibitors. *Biology and Fertility of Soils*, 3, 189-194.

De Datta, S.K., & Buresh, R.J. (1989). Integrated nitrogen management in irrigated rice. *Advances in Soil Science*, 10, 143-169.

Devakumar, C., & Goswami, B.K. (1992). Nematicidal principles from neem isolated and bioassay of some melicians. *Pesticide Research Journal*, 4, 79-84.

Dobermann, A., Witt, C., & Dawe, D. (Eds.). (2004). *Increasing productivity of intensive rice systems through site-specific nutrient management*. (pp. 101-286). Enfield, N.H. and Los Banos, Philippines: Sci. Publ./ IRRI.

Dobermann, A., Witt, C., Dawe, D., Abdulrachman, S., Gines, H.C., Nagarajan, R., Satawathananont, S., Son, T.T., Tan, P.S., Wang, G.H., Chien, N.V., Thoa, V.T.K., Phung, C.V., Stalin, P., Muthukrishnan, P., Ravi, V., Babu, M., Chatuporn, S., Sookthongsa, J., Sun, Q., Fu, R., Simbahan, G.C., & Adviento, M.A.A. (2002). Site-specific nutrient management for intensive rice cropping systems in Asia. *Field Crops Research*, 74, 37-66.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z.C., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., & Sutton, M.A. (2008). Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science*, 320, 889–892.

Giller, K.E., Chalk, P.M., Dobermann, A., Hammond, L., Hever, P., Ladha, J.K., Maene, L., Nyamudeza, P., Sali, H., & Freney, J.R. (2004). Emerging technologies to increase the efficiency of use of fertilizer nitrogen. In A.R. Mosier, J.K. Syers, J.R. Freney (Eds.), *Agriculture and the N Cycle: Assessing the impacts of fertilizer use on food production and the environment.* (pp. 35-51). Paris, France : SCOPE 65.

Katyal, J.C., Bijay-Singh, Vlek, P.L.G., & Craswell, E.T. (1985). Fate and efficiency of nitrogen fertilizers applied to wetland rice in Punjab, India. *Fertilizer Research*, 6, 279-290.

Keeney, D.R. (1983). Factors affecting the persistence and bioactivity of nitrification inhibitors. In J.J. Meisinger, G.W. Randall, M.L. Vitosh (Eds.), *Nitrification Inhibitors- Potentials and limitations*. (pp. 33-46). Madison: American Society of Agronomy.

Ladha J.K., Pathak H., Krupnik T.J., Six J., & van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy*, 87, 85-156.

Malla, G., Bhatia, A., Pathak, H., Prasad, S., Jain, N., & Singh, J. (2005). Mitigating nitrous oxide and methane emissions from soil under rice–wheat system with nitrification and urease inhibitors. *Chemosphere*, 58. 141-147.

McCarty, G.W., & Bremner, J.M. (1989). Formation of phosphoryl triamide by decomposition of thiophosphoryl triamide in soil. *Biology and Fertility of Soils*, 8, 290-292.

Meelu., O.P., Rekhi, R.S., Brar, J.S., & Katyal, J.C. (1983). Comparative efficiency of different modified urea materials in rice. In Proceedings of the Fertilizer Association of India Northern Region Seminar on Fertilizer Use Efficiency. (pp. 47-59). New Delhi: The Fertilizer Association of India.

Pathak, H., & Nedwell, D.B. (2001). Strategies to reduce nitrous oxide emission from soil with fertilizer selection and nitrification inhibitor. *Water Air and Soil Pollution*, 129, 217-228.

Pathak H., Li, C., Wassmann, R., & Ladha, J.K. (2006). Simulation of nitrogen balance in the rice-wheat systems of the Indo- Gangetic plains. *Soil Science Society of America Journal*, 70, 1612-1622.

Peng, S., Garcia, F.V., Laza, R.C., & Cassman, K.G. (1993). Adjustment for specific leaf weight improves chlorophyll meter's estimate of rice leaf nitrogen concentration. *Agronomy Journal,* 85, 987-990.

Peng, S., Garcia, F.V., Laza, R.C., Sanico, A.L., Visperas, R.M., & Cassman, K.G. (1996). Increased N-use efficiency using a chlorophyll meter on high yielding irrigated rice. *Field Crops Research,* 47, 243–252.

Peoples, M.B., Freney, J.R., & Mosier, A.R. (1995). Minimizing gaseous losses of nitrogen. In P.E. Bacon (Ed.), *Nitrogen fertilization in the environment*. (pp. 565-602). New York: Marcel Dekker.

Prasad, R., & Power, J.F. (1995). Nitrification inhibitors for agriculture, health and the environment. *Advances in Agronomy,* 54, 233-281.

Sahrawat, K.L., Keeney, D.R., & Adams, S.S. (1987). Ability of nitrapyrin, dicyandiamide and acetylene to retard nitrification in a mineral and an organic soil. *Plant and Soil,* 101, 179-182.

Shukla, A.K., Singh V.K., Dwivedi B.S., Sharma S.K., & Singh, Y. (2006). Nitrogen use efficiencies using leaf colour chart in rice (*Oryza sativa*) and wheat (T*riticum aestivam*) cropping system. *Indian Journal of Agricultural Sciences,* 76, 651-656.

Shukla, A.K., Ladha, J.K., Singh, V.K., Dwivedi, B.S., Blasubramanian, V., Gupta, R.K., Sharma, S.K., Singh, Y., Pathak, H., Pandey, P.S., Padre, A.T., & Yadav, R.L. (2004). Calibrating the leaf color chart for nitrogen management in different genotypes of rice and wheat in a system perspective. *Agronomy Journal,* 96, 1606-1621.

Simpson, J.R., Freney, J.R., Wetselaar, R., Muirhead, W.A., Leuning, R., & Denmead, O.T. (1985). Transformations and losses of urea nitrogen after application to flooded rice. *Australian Journal of Agricultural Research,* 35, 189-200.

Singh, M., & Singh, T.A. (1986). Leaching losses of nitrogen from urea as affected by application of neem-cake. *Journal of the Indian Society of Soil Science,* 34, 766-773.

Singh, B., Singh, Y., Ladha, J.K. et al. (2002). Chlorophyll meter- and leaf color chart-based nitrogen management for rice and wheat in northwestern India. *Agronomy Journal,* 94, 821-829.

Spiertz, J.H.J. (2010). Nitrogen, sustainable agriculture and food security: A review. *Agronomy for Sustainable Development,* 30, 43-55.

Velmurugan A., Dadhwal V.K., & Abrol Y.P. (2008). Regional nitrogen cycle: An Indian perspective. *Current Science,* 94, 1455-1468.

Yadvinder Singh, Singh, B., Ladha, J.K., Bains, J.S., Gupta, R.K., Singh, J., & Balasubramanian, V. (2007). On-farm evaluation of leaf color chart for need-based nitrogen management in irrigated transplanted rice in northwestern India. *Nutrient Cycling in Agroecosystem,* 78, 167-176.

*****