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Enhancing nutrient-use efficiency in crop production – A review

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ABSTRACT

The nutrient-use efficiency of all the major, secondary and micronutrients continuous to be low despite increasing consumption of fertilizers in India. Improvement in nutrient-use efficiency is necessary to reduce the cost of production as well as to prevent environmental pollution. Adoption of best management practices is essential to get higher input-use efficiency and profitability. Among all the major nutrients, nitrogen is most vulnerable, and increasing its use efficiency through physical manipulation of the size of granules, coating of granules with films, amendments or chemicals to prevent their fast dissolution or prevent bacterial-mediated denitrification did not prove economically viable. Split application is effective but costly. Reliance on biological N_2 fixation through inclusion of legumes in cropping system and maintenance of higher soil organic matter will help to build-up soil fertility and better soil physical and microbial environment with good buffering capacity. The recent developments in the field of biological nitrification inhibition offer good opportunity in effective nitrate management. Identification of efficient genotypes for low nutrient situations or higher response to applied nutrients through better acquisition and assimilation are encouraging. Phosphorus management should consider proper source and the cumulative effects that can be exploited through biological processes for nutrient availability and root acquisition. Adoption of conservation tillage, site-specific nutrient management and best fertilizer management practices will go a long way in increasing nutrient-use efficiency. Adoption of new technology through the gadgets such as leaf colour charts, sensor-based technology, laser land leveling etc. can reduce the dependence on laboratory assistance and manual labour.

Key words: Balanced fertilization, Biological nitrification inhibition, Nutrient-use efficiency, Site-specific nutrient management

Nutrient use for agricultural production is essential to increase food production but it is a major cause of pollution. With the discovery that plant growth requires nutrient elements in addition to the basic factors of soil, water and air, agricultural production has increased by leaps and bounds. The manipulability of nutrient production and application has provided easier options to overcome the limitations of a desired soil quality for optimum crop production. The urgency for higher agricultural production and the greed for higher profits have made nutrient applications in agriculture unscientific with more wastage leading to pollution of soil, air and water.

Although fertilizer consumption is increasing quantitatively, the corresponding yield increase per unit of nutrient is substantially diminishing over the years. Nutrient-use efficiency depends on several agronomic factors including tillage, time of sowing, appropriate crop variety, proper planting or seeding, sufficient irrigation, weed control, pest/disease management, and balanced and proper nutrient use. These factors largely influence nutrient-use efficiency, either individually or collectively. For example, selection of proper planting material, population density, and balanced fertilization could collectively improve nutrient-use efficiency by 25 to 50% (Rao, 2007).

Soil degradation is occurring due to inadequate and imbalanced fertilization leading to nutrient mining and development of second generation problems in nutrient management. The estimated supply-demand gap would be about 1.8 million tonnes of N and 1.9 million tonnes of P by 2011-12. The entire demand for K will continue to be met through imports. It is of concern that the partial factor productivity of fertilizers has been continuously declining. The efficiency of fertilizer N is only 30-40% in rice and 50-60% in other cereals, while the efficiency of fertilizer P is 15-20% in most crops. The efficiency of K is 60-80%, while that for S is 8-12%. As regards the micronutrients, the efficiency of most of them is <5% (NAAS, 2006). Low nutrient recovery efficiency not only increases cost of crop production but also causes environmental pollution.

The developed economies of the world (France, Japan, USA, UK) operate at potential yields of crops, with highest rate of fertilizers per unit area (300 to 600 NPK kg/ha). In USA, the fertilizer-N efficiency in maize has increased by >30% over the last 20 years (Fixen and West, 2002). In

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Japan, fertilizer N use has decreased by about 30% from 1960 to 2000, while keeping a little increase in cereal yields. This has resulted in significant increase in apparent N-use efficiency, in particular for rice (Yagi and Minami, 2005). In our country operating at the lowest productivity of most crops, the fertilizer consumption has reached 107 kg/ha. Yet, our advantage to achieve higher use efficiency or recovery even at this low rate of application is not realized due to the limiting agro-ecological conditions of crop production. Large areas of cropping under rainfed condition, uncontrolled water application in irrigated agriculture, imbalanced fertilization, tropical climate, cultivation of traditional crops and varieties/genotypes, above all, general low investment capacity of farmers result in low nutrient-use efficiency and profitability.

Nutrient-use efficiency can be expressed in agronomic, physiological, and economic terms. It is primarily judged as a portion of crop uptake (the end-point of nutrient flow and accumulation in production systems) out of the applied nutrient (through different sources). The expression is a ratio of crop uptake to total supply (applied + native) or incremental increase. Agronomic efficiency means the crop response to applied nutrients. The crop response to applied nutrients typically follows a diminishing return function as yields approach the potential limit. The complexity further aggravates owing to the additional limitations of moisture, nutrient imbalance, inadequate plant stand, pest incidence, weed infestation etc.

Two main strategies to improve nutrient-use efficiency are:

Product strategy: Enhanced efficiency of fertilizers.

Primary focus is on product features, viz. coated fertilizers, slow-release fertilizers, nitrification inhibitors and urease inhibitors.

Fertilizer management strategy: Enhanced efficiency of fertilization

Primary focus is on nutrient management, viz. split application, N rate based on plant analysis, variable rate (time and space, precision farming).

Bottlenecks and strategies for increasing nutrient-use efficiency can be well understood by analyzing the pathways of nutrients reaching the plant roots and its uptake and incorporation in plant tissues. Both these processes can be delineated as the factors external to plant and the factors internal to plant. This review is presented in the light of the processes and mechanisms that lead to increasing the use efficiency of applied nutrients.

New sources or materials

Numerous products supplying plant nutrients have emerged, offering a variety of nutrient contents, physical forms, and other properties to meet individual needs. Finding new sources of fertilizers and modifiers to minimize losses, thereby achieve higher use efficiency is a challenging task. Much of the work has been done on N with major source as urea containing high N (46%) and its proneness to losses. Recently due to the patent regime, the details of technologies are not freely available while their effects are published.

The complexities of N management occur due to its solubility, mobility and vulnerability to denitrification. The approaches have been to manipulate the granule size variations, coatings with neem or coal tar, modifiers or additives to control the nutrient release rate (Aulakh and Malhi, 2005; Fageria and Baligar, 2005).

Application of controlled release fertilizers (CRFs) is a new approach for minimizing non-point contamination in agriculture. The CRFs have higher N-use efficiency, thus reducing N loss through leaching and volatilization while keeping higher yields (Mao *et al.*, 2005). The CRF significantly increased the contents of alkalytic N and NH_4^+-N in the paddy soil, facilitating N uptake by the roots of rice (Song *et al.*, 2005). The CRF applied at $^1/_3$rd of the rate of common urea fertilizer (CUF) also increased the yield by 15.1% and raised NUE up to 51.2%. The CRF showed advantages in controlling release of N, promoting N uptake by rice, increasing grain yield and reducing N application. The N uptake efficiency of sesame, upon application of slow-release fertilizers such as cyclodiurea and latex-coated urea, increased by 10-25% in polyethylene film mulching and 3-10% in non-mulching compared with that of urea in silty clay-loam soils of Korea (Lee *et al.*, 2006). Chen *et al.* (2005) showed that single basal application of rice-specific CRFs could increase the use efficiency of N and P by 12.2-22.7% and 7.0-35.0%, respectively in pot experiment, and the use efficiency of N by 17.1% in field experiment.

A slow-release and super-absorbent N fertilizer (SSNF) was synthesized by Liu *et al.* (2005) that had good slow release property as well as excellent soil moisture preservation capacity, which could effectively improve the utilization of fertilizer and water resources simultaneously. The SSNF could be especially useful in drought-prone areas where the availability of water is insufficient.

New gel-based CRFs were developed by mixing and processing N, P and K fertilizers with natural and semi-natural organic materials and inorganic materials (Hong and Zhang, 2006). These gel-based fertilizers were easily produced, had lower price than coated CRFs, and expressed better physical and chemical properties. The gel-based CRFs showed significant positive influence on agronomical, physiological and biochemical characteristics of maize plants. These increased dry biological yield of maize by 26.8~42.3%, and improved N-use efficiency by 17.0~31.7%, P-use efficiency by 8.0~16.0%, and K-use efficiency by 4.6~18.3%. Besides, the nutrients (N, P and K) in gel-based fertilizers were leached more slowly into the soil than common fertilizers.

The IARI's urea coating technology employing neem oil emulsion needing 0.5-1.0 kg neem oil per tonne of urea was found superior to prilled urea (Prasad *et al.*, 2001). The neem coated urea of National Fertilizers Limited recorded better shelf-life, slow dissolution as well as nitrification inhibition property. With marginal additional cost for coating, the product showed increased NUE in Punjab, Uttar Pradesh and Himachal Pradesh (Mangat, 2004).

The use of nitrification inhibitors might contribute to increased NUE or apparent N recovery efficiency. Maintenance of more NH_4^+ available in the soil might also increase P absorption, and therefore increase P-use efficiency (PUE) (Ortega, 2006). The use of ammonium N sources with the nitrification inhibitor 3, 4-dimethylpyrazole phosphate (DMPP) shows promise to increase NUE and PUE. Large granular forms of N and P fertilizer proved better than powdered and prilled forms for increasing nutrient uptake and grain yield of rice in irrigated lowland soils (Subbaiah *et al.,* 2006). Compacting phosphogypsum (PG), diammonium phosphate (DAP), $ZnSO_4$ and KCl separately with urea slowed down urea hydrolysis and reduced NH_3 volatilization loss (Purakayastha and Katyal, 1998a). The new product increased the rice yield and NUE as compared to that obtained with prilled urea. A significant positive correlation between potential N loss (measured by soluble N in floodwater) and NH_3 volatilization (measured by forced air draft system) was also observed (Purakayastha and Katyal 1998b). Thus, NUE could be increased through suitable modification of urea by compacting it with acid and non-acid producing fertilizers such as NH_4Cl, KCl, $ZnSO_4$ and DAP or industrial byproduct like PG.

Coating P fertilizer could limit the contact of applied P with soil resulting in early season deficiencies for crops like wheat. The development of thin polymer coatings has improved the opportunity to coat fertilizer granules and increased the predictability of time of availability of nutrients from the controlled release product. Malhi *et al.* (2002) showed that polymer coating on monoammonium phosphate (MAP) in barley improved plant recovery of fertilizer P and provided modest grain yield advantage compared to uncoated MAP. It was reported that for a coated phosphate product to work, it must reduce short-term P fixation by soil, yet provide adequate release for rapid P uptake in the critical early season period.

Silicate fertilizers increased significantly rice yield and N efficiency. Rates of 1 and 2 times of the recommended Si fertilization decreased the N application level to about 76 and 102 kg N/ha to produce the target yield. Silicate fertilizer improved soil pH and significantly increased available P and Si contents (Chang *et al.*, 2006).

Scope of nanoparticles/materials in slow-release fertilizers

Nanotech materials (scale below 100 microns) are in development for the slow release and efficient dosage of water and plant nutrients for increasing the efficiency of nutrients and water. These inexpensive nanotech applications to increase soil fertility and crop production would be a major growth in agriculture in developing countries in near future. The nanoporous zeolites are being utilized for slow release and efficient dosage of water and fertilizer for plants. In China, Fudao *et al.* (2006) tried different nanoparticles (clay-polyester, humus-polyster and plastic-starch) for slow release of N to wheat. The increase in yield due to clay and plastic (nanomaterial coating) was around 4.5% over chemical fertilizer application apart from savings through leaching losses of N fertilizer. There is great scope in Indian agriculture for improving fertilizer-use efficiency of major crops through nanotechnology.

Organic materials

Organic materials have a major role to play in maintaining buffering capacity of soil and are important for maintaining soil physical and biological properties. A range of factors such as soil temperature, moisture and chemical composition of the organic material influence N release from organic sources in soil. Nitrogen losses also occur from their use. Controlling N release from organic sources depends on their nutrient content and quality, soil properties, and the environmental and management factors (Singh *et al.*, 2001). The build-up of soil organic matter is required to increase the potential for N mineralization. The challenge in optimizing crop N uptake in organic and cover crop-based systems does not entirely rely on developing organic matter pools but is more important to influence the rate and timing of N mineralization. It was found that interactions among inputs (manure, cover crops and fertilizer) and soil organic matter influence the rate of soil N mineralization (Horwath *et al.*, 2006). It is also well known that N from many organic fertilizers often shows little effect on crop growth in the year of application because of the slow release characteristics of organically-bound N. Nitrogen immobilization after application can occur, leading to enrichment of the soil N pool. This process increases the long-term efficiency of organic fertilizers. However, if short-term N release from organic sources is measured as mineral fertilizer equivalents, it varies from

0 (some material) to 100% (urine). Addition of green manure along with NPK was promising during the first three seasons, while FYM along with NPK was better during later three seasons, indicating long-term use of FYM for better yields in rice-rice cropping systems in Vertisols (Subbaiah *et al.*, 2006). In rice–wheat cropping system, grain yields were significantly greater with green manure of *Sesbania* turned into the soil after 30 days of sowing (Yadav, 2004). In general, advantages of green manuring were greater at low levels of N, and the residual effect of green manuring on succeeding wheat was small.

In wheat–soybean cropping system conducted for seven years during 1995-2002 under the fine-textured Vertisols, the highest productivity was obtained when the organic sources were applied along with 100% NPK (Behera and Pandey, 2006). Soil fertility parameters showed conspicuous improvement over the initial status under FYM and poultry manure.

Integrated nutrient management practice of using green leaf manure (*Melia*, neem and subabul) with chemical N fertilizer significantly enhanced N uptake, agronomic efficiency, apparent N recovery and yield of sunflower (Panneer and Bheemaiah. 2005). The combined application of crop residue with 60 kg N/ha and 13.1 kg P/ha in sunflower – groundnut cropping system further improved the yield potential of sunflower by 10-11% and of succeeding groundnut by 10-24% over that of fertilizer N and P (Aulakh, 2007).

Nitrogen-use efficiency was lower on zero-till plots when straw was either burned or removed compared with straw incorporation and straw mulch treatments, particularly at low N rates (Singh *et al.*, 2006c). In groundnut - maize cropping system, incorporation of groundnut stover improved the subsequent maize yield than surface application. A higher N recycling efficiency was observed when residues were incorporated (Sakonnakhon *et al.*, 2005). The seed yield of sunflower in recommended fertilizer treatment was 1.49 t/ha which increased to a maximum of 1.87 t/ha due to incorporation of pigeonpea stalks treated with *Aspergillus awamori* along with recommended fertilizer (Qureshi, 1991). The residual effect of residue incorporation significantly improved the performance of chickpea, with improved physical and fertility parameters.

Asynchrony between N released by organic materials and N demand by the crop leads to low NUE. Nitrogen-use efficiency for maize could be improved when *Glyricidia sepium* prunings were incorporated 4 weeks ahead of maize planting. Addition of small doses of inorganic N fertilizer increased N uptake and yield (Makumba *et al.*, 2006). Application of fertilized green manure such as *Sesbania rostrata* proved superior as compared to paddy straw and FYM on rice yield and residual effect on linseed. Rice yield and N uptake were significantly higher under combined application of green manure and urea N on an equivalent basis. A saving of urea N up to 50% could be achieved by applying 1 t/ha (dry weight) *Sesbania rostrata* in rice (Singh *et al.*, 1999). Srinivas *et al.* (2005) showed that agronomic efficiency and apparent recovery of applied N were higher with *Glyricidia*. It was proved that *Glyricidia* could be used as source of N to crops with partial inorganic N fertilizer. Laxminarayana and Patiram (2005) showed that conjunctive use of organic manure (15 t FYM or 5 t pig manure or 5 t poultry manure/ha) along with inorganic chemical fertilizers resulted in enhanced fertilizer-use efficiency in groundnut. Similar results were reported in mustard (Bhat *et al.*, 2005), maize (Baijukya *et al.*, 2006) and in rice–wheat cropping system (Beri *et al.*, 2004). Alfalfa mulch holds promise for low-input cropping systems, when used on wheat - oat cropping system @ 3.9-5.2 t/ha, produced higher N uptake and grain yield compared with ammonium nitrate. Nitrogen-use efficiency of mulch-supplied N by wheat and oats was between 11 and 68%. The higher nutrient-use efficiency achieved through mulching was due to weed suppression and increased soil moisture conservation (Wiens *et al.*, 2006).

Biological nitrification inhibition

Nitrification results in substantial losses to agricultural systems. As much as 50-70% of the fertilizer N can be lost because of nitrification-associated processes, contributing significantly to global warming, destruction of the ozone layer in the stratosphere through nitrous oxide emissions, and serious nitrate pollution of surface and groundwater bodies. Nitrification inhibition by the ethylene diamine-based chelating agents such as ethylene diamine tetraacetic acid (EDTA), diethylene triamine pentaacetic acid (DTPA), and ethylene diamine (EDA) inhibited ammonium oxidation but did not inhibit nitrite oxidation (Hu *et al.*, 2003). The EDA appears to inhibit nitrifying activity by a different operative mechanism than EDTA and DTPA.

Operationally, the only way to regulate the rate of nitrification in agricultural systems is through application of synthetic nitrification inhibitors or slow-release N fertilizers. Subbarao (2006) discovered that some forage crops e.g. *Brachiaria* grasses have the ability to regulate nitrification in soils by releasing inhibitors through root exudates. This biological mechanism has evolved to minimize N losses associated with nitrification, thus improving NUE. The inhibitory activity produced / released from plants is termed as biological nitrification inhibition (BNI). Wide variation in BNI capacity was recorded among the 18 species tested for it. The BNI capacity could either be managed and/or introduced into pasture / crops with an expression of this phenomenon via genetic improvement approaches that combine high productivity along with some capacity to regulate soil nitrification process (Subbarao *et al.*, 2007). Sustained release of BNI compounds occurred only in the presence of NH_4^+ in the root environment. This is of practical utility that there is no need to change the present sources of N application wherein the BNI activity will be rather triggered.

Nutrient-use efficiency in cropping systems

Individual crop nutrient management relies on the crop requirement matching the soil fertility. Cropping systems with differential requirement and contribution to modifying the rhizosphere by different crops provide newer challenge as well as opportunity for management to achieve higher nutrient-use efficiency. Pigeonpea substitution for rice during monsoon season in rice – wheat cropping system improved wheat yield by 16%, and total N and P uptake by 31 and 10%, respectively. The better N and P-use efficiency in pigeonpea–wheat system was due to improvement in soil physical properties (Singh *et al.*, 2006b). Garcia *et al.* (2006) summarizing the nutrient-use efficiencies in major cropping systems of Argentina reported increased agronomic nutrient-use efficiencies and yield differences over time as a consequence of residual effects on soil fertility.

Role of legumes

The beneficial effect of important legumes on increasing productivity and nutrient use-efficiency in various systems was recently reviewed by Ghosh *et al.* (2007). In alley cropping system, *Leucaena leucocephala* (subabul) prunings provide N to the extent of 75 kg, which benefit castor and sorghum. Legumes with indeterminate growth are more efficient in N_2 fixation than determinate types. Fodder legumes in general are more potent in increasing the productivity of succeeding cereals. Symbiotic N_2 fixation with compatible rhizobial strains resulted in carryover of N for succeeding crops to the tune of 60-120 kg in berseem, 75 kg in Indian clover, 75 kg in clusterbean, 35-60 kg in fodder cowpea, 68 kg in chickpea, 55 kg in urdbean, 54-58 kg in groundnut, 50-51 kg in soybean, 50 kg in *Lathyrus*, and 36-42 kg/ha in pigeonpea. Direct and residual effect of partially-acidulated material and mixture of rock-phosphate + single superphosphate were observed to be better when these were applied to mungbean in winter season than to rice in rainy season simply because of legume effect.

Use of microbial sources

Microbes harbouring rhizosphere of crops provide benefits to crops through better nutrient availability by way of atmospheric N_2 fixation or solubilising fixed mineral forms of nutrients. The symbiotic and non-symbiotic N_2 fixation is well-known phenomenon involving legumes and non-legumes. Rice-based cropping system offers a lot of scope for the effective utilization of a wide range of biofertilizers such as *Azolla, Cyanobacteria, Azospirillum, Rhizobium, Azorhizobium, Acetobacter* and other heterotrophic N_2 fixing bacteria as well as leguminous green manures and phosphate solubilizing bacteria, which help in increasing nutrient-use efficiency and yield by reducing the cost of cultivation.

Phosphorus use efficiency of frenchbean on vertisol was improved when rock-phosphate was applied with FYM or vermicompost at 1 : 2 ratio along with phosphate solubilizing bacteria (Manjunath *et al.*, 2006). Utilization of soybean residues and *Azospirillum brasilense* inoculation with or without inorganic N fertilizer on poor fertility sandy soils showed significant increase of N uptake by either shoot or grains of wheat plants (Galal and Thabet, 2003).

Hodge (2006) described the phenomenon of 'patchy soils' and 'plastic plants' explaining the additional nutrient acquisition mechanism through mycorrhizal symbiosis. Mycorrhyza is a soil fungus and effective arbuscular mycorrhizal (AM) associations may help to improve early-season P nutrition in crops. The external hyphae of AM extend from the root surface to the soil beyond the P depletion zone and so access a greater volume of undepleted soil than the root alone. Therefore, a root system that has formed a mycorrhizal network will have a greater effective surface area to absorb nutrients and explore a greater volume of soil than non-mycorrhizal roots. The VAM endophytes are not host-specific in general, although preferential associations are observed with some host plants (Bagyaraj *et al.*, 2002).

Rengel and Marschner (2005) worked on exploiting genotypic differences to manipulate nutrient availability and management in the rhizosphere. Mycorrhizal inoculation significantly increased plant growth, P and N contents, acid and alkaline phosphatases and total soluble protein of soybean (Fattah, 2002). In cowpea, significant genotypic variations in N_2 fixation were observed. A better root infection by arbuscular mycorrhizal fungi in genotype 'IT90K-59' and root morphological and physiological characteristics in 'IT89KD-391' were the most important factors for increasing P uptake (Martin *et al.*, 2006). Mycorrhizal plants can absorb more P at lower concentration in the soil solution than non-mycorrhizal plants. Inoculation of VAM (*Glomus mosae*) in wheat varieties improved the uptake of P fractions from Olsen-P, Ca-P, Al-P and Fe-P (Liu *et al.*, 2001). Mycorrhizal inoculation stimulated the growth of soybean. The external P requirements were 0.11 ppm for mycorrhizal and 0.15 ppm for non-mycorrhizal soybeans to obtain 80% of the maximum yield, which corresponded to a saving of 97 kg P/ha (Plenchette and Morel, 1996). Incorporation of VAM along with starter dose of P in P-deficient acid soils improved the total uptake of P, K, Ca, Mg and Zn by 2.5-6.0 fold in sorghum and cowpea when compared to only P application (Bagayoko *et al.,* 2000). The VAM fungal hyphae also play an important role in soil aggregation by creating skeletal structure of macro-aggregates through physical entanglement of soil particles and organic materials (Tisdall, 1994).

Tillage and weed management

Reducing tillage and optimizing N fertilization are important strategies for soil and water conservation and N-use efficiency for sustainable agriculture. Based on soil type, it was shown that no-tillage system does not require increased amounts of N fertilizer for barley production. In dry years with scarce rainfall, N should not be applied in any tillage system (Angas *et al.*, 2006). Chickpea N uptake was directly related to soil nitrate content; it was greater under conventional tillage than under no-tillage, and increased when higher N fertilizer rates were applied to the preceding wheat (López-Bellido and López-Bellido, 2001).

Though tillage systems did not significantly affect the plant tissue contents of wheat (at tillering) and cotton (at flowering), tillage and fertilizer treatments had a positive effect on nutrient uptake by wheat (Ishaq *et al.*, 2001). Conservation tillage and deep tillage increased N, P and K uptake compared to minimum tillage. Soil, water and nutrients play an important role in increasing yields of crops in black soils of semi-arid tropics during post-rainy season. Tillage practices along with organic material further affected the moisture and nutrient availability to crops. Availability of nutrients and water at different growth stages of sorghum were increased by deep tillage (Patil and Sheelavantar, 2006).

Nitrogen-use efficiency and N uptake efficiency were greater with conventional tillage than with no-tillage (López-Bellido and López-Bellido, 2001). In general, crop yields under no-till practices are more stable than under tilled systems with greater efficiency in the use of nutrients (Martin, 2006).

Improper land leveling is the serious cause for losses in water, nutrients and improper population resulting in low yields and profits. Rickman (2002) showed 24% increase in yield of rice due to precision land leveling. Choudhary *et al.* (2002) observed higher fertilizer-use efficiency in wheat in laser-leveled fields. Agronomic efficiency was also significantly improved in laser-leveled field of a rice - wheat cropping system. On-farm investigations in western Uttar Pradesh showed significant improvement in NUE in rice - wheat cropping system from 45.1-48.4 and 34.7-36.9 kg grain/kg applied N in rice and wheat, respectively. A reduction in the yield of seed cotton up to 20.1% was observed on traditionally-leveled fields compared to precision leveling (Sattar *et al.*, 2003). The uptake of applied nutrients in a sandy loam soil increased significantly under precision land leveling. A significant increase in the uptake efficiency as well as apparent recovery fraction of the applied N, P and K in a typic *Ustochrept* in rice was observed due to precision land leveling (Pal *et al.*, 2003).

Weeds are naturally efficient and aggressive in utilizing the resources - nutrients and moisture and can compete with the crops to cause economic loss. Controlling weeds enhances the use efficiency of applied nutrients by the crops. When weeds were removed, the rice yield increased by 10% under rainfed lowland conditions and by 17-19% under irrigated conditions (Inumara *et al.,* 2003, Burgos *et al.,* 2006). Similarly, in winter maize, the total nutrient uptake was maximum 169.4 kg N, 24.3 kg P, and 50.7 kg K/ha in comparison to unweeded treatment, when field was treated with alachlor @ 1.5 kg/ha (Sinha *et al.,* 2005).

Precision agriculture and nutrient-use efficiency

Significant increases in N-use efficiency have taken place over the past 10 years using precision agricultural management practices (Raun, 2006). Achieving synchrony between N supply and crop demand without excess or deficiency is the key to optimizing trade-offs amongst yield, profit, and environmental protection in both large-scale systems in developed countries and small-scale systems in developing countries (Cassman *et al.*, 2002). The determination of rates and dates for N application must be more precise in this context. Models and diagnosis indicators have been developed to meet these needs of forecasting crop requirements and the diagnosis of N deficiencies during the crop cycle apart from breeding of new adapted varieties. Equipments that help improve N management for crops include the use of hand-held active sensors, aerial photography, satellite imagery, and virtually any other approaches that assist in managing the variability in producer fields.

Crop modeling can provide us a vast amount of real time information about fertilizer dose to achieve the target yield, crop conditions etc. Estimation of fertilizer requirements based on quantitative approaches can assist in improving yields and nutrient-use efficiency. The QUEFTS (QUantitative Evaluation of the Fertility of Tropical Soils) model for site-specific, balanced fertilizer recommendations was validated, and used for site-specific nutrient management in wheat (Maiti *et al.,* 2006) and maize (Liu-Ming *et al.,* 2005).

Site-specific nutrient management (SSNM) and integrated crop management (ICM) strategies significantly improved the grain yields of rice - wheat system in Indo-Gangetic plains of Southeast Asia (Regmi and Ladha, 2005). Overall, yield increment by ICM over farmers' practice reached 2.3 t/ha (66%) in rice and 2.3 t/ha (87%) in wheat. This was owing to increased N-use efficiency in rice up to 50% and 70% with SSNM and ICM, respectively over farmers' practice. Li *et al.* (2006) adopted Stella software to develop simulated unidimensional first order model to study the soil N dynamics and plant N use in potato cropping system. The predicted N uptake and potato tuber yield were correlated to N inflows in the model. This model helped in balancing the amounts of N needed by crops, optimize plant growth and N-use efficiency and to minimize N lost to the environment. A linear model for using chlorophyll meter measurements to make maximum economical N fertilizer recommendations for maize was also developed.

Nutrient buffer power concept, the technique precisely quantifies a soil nutrient's 'Buffer Power' which is then integrated into the computations to devise accurate fertilizer recommendations, was proposed by Nair (2006). The concept centers on the dynamics of soil nutrient bioavailability. In consonance with the quantity and intensity aspect of nutrient availability in soil, the power of plant uptake mediated nutrient dynamics is highlighted by this concept.

Detailed analysis on N absorption and use within the crop, plant responses to deficiencies and excesses of N to be taken into account in major agronomic models was made by Jeuffroy *et al.* (2002). They suggested the ways in which the most recent molecular plant physiology findings can be integrated for improving current agronomic models and diagnostic tools, and for breeding more efficient varieties.

Fertigation provides an opportunity to use nutrients more efficiently through better timing and placement. Nutrient-use efficiency was higher in drip systems in the dry year in once harvest cucumbers. Increasing the fertilizer application rate through fertigation increased yield and water-use efficiency while decreasing nutrient-use efficiency up to currently recommended application rates. In multi-pick harvested cucumber production, drip irrigation systems coupled with fertigation were found to increase N and K-use efficiency compared with other irrigation strategies (Beyaert, 2004). The problem of nitrate leaching is serious with respect to the environment, as nitrate has been linked to the dead zone. In sandy soils with potato production by improving water-use efficiency, there was as much as 35% reduction in the peak soil nitrate N concentration at 1 m depth (Lowery *et al.*, 2006). Most efficient use of N for maize requires application of small amounts of N at planting and avoiding large N applications during high rainfall events (Al-ali and Morris, 2006). Katyal and Gadalla (1990) working on fate of urea-N in floodwater from ^{15}N balance measurements to understand the relation with total N loss, found that duration of presubmergence did not alter the relationship between potential and actual N loss although it influenced the rate of urea hydrolysis in floodwater. It was suggested that potential N loss calculated from one-time determination of water-soluble N in floodwater can be a good index of actual N loss from flooded, puddled rice soils.

Chasing for high yields of rice, many small farmers in Asia tend to apply fertilizer N in excess of the requirements. Synchronization of fertilizer N application to rice with crop N demand can result in high yields, reduce losses of N and efficient utilization of applied N. Real-time N management revolves around quick and reliable tools to decide on the time when fertilizer N needs to be applied to the crop. Leaf colour chart (LCC) is a simple innovation enabling farmers to apply N fertilizer as and when needed by a rice crop (Singh *et al.*, 2006a). Savings of 16-43 kg N/ha were observed for 7 different rice cultivars by applying N using LCC. Crop need-based N management for direct dry seed rainfed lowland rice through LCC and incorporation of green manure resulted in saving of 20-40% inorganic N (Premlatha and Angadi, 2005). In rice - wheat system of Indo-Gangetic plains, the low N-use efficiency is reported due to inefficient management of fertilizer N. Use of LCC for N management consistently increased grain yields and net returns compared to farmers' practice (Alam *et al.*, 2006). Integrated nutrient management practice of using organic manures and LCC threshhold value 3 for rice proved to be the best for high N-use efficiency (Pandu *et al.*, 2005). As an extension to this, Arnall *et al.* (2006) reported sensor-based N rate calculator (SBNRC) developed at Oklahoma State University showing increased NUE for many crops. The SBNRC technology works with the combination of sensor technology and a reference strip (N-rich strip). The results show a positive correlation between NUE and response index, and also between NUE and yield.

Optimal rates of N fertilizer depend mainly on the total N demand of crops, the amount of available N from sources other than applied N, and the efficiency of fertilization in order to increase plant available N. In order to improve N fertilizer recommendations, the prediction of the total N demand as well as the prediction of the fertilizer efficiency is essential. The soil N mineralization appeared to be an important N source for cereals (Rao *et. al.*, 2006), which was independent of the applied N rate. Soil N tests, which provide an index of mineralizable soil N, therefore merit consideration for adoption into N fertilizer recommendations for cereals.

The consequences of increasing global warming with the resultant increased CO_2 levels in the environment have direct effect on plant nutrient relationships. Increasing CO_2 concentration increases the uptake of all mineral nutrients (Baligar *et al.*, 2004). Increasing photosynthetic photon flux density (PPFD) increased nutrient influx for Na, B, Mn and Zn, and decreased influx for other mineral nutrients. At both low and high CO_2 levels, increasing PPFD decreased nutrient transport for Na and S, and increased transport for Mg, B, and Zn only. At both CO_2 levels, with the exception of nutrient-use efficiency ratio (ER) for B, increasing PPFD increased ER for N, Na, S and Zn, and decreased ER for other mineral nutrients. At all PPFD levels, with few exceptions, increasing CO_2 increased ER for N, Na, Mg, Cu, Mn and Zn, and decreased ER for other mineral nutrients. Further, it was found that elevated CO_2 stimulated above- and below-ground plant biomass by 20 and 30%, respectively (Groenigen *et al.*, 2006). Stimulation of gross N immobilization at elevated CO_2 was significant, but gross and net N mineralization rates remained unaffected. Combined with a significant increase in microbial N contents, higher CO_2 levels enhanced microbial N demand. Elevated CO_2 only increased soil C contents when N was added at rates exceeding typical N deposition. These results are in line with the progressive nitrogen limitation theory, which states that when elevated CO_2 stimulates biomass production in unfertilized ecosystems, the resulting increase in soil C inputs will gradually reduce N availability.

Efficient nutrient-use genotypes

It is visualized that in the 21st century, nutrient efficient plants will play a greater role in increasing crop yields (Fageria, 2006). Limited land and water resources, higher cost of inorganic fertilizers inputs, and declining crop yields in the future will create greater demand for cultivars with higher nutrient efficiency. Furthermore, at least 60% of the arable land in the world has mineral deficiencies or elemental toxicity problems. About 50% of the world population suffers from micronutrient deficiencies. Development of varieties with better nutrient-use efficiency is becoming a necessity both to allow the maintenance of a sufficient profit for the farmer and preserve groundwater and water bodies from pollution. The efficiency of a genotype to utilize nutrients arises from a balance of several processes associated with acquisition and usage. Genetic variation in nutrient efficiency may be attributed to two multi-factorial components: (i) genotypes may differ in the efficiency with which the nutrients in the plant are utilized to produce yield (utilization efficiency), and/or (ii) they may differ in their effectiveness in absorbing nutrients from the soil (uptake efficiency) (Sattelmacher *et al.*, 2007).

Many studies show a genetic variability for nutrient-use efficiency at a given level of fertilization, with a significant genotype × nutrient interaction. However, genetic variation is expressed differently at low- and high-nutrient input. Kyu *et al.* (2005) found only 3 rice genotypes out of 34, which were efficient in N use that produced high grain yield at both low and standard levels of N. In maize, variation in NUE at high N input was mainly related to variation in N uptake, where as at low input, N utilization efficiency played important role. Leaf area duration appears to be an important factor for post-silking N uptake (Gallais and Coque, 2005).

Remobilization also plays an important role at low N input. Results of quantitative trait loci (QTL) detection tend to confirm that genetic variation is expressed differently at low and high N input. It appears to be quite possible to develop new varieties adapted to low N input than present varieties as well as the possibilities of high-yielding cultivars with higher N-use efficiency for grain yield through QTL controlling NUE (Ju Jing *et al.*, 2006). Nitrogen concentration in above-ground plant parts of N efficient cultivars produced greater plant biomass than inefficient cultivars (Svecnjak and Rengel, 2006). Such cultivars performed best at high N supply or under N deficient conditions. Based on the N, P and K uptake by dry leaves, green tops, stem and total above-ground parts and nutrient per tonne of cane, five sugarcane clones were identified as efficient users of N, P and K (Rakkiyappan *et al.*, 2005). Among three sorghum genotypes, 'M-53-1' performed as the best for N and moisture-use efficiency (Bhanavase *et al.*, 2005).

Apart from traditional breeding, new marker-assisted selection uses novel gene constructs designed to improve specific aspects of NUE (Good *et al.*, 2004). Cho *et al.* (2007) from Korea delineated identification of QTL associated with physiological N-use efficiency in rice that was positively correlated with the harvest index and grain yield. The total phenotypic variance explained by all the QTL for each trait ranged from 35.8-71.3%, showing that the expression of physiological N-use efficiency and related characters depends significantly upon genetic factors.

The challenge of improving N-use efficiency in crop plants was reviewed by Hirel *et al.* (2007) that provide an insight on understanding of the physiological and molecular controls of N assimilation under varying environmental conditions. The NUE in crops has been improved through the use of combined approaches, mainly based on whole-plant physiology, quantitative genetics, and forward and reverse genetics approaches.

Balanced fertilization

Balanced fertilizer use is not only the first requirement, it is rather a pre-requisite since no amount of agronomic manipulation can produce high efficiency out of an imbalanced fertilizer dose. In fact, efficient nutrient use is essentially an offspring of balanced fertilizer use and sound management practices and decisions. With the adoption of exhaustive cropping systems, widespread deficiencies of S and Zn, sporadic deficiencies of Fe, Mn, and B have been noticed in intensively cultivated areas.

Acharya and Sharma (2008) made a detailed review on integrated input management for improving N-use efficiency and crop productivity. The P-use efficiency of applied fertilizer by crops ranges from 10-30% in the year it is applied. The remaining 70-90% becomes part of the soil P pool that is released to the crop over the subsequent months and years. A detailed review on P-use efficiency through selecting proper P source, dose based on soil P status, and time and method of application was documented by Dev (2006). The results of many on-farm trials indicated that rationalization of fertilizer P dose based on P status of the soils was critical in determining its efficiency. Soils with low P status needed relatively higher input of fertilizer P (125% of locally recommended dose). Reduction in fertilizer P dose to 75% of locally recommended dose in medium or high P status soils resulted in its low efficiency. Drilling of water soluble phosphate in low P status alkaline calcareous soils produced more crop yield over broadcast method, while this difference was less pronounced in soils testing medium to high in P status.

It was commonly held that P was irreversibly fixed in soils because of precipitation reactions and as a consequence, the efficiency of P fertilizer was low. The recent and ongoing analysis of experimental data from long-term experiments, which permit an adequate evaluation of the efficiency of soil and fertilizer P, support the thinking that the recovery of added P over time can be high, thus supporting the concept of reversibility, given adequate time. This new paradigm has major implications for fertilizer use in the context of both agronomy and the environment (Lee *et al.*, 2004; John, 2006). The best strategies for sustainable crop production and environmental safety with respect to P are to produce optimum crop yields by: (a) alternative P application only to winter crops, (b) periodic reduction in P rates according to accumulated P, and (c) occasionally without fertilizer P to enable the utilization of residual fertilizer P that had accumulated in the soil over the years (Aulakh, 2006, 2007; Roberts, 2006). Application of rock-phosphate along with green leaf manure and P solubilizing fungi gave significantly higher grain yield compared to application of rock-phosphate alone (Srinivasamurthy *et al.*, 2006). The total dry matter, P and Ca uptake in soybean was significantly improved with the use of low-grade rock-phosphate in conjunction with phosphate solubilizers and FYM. *Aspergillus awamorii* was found to be efficient P-solubilizer, followed by *Bacillus striata* in solubilizing North Carolina and Mussoorie rock-phosphates (Qureshi and Narayanasamay, 1999). About 64-71% equivalent of water-soluble P requirement of crops could be met through rock-phosphates, seed inoculation of P solubilizing microbes and FYM (Qureshi *et al.*, 2005).

Potassium, an essential nutrient required by plants in large quantities is present in soils in four pools, of varying availability to plants, in dynamic equilibrium. Potassium deficiencies have been observed in crops, such as cotton, maize and sorghum in vertisols (Kathryn *et al.*, 2006). Application of K fertilizers in many of the soils exhibits no yield response to applied K despite an increase in K uptake. The high K uptake or tissue concentration might improve the quality of produce but not the yield. Though most Indian soils are testing medium to high in K status, variable response to applied K is reported in many crops. This is due to the K dynamics interplay between pools in different soil types modified by moisture and luxury consumption from plants.

Increased use of S-free fertilizers, intensive cropping, and use of high-yielding varieties have led to S deficiency in many countries. Sulphur deficiency is increasingly becoming one of the limiting factors to further sustainable increases in agricultural production. Sulphur fertilizer, besides enhancing yield and quality of crops, enhances nutrient uptake and fertilizer-use efficiency through interaction of S with other fertilizer nutrients (Tandon and Messick, 2007). Residual effects have also been reported even at a low rate of 20 kg S/ha. Thus, S does not need to be applied every season (De Datta *et al.*, 2005).

Application of S along with N, P and K to pulses and oilseeds showed greater response than to cereals. Sulphur not only improved grain yield but also improved the quality of crops (Hegde and Sudhakara Babu, 2004; Hegde and Murthy, 2005). Interactions of S with N and P are positive, while its application decreases the contents of Zn, B and Mo in plant system. The combined use of LCC for N management and recommended P, K, S and Zn fertilizers increased the yield of rice and wheat in rice - wheat cropping system in Bangladesh (Alam *et al.*, 2006). Improved N-use efficiency or full benefit of applied N was noticed due to overcoming deficiency of K, S and Zn through fertilizer application. Riley *et al.* (2002) reported that sulphate was highly mobile and prone to leaching under the experimental conditions, whereas the slow release characteristics of elemental S led to smaller leaching losses and larger residual effects.

Inclusion of limiting nutrients in fertilization programme has shown excellent results. Balanced and adequacy of all limiting nutrients for different cropping systems in alluvial and lateritic soils of West Bengal ensured high relative agronomic efficiency (RAE). For rice and jute, the RAE for the soil test and yield target-based recommendation exhibited the highest value, much in excess of 100%. The RAE gradually declined with the absence of P, K and micronutrients from the fertilization schedule. In hybrid rice in Orissa, grain yield and relative agronomic efficiency was strongly affected by reduction of P and K application as well as skipping of Ca, Zn and B. Significant reduction in RAE compared to soil test and yield target-based treatment was observed under inadequate nutrient application. It was also found that N, P and K-use efficiency of hybrid rice declined with gradual decrease in application of associated nutrients recommended through soil test.

Alam *et al.* (2000) revealed that application of Zn along with N and P through fertigation increased grain yield of wheat by 9%, and improved the agronomic efficiency, recovery efficiency and physiological efficiency by 30, 20 and 12% respectively, over that applied by other methods.

High levels of P application may induce Zn deficiency in plants grown on Zn-deficient soils. On P- and Zn-deficient typic *Ustochrept* soils, it was found that increasing P up to 13.5 mg/kg soil increased Zn concentration, while further increase led to decreased Zn concentration. Iron concentration decreased with increasing P levels. Up to 13.5 mg/kg P application, Cu concentration increased, and thereafter decreased. Manganese concentration gradually increased with increasing P levels (Srinivasarao *et al.*, 2006). The accrued benefit were reduced by 18, 29, 19, 20, 27 and 6% when P, K, S, Zn, Fe or Mn, respectively, were omitted from the complete SSNM treatment in sugarcane (Phonde *et al.*, 2005). The SSNM produced significantly higher yields compared to the generalized state recommendation.

Summary

Farm yields are presently only 40-60% of the attainable yield potential, and so an appreciable exploitable yield gap remains in the production potential. The low nutrient-use efficiency is due to the practice of general state recommended fertilizer applications without reference to soil fertility assessment, unfavourable nutrient ratios, nutrient imbalance, low soil organic matter, rainfed cultivation or flooding irrigation, poor land preparation resulting in low plant stand, weed competition, and above all, the nature and varieties of crops. Even under ideal conditions, the nutrient-use efficiency of N and K is higher, while that of P, secondary and micronutrients is low due to their chemistry of reactivity resulting in synergistic and antagonistic reactions. Besides the low nutrient-use efficiency, the non-point source contamination of nutrient pollution to environment is a concern. Thus the economic loss both due to low nutrient-use efficiency and nutrient wastages into environment is a serious problem. The crop response to applied nutrients typically follows a diminishing return function as yields approach the potential limit. To maintain and even increase the efficiency of nutrient use, more precise and diverse nutrient management strategies are needed.

The efficiency of fertilizer can be increased and losses reduced by matching supply with crop demand, optimizing split application schemes, changing the form to suit the conditions, and use of slow-release fertilizers and inhibitors. For the required nutrient rate, management decisions should consider appropriate integrated plant nutrient supplies with considerations of site-specific nutrient management including contributions from organic sources and preceding legume effects.

Technologies that have resulted in higher nutrient-use efficiency include improved production practices such as conservation tillage, increased BNF in crops, weed control as well as improved nutrient management with regard to form, placement and timing of fertilizer materials. Newer conceptual approaches for higher nutrient-use efficiency include biological nitrification inhibition, precision farming, QUEFTS model, consideration of cumulative effects of continuous fertilization and manuring, site-specific nutrient management etc. along with breeding for efficient genotypes of crops. Fertilizer best management practices focusing on five Rs, viz. right product, right rate, right time, right place and right method will continuously guide the efficient nutrient management.

Future strategies

- Balanced fertilization on cropping system basis and exploiting positive interactions among inputs for sustainable high nutrient-use efficiency and environmental protection.
- Influence of weather / climate change that has a marked influence on nutrient dynamics in soil and plant uptake should be considered in fertilization programmes.
- Developing precision farming methodology for higher nutrient-use efficiency.
- Nitrogen-nutrient augmentation through improvements and exploitation of alternative sources such as BNF and potential of BNI to control nitrification in

cropping systems should be intensified.

- Identifying and developing superior plant types and genotypes for high nutrient-use efficiency.
- Results of long-term fertilization practices have to be critically examined for their trends of responses for guiding the management strategies.
- Development of sustainable farming systems with higher nutrient-use efficiency and specific guidelines for good agricultural practices.

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