Proc Indian Natn Sci Acad **79** No. 4 December 2013, Spl. Issue, Part B, pp. 997-1010

Review Article

Fertilizer Nitrogen, Food Security, Health and the Environment

R PRASAD*
Indian Agricultural Research Institute, New Delhi 110 012, India

(Received 06 May 2013; Revised 23 June 2013; Accepted 29 August 2013)

Fertilizer nitrogen has been the key input in increasing food production globally. The global food production has to be doubled in the next 37 years (by 2050), and this will require doubling the fertilizer nitrogen consumption. Efficiency of fertilizer nitrogen is quite low, especially in the tropical regions, where rice is the principal crop. About one-third of the applied fertilizer nitrogen is lost to the atmosphere or leached down to groundwater. Thus as the nitrogen consumption increases, its contribution to environmental pollution with ammonia and nitrous oxide and groundwater contamination with nitrates will also increases. Nitrate in drinking water above 50 mg nitrate per litre can lead to blue baby syndrome and diarrhoea in infants and may even lead to the development of nitroso compounds that are carcinogenic in nature. It is therefore important that nitrogen use efficiency in crop production is increased. In addition to agronomic practices, such as growing nitrogen efficient cultivars and deep placement and split application, sincere efforts need to be made to develop controlled release or nitrification inhibitor blended nitrogen fertilizers and make them available to the farmers. While working out the economics of these new nitrogen fertilizers their contribution to reducing environmental pollution and health hazards in addition to increase in crop yield needs to be accounted for.

Key Words: Ammonia Volatilization; Nitrous Oxide; Nitrogen Use Efficiency; Environmental Pollution; Nitroso Compounds; Nitrate Toxicity; Nitrification Inhibitors; Controlled Release Fertilizers

1. Introduction

World population was 10 million nearly 10,000 years ago and it took almost 8000 years to reach 100 million and another 3804 years to reach 1 billion mark in 1804 (Kamboj 2006). The next billion was added in 123 years in 1927 and another billion in the next 33 years in 1964. Since then an additional billion has been added each 12 to 14 years and seven billionth child was born on 31st October 2011 in India near Lucknow [Times of India, 1 November, 2011]. According to UN, global population will level off at 9 billion by 2050. The two most populous countries of the world, namely, China (19.4%) and India (17.5%) together account for 37.9 % world's population (UN-DESA 2011) and anything that can be done to stem the population increase in these two countries, can go a long way in reducing world food demand. However, Sub-Sahran Africa is likely to have the highest population increase rate; its population is estimated to double from 770 million in 2005 to 1.5 billion in 2050 (Seck 2011). Zeigler (2011) pointed out that if fertility rate was reduced just 0.5 child per woman, the global population by 2050 could be 8.1 billion as against the present UN estimate of 9 billion.

2. Food Demand and Hunger

Obviously with such an increase in population, the food demand will also increase proportionately. FAO's Millennium Project 2008–State of Future attributes food crisis in developing nations to high oil prices, bio-fuel production, high fertilizer prices, low global cereal stocks and market speculation

**Author for Correspondence: E-mail: rajuma36@gmail.com*

(Glenn *et al*. 2008). Recently Tilman *et al*. (2011) forecasted the need for a 100-110 % increase in global food production from 2005 to 2050.

The world is already under a high level food deficit crunch. Globally the number of hungry people was estimated at 925 million (out of a total of 6.6 million); Asia and the Pacific had the largest share at 575 million followed by the Sub-Saharan Africa at 329 million (FAO 2010). According to IFPRI (IFPRI 2011) the hunger index is the highest in India (Table 1).

Table 1: Global hunger index* in some countries and the world

World/country	2001	2011
World	16.0	14.6
Brazil	5.3	<5
China	6.8	5.5
India	24.1	23.7

*Global hunger index (GHI) = [PUN+CUW+CM]/3, where PUN is the percentage undernourished people, CUW is the percentage of underweight children under 5 years of age and CM is the percentage of children dying before the age of 5.
Source: IFPRI (2011)(IFPRI 2011)

(a) Food Production and Fertilizer Nitrogen

Many believe that plant biotechnology holds the key to produce more food and the genetics and biotech industries have assured that they can deliver increased yields, promising a leap in genetic yield potential of 3-4% (Jepson 2008). However, for full exploitation of the higher yield potential increased fertilizer nitrogen application is a must (Roberts 2009) and it is estimated that by 2050 about 250 million tonnes of fertilizer nitrogen may be needed (Tilman *et al*. 2011). This is because for each increase of one tonne of cereal grain, the crop will need 20-27 kg N (Prasad *et al*. 2004). This review focuses on nitrogen, because nitrogen is essential for protein production in plants, which is the direct or indirect source of protein for animal and human nutrition. Protein malnutrition has received considerable attention in the past (Prasad 2003).

Role of fertilizer nitrogen in augmenting food production has been realized since early 20^{th} century, when two Nobel prizes were given to the development of the process for synthesis of ammonia, first to German chemist Fritz Haber in 1918 and the second to another German chemist Carl Bosch in 1931 (Sohlman 1966). Again the German chemist Friedrich Wohler synthesized urea from ammonium cyanate, and this marked the beginning of organic chemistry (Wohler 1828). Urea is the major nitrogen fertilizer today; it contributes about 80% to the total fertilizer consumption in India. Globally, it contributes to about 55% of total fertilizer nitrogen consumption.

Defining Nitrogen Use Efficiency (NUE)

NUE means different things to different people. Some of the most commonly used terms related to NUE are given below (Prasad 2009).

(a) Apparent Recovery efficiency (AREn) = 100 (Uf – Uc)/ N = $\Delta U/\Delta N$ (% of applied N) Agronomic efficiency (AEn) = (Yf-Yc)/N = $\Delta Y/\Delta N$ (kg grain/kg N applied).

(b) Physiological efficiency (PEn) = (Yf – Yc)/Uf-Uc = $\Delta Y/\Delta U$ = AE/RE (Kg grain/Kg N absorbed).

(c) Partial factor productivity of fertilizer (PFPn) = Y/N (Kg grain/Kg N applied).

In the above expressions, Yf and Yc are grain (or other economic produce) yield in kg/ha in fertilized and control (check) plots, while Uf and Uc refer to the nitrogen uptake (kg/ha) in fertilized and control plot, respectively and N refers to the nitrogen applied (kg/ha). PFPn does not take into account the control plot yield and is therefore a very useful term because it can be calculated for the experiments on tillage, sowing dates, seed rates, weed control, water management etc, where a blanket fertilizer application is made. PFPn can also be used for comparing NUE in different countries or in different parts of a country. When tracers such as ^{15}N are used the recovery is known as true recovery efficiency (TRE). A lower case letter as suffix is generally provided to indicate the nutrient for which the NUE refers to egAEn refers to the Agronomic efficiency of N.

(b) Low and Declining NUE

One of the major concerns is low and declining NUE. Enormous data exist on NUE in India and abroad. Only a few are cited here to focus the attention on low NUE specially that of N. Globally the value of AREn is 55%, while TREn (True Recovery Efficiency) is 44% (Ladha *et al*. 2005). TREn values are specially low in rice, for example, Katyal*et al.* (Katyal *et al*. 1985) from Ludhiana reported a TREn value of 21-31%, while Goswami *et al.* from Delhi reported a TREn value of 33%. TREn is higher (32-51%) for wheat. Some more data from ^{15}N on TREn in crops and cropping systems are in Table 2. One important point that these data bring out is that inclusion of legumes reduces the unaccounted or lost N. This shows the importance of legumes from the viewpoint of N conservation.

Averaged over a number of experiments at the Indian Agricultural Research Institute, New Delhi, Prasad *et al*. (2000) reported that AEn in rice decreased from 22 to 13 kg grain/kg N and that in wheat from 84 to 31 kg grain/kg N as the level of N was increased from 40-60 to 121-180 kg N/ha. PFPn values were same for rice and wheat and decreased from 84 kg grain/kg N at 40-60 kg N/ha to 32 kg grain/kg N at 121-180 kg N/ha. PEn values in this study were 40-44 kg grain/kg N for rice and 24-48 kg grain/kg N in wheat. In China, where N rates are generally 150 kg N/ha or more, AEn values are reported to be 10.4, 8.0 and 9.8 kg grain/kg N for rice, maize and wheat, respectively (Zhang *et al*. 2007).

The data from research centres under the Project Directorate of Cropping System Research, Modipuramshowed an average AEn value of 9.5 kg grain/kg N for cereals (Sharma and Batra 2011). Similarly, in a large number of on-farm trials conducted by FAO in 48 countries of Asia, Africa and Latin America, where a package NPK application was studied, the average AEnpk (kg grain/kg NPK) was 8-12 kg for rice and maize and 4-8 for wheat (FAO 1989). Thus the NUE is very low in developing countries of Asia, Africa and Latin America.

Besides the low NUE in India more disturbing is its decline over time. Recently, Biswas and Sharma (2006) reported that during 1970-2005 the AEn in irrigated areas declined from 13.4 to 3.4 kg grain/kg nutrient, respectively. This is supported by the fact that the farmers in the rice-wheat cropping system belt (Punjab, Haryana and Western UP) are forced to apply more and more fertilizer to obtain the same yields as in the preceding years.

The agricultural importance of enhancing NUE can be judged from the fact that a 10% increase in NUE can save about 20 million hectares of land at the present level of productivity in India. Another way of looking at the importance of enhancing NUE in India is the fact that a 1% increase in use efficiency of nitrogen, which is estimated to be 17 million tones in 2011-12, will amount to a saving of 0.17 million tonnes of N or 0.4 million tonnes of urea, which is equal to the annual production of four urea plants producing 1 lakh tonnes of urea per annum.

Table 2: ^{15}N balance sheet in some crops and cropping systems

Crop/cropping system	Location	TREn (%)			Reference
		Plant	Soil	Unaccounted (lost)	
Crop					
Rice	Ludhiana	21-31	24	46-50	(Katyal *et al*. 1985)
Wheat	Ludhiana	32-52	32-35	16-42	(Katyal *et al*. 1985)
Cropping system					
Rice-Wheat	New Delhi	35.8	25.6	38.6	(Goswami *et al*. 1988)
Maize-wheat-Mungbean	New Delhi	23-27	55-65	0-13	(Arora *et al*. 1980)
Wheat-Mungbean-Maize	New Delhi	49	41-47	4-10	(Arora *et al*. 1980)

Note: The soil at Ludhiana is classified as an Ustipsamment, while that at Delhi is anUstochrept

(c) Nitrogen Loss Mechanisms

The main reason for low NUE is that nitrogen is lost from soil in different forms at different stages (Prasad 1998). When applied as urea, it is subject to run-off losses when the heavy rains come especially on sloping lands, because being a non-polar molecule it cannot be retained on clay particles. Once hydrolysed to ammonium form it is subject to ammonia volatilization losses. Further, when ammonia is oxidized to nitrate it is subject to leaching under well drained conditions and as gases N_2, N_2O or NO_x under anaerobic conditions.

(d) Ammonia Volatilization

The ammonia emission from soil varies from 1 to 26 kg ha^{-1} depending upon soil type, crop and fertilizer material. Some other studies have shown that ammonia volatilization loss is 20-30 kg N ha^{-1}with application of 120 kg N ha^{-1} in rice and wheat (Katyal *et al*. 1987, Aulakh and Bijay-Singh 1997). Banerjee *et al.* (Banerjee *et al*. 2002) reported volatilization loss ranging from 1 to 69 kg ha^{-1} from rice-wheat system of North India depending upon fertilizer management practices. Pathak *et al*. (Pathak *et al*. 2006) simulated N loss through NH_3 volatilization from rice-wheat cropping systems of the Indo-Gangetic plains (IGP), and found that total loss of N was 16 to 62 kg N ha^{-1} in the various states of the IGP. Average N loss was 30 kg N ha^{-1} with average fertilizer application of 98 kg N ha^{-1}.

(e) Leaching

Leaching of N in the form of NO_3 beyond soil profile is one of the major losses particularly in the developed countries. In developing countries like India its importance is being felt recently because of sporadic reports of NO_3 enrichment in groundwater in a few agriculturally intensive areas in Punjab (Sekhon 1995), Haryana (Bijai-Singh and Singh 2004), Delhi (Gupta and Chandrasekharan 1999), where N loss due to leaching can be as high as 80% depending upon the soil properties and water and nutrient management practices. It is particularly a major sink for surplus N in agro-ecosystems on well-drained porous soils (Watts *et al*. 1991). Sporadic reports of high NO_3-N contamination in groundwater from different parts of India may be related more to sewage and dumping of organic wastes rather than agricultural chemical N fertilization barring a few sites where soils are highly coarse textured and hence permeable (Pathak *et al*. 2004). Ladha *et al.* (Ladha *et al*. 2005) opined that in lowland rice fields with fine-textured soils, leaching loss of N is low because of restricted percolation. Using crop simulation model, Pathak *et al.* (Pathak *et al*. 2006) calculated that N losses due to leaching from rice-wheat cropping systems of the Indo-Gangetic plains could account for 10% of applied N.

(f) Denitrification

In India only a few denitrification measurement data are available for arable land. On an average, denitrification losses reported in India range from 10-15 and 5-10 kg N ha^{-1} in rice and wheat, respectively, with application of 120 kg N ha^{-1} (Pathak *et al*. 2004). In a study, denitrification loss from a continuously flooded rice fields in northwest India was 30 kg N ha^{-1} (IPCC 2000, Aulakh *et al*. 2001).

In general, about one-third of fertilizer N applied to farm fields in India is lost to the atmosphere. Thus in 2011-12, when 17 million tonnes of fertilizer N was consumed, about 5.4 million tonne was lost by various N loss mechanisms. At the current price of fertilizer N it amounts to a loss of 2894.4 crores of rupees. The global monetary loss of fertilizer nitrogen is estimated at $15.9 billion per annum (Raun and Johnson 1999). In addition to such a colossal loss of money, the lost N contributes to environmental pollution, which is discussed later.

(g) Ways to Increase NUE

Proper management of soil, crop and fertilizer is the key to enhance NUE.

(h) Soil Management

Since crop yield is the determining factor for NUE soil factors that affect crop yield, such as, pH, initial fertility, texture, structure, topography and drainage (Prasad and Power 1995), liming of acid soils (Bhat *et al*. 2010) and application of gypsum on sodic soils

(Abrol *et al*. 1988) can considerably enhance NUE. Destruction of soil texture due to puddling in rice may lower NUE in wheat in the rice-wheat cropping system (Aulakh *et al*. 1992).

(i) Crop Management

The best way to enhance NUE is to increase crop yield, which is directly or indirectly the nominator of all NUE terms. A good agronomic package (best management practices) required for high yields includes, right variety, desired seed rate, optimum date of sowing, effective weed control and necessary disease and pest management (Prasad 2007). Choice of a variety of crop is quite important in determining NUE. For example in rice, hybrids outperform the high yielding varieties and therefore result in higher NUE. In a study at New Delhi (Kumar and Prasad 2004) rice hybrid PRH3 recorded an AREn value of 66.6% as compared to 49.5% obtained with Pusa 834. This was because of the difference in N uptake pattern in two rice cultivars. Pusa 834 removed on an average 1.6 kg N/ha/d in the first 30days after transplanting (DAT), 0.8 kg N/ha/d during 30-60 days after transplanting and only 0.6 kg N/ha/d in the last 30 days. As a contrast PRH3 recorded an average N uptake of 1.40 kg N/ha/d during the first 60 DAT and 0.7 kg N/ha/d in the last 50 days.

As regards date of sowing, delayed sowing of wheat after rice in rice-wheatcropping system can reduce wheat yield by 1 t/ha or more. This can be overcome by seeding wheat with zero till machines immediately after rice harvest. For example, Verma and Singh (2008) showed that zero-till sowing gave a wheat yield of 3.4 t/ha as against an yield of 3.1 t/ha obtained with conventional tillage. Similarly if weeds are not controlled there can be a loss of up to 33% in crop yield resulting in a low NUE. For example a study at Cuttack showed that effective weed control in rice increased grain yield of rice by 1.34 t/ha and PFPnpk by 11.2%. Similarly control of *Phalaris miner* in wheat by an application of Sulfosulfuron @25g/ha increased wheat yield by 3.2 t/ha and AEnpk by two and a half times. Efficient water management is equally important for enhancing NUE (Yadav *et al*. 2005, Prasad 2011). With increasing area under sprinkler and drip irrigation research on conjunctive use of water and fertilizer has become much more important.

(j) Genetic Engineering for Nitrogen Use Efficiency

Research is underway to identify genes that can increase NUE by crop plants, which may reduce the rate of N application to crops. The available information has been reviewed by McAllister *et al*. (2012). Sofaran enhanced NUE phenotype has not become available in any crop.

3. Fertilizer Management

(a) Method of application

The common practice of surface broadcasting N fertilizer leads to ammonia volatilization, which can be reduced by deep placement of fertilizer N (Mohanty *et al*. 1998). Humphreys (Humphreys *et al*. 1992) reported that the recovery efficiency (REn) increased from 37% for broadcasting to 46% for banding in direct-seeded rice in Australia. Devasenapathy and Palaniappan (1995) from India reported that band placement of urea solution at 50 kg N ha^{-1} resulted in higher rice yield and improved agronomic and recovery efficiency than the conventional three split applications of urea. Schnier *et al*. (1993) reported that band placement of urea solution into the reduced soil layer was as effective as deep placement of urea supergranules (USG) in reducing N losses and improving rice grain yield. Where water can be drained, fertilizer N is best applied after draining the soil and incorporating it into the soil with a rotary weeder and then flooding the soil after 2-3 days. This practice is reported to give a yield advantage of about 1 t/ha (Ponnamperuma and Deturck 1994).

In wheat the common practice in India is to deep place basal N dose (about 50% of the total) along with P, K and Zn (if needed) at seeding. The rest 50% is banded or broadcast at first irrigation at 21-25 days after sowing. The second dose of N is to be applied before irrigation on light sandy soils (Katyal *et al*. 1987) and after irrigation on medium to heavy soils (Verma and Srivastava 1995).

Foliar application on N is reported to have high recovery efficiency (De 1971, Novoa and Loomis 1981). In rice, Balasubramanian *et al*. (2004) reported higher efficiency of foliar applied N Thannunathan *et al*. (2004) recommended foliar application of N in flooded rice fields where soil application is not possible. The major disadvantage with the foliar application is that about 10 kg N ha^{-1} can be applied in a single spray with high volume (500-600 L ha^{-1}) sprayers; generally available with the farmers, since the highest permissible concentration of urea in the spray solution is 3%, beyond which the leaves get scorched.

(b) Split Application

Split application of N is a well-established practice adopted in most crops grown under irrigation; the number of splits and the proportions in different doses vary with the crop and soil (Tandon 1989a). Smaller the doses of N in each application and more the splits, the better it is. According to Shihua and Wenquiang (Shihua and Wenquiang 2000) efficiency of N in rice in China is low because about 70% N is applied at transplanting and the rest 30% one week after transplanting; thus nearly all N is applied within a week of rice transplanting. On the contrary, in a China-Japan joint study (Katsura *et al*. 2008) when N was applied in 4 splits (22% one week after transplanting, 28% at panicle initiation, 28% before heading and 22% at heading), the ARn was 47% at Yunnan (China) and 37% at Kyoto (Japan) at 140 kg N ha^{-1}. The best way to obtain high NUE is to make crop need-based N application using SPAD chlorophyll meter or leaf colour chart (LCC) (Bijai-Singh 2008, Khan *et al*. 2009, Yadvinder and Bijai-Singh 2009).

(c) Balanced NPK Fertilization

Balanced NPK fertilization can certainly increase NUE and it has received considerable attention in India (Prasad 2009). Swarup (2002) reported that at Ludhiana in maize the ARn increased from 16.2 to 30.2 %, when P was applied along with N and to 32% when PK was applied along with N. In wheat the ARn value was 32.2 % for N, 51.4% for NP and 64% for NPK.

With 45% soils deficient in S and 48% deficient in Zn and some in B, especially in eastern India the emphasis has now shifted to site specific nutrient management (SSNM). Needless to say that when all essential plant nutrients are available in needed amounts the efficiency of all nutrients is likely to be optimum. To promote balanced fertilization Govt. of India has now moved towards nutrient based pricing of fertilizers.

(d) Integrated Nutrient Management

Integrated nutrient management (INM) or integrated plant nutrient supply (IPNS) is yet another approach to enhance NUE (Prasad 2008). Based on the long term fertilizer experiments (LTFE), it is reported that a good NUE was maintained in the presence of farmyard manure. Legumes as a green manure or a dual purpose crop (grain + green manure) or as inter-crop can contribute up to 40-90 kg N/ha and thus reduce fertilizer N application to crops. For example, Sharma and Prasad (2008) showed that the productivity and N uptake in rice-wheat cropping system with 60 kg N/ha + *Sesbania* green manure or mungbean (*Vigna radiata*) residue left after one picking of pods applied to rice and 40 kgN/ha applied to wheat was at par with 120 kg N/ha applied to rice and 40 kg N/ha applied to wheat. However, incorporation in soil of *Sesbania* green manure or mungbean residue doubled the PFPn as compared to application of inorganic N alone. Legume residues decompose fairly fast under subtropical and tropical conditions especially under submerged conditions and make the N in them readily available to the growing rice crop.

Bio-fertilizers can also chip in towards meeting part N requirements of crops and also in enhancing the availability of native or applied P.

4. New Fertilizer Materials

(a) Nitrification Inhibitors

Nitrification inhibitors (NIs) are chemicals that inhibit or retard oxidation of ammonium to nitrate N. Use of NIs increases the efficiency of N-fertilizers, because nitrates formed on the oxidation of ammonium are easily lost by leaching under upland and denitrification under submerged soil conditions. A large number of chemicals are known to have nitrification inhibiting properties. These include, N-Serve or nitrapyrin (2-chloro-6-(trichloromethyl) pyridine), DCD (dicyndiamide), AM (2-amino-4-chloro-6-methyl pyrimidine), CMP (1-carbamoyle-3-methylpyrazole), terrazole (etridiazole), CP (2-cyanimino-4-hydroxy-6-methyl pyrimidine), AT/ATc (4 aminotriazole), ST (sulphatiazole or sodium thiosulphate), ATS (ammonium thiosulphate), ZPTA (thiosulphoryltriamide) (Prasad and Power 1995, Trenkel 1997, Prasad 2005), neem extractives (containing epinimbin, deacetylnimbin, azadirachtin (Prasad *et al*. 1993) and pyrites (Blaise *et al*. 1997). Of this long list of NIs only nitrapyrin, AM and DCD have been widely tested.In a laboratory study, Rajale and Prasad (1973) found that under field capacity moisture regime, nitrification rate (nitrate expressed as percentage of total mineral N) after 40 days of incubation was 78% for N-Serve and 76% with AM.

Nitrapyrin, discovered in USA, was reported to inhibit nitrification and increase corn yield (Goring 1962ab). AM was discovered in Japan (Toyo Koatsu Industries, 1965) and DCD in Germany (Amberger and Guster 1978). Nitrapyrin is a volatile compound and is difficult to use with solid fertilizers. Its use is therefore restricted with the use of anhydrous ammonia in USA and is injected in soil. Patrick *et al*. (1968) reported no advantage with nitrapyrin in rice, while Nishihara and Tsunyoshi reported that ammonium sulphate treated with nitrapyrin increased rice yield by 15-20%. Yield increase in rice with nitrapyrin and AM has also been reported from India (Thomas and Prasad 1987). The DCD on the other hand did not increase rice yield (Sudhakara and Prasad 1986) but increased wheat yield (Joseph and Prasad 1993). The DCD is less effective above 20^oC because of its rapid decomposition (Amberger and Vilsmeier 1979). This is why it did not perform well in rice experiments in India, where mean daily temperature during most rice growth is above 30^oC.

(b) Slow Release N Fertilizers

Since the major cause of low NUE is the high solubility of N fertilizers, attempts have been made to develop slow-release or controlled-release fertilizers. These are broadly of two types: inherently low solubility N fertilizers and coated conventional fertilizers. Inherently low solubility N fertilizers include oxamide, guanylurea, glycoluril and urea-aldehyde condensates (Prasad *et al*. 1971, Trenkel 1997, Shaviv 2001). Of these urea-aldehyde condensates such as urea form (urea-formaldehyde), isobutylidenediurea (IBDU) or urea-butyraldehyde and crotolydinediurea (CDU) or urea-crotonaldehyde have received considerable attention and have been tested for rice and other crops. Conventional N fertilizers can be coated with pervious or semi-pervious substances such as sulphur, oilseed cakes or polymer to control the release of N. The earliest coated slow release fertilizer tested for rice was sulphur coated urea (SCU), developed by the Tennessee Valley Authority, USA. A number of researchers reported SCU to be better than urea (Bijai-Singh and Katyal 1987, Pandey *et al*. 1989). In the RWCS at New Delhi, SCU gave a 15.6% increase in grain yield (Prasad *et al*. 1981). Rajale and Prasad (1970) studied the release of N from a number of SRFs both under field capacity and submergence. After 20 days of incubation mineral-N (ammonium +nitrate) was 67, 43, 31, and 27 mg/kg soil with urea, oxamode, IBDU and SCU respectively. As would be expected under submergence nitrate was not detected and ammonium-N content in soil was 67, 61, 46 and 15 mg/kg soil with urea, oxamide, IBDU and SCU, respectively. Thus oxamide released N the fastest and SCU the slowest. They opined that mineralization of urea-N in SCU is slow due to formation of a sulphide coating on urea under reduced conditions.

(c) Neem Coated Urea

Neem cake coated urea (NCCU), developed at the Indian Agricultural Research Institute, New Delhi, was primarily based on the nitrification inhibiting properties of neem (Thomas and Prasad 1983), although some slow release property was provided by the carbon in the neem cake. Reddy and Prasad (1975) reported that after 3 weeks of incubation, per cent inhibition of nitrification by N-Serve, ST and NCCU was 90, 49 and 5, respectively. Neem cake coating of urea inhibited nitrification only for 2 weeks. Joseph and Prasad (1993) compared the inhibition of nitrification by DCD and NCCU under wheat field conditions. Per cent inhibition of nitrification was 48-53% at 10% DCD (10% of N as DCD) and 69-75 at 20% DCD at 30 days after application of 120 kg N/ha. The values of nitrification for 10% NCCU (neem cake at 10% of urea) and 20% NCCU were 7-16 and 33-42. A number of researchers have confirmed nitrification inhibition of fertilizer N by neem seed extract/cake/oil coating of urea; of course the results vary with soil type and experimental conditions.

The NCCU was at par with SCU giving 13.4% increase in grain yield. However, since 15-20% neem cake was needed to make NCCU, this could not be manufactured at the factory level. Again, since nitrification inhibiting chemicals in neem are lipid associate, a neem oil micro-emulsion was developed for coating urea (Prasad *et al*. 2002, Suri *et al*. 2004). Only 0.5 kg neem oil per ton of urea is needed in the technique. Neem coated urea was superior to urea. This technique or its modifications are currently used in India by several fertilizer manufacturers. The cost of coating urea with neem oil emulsion is only US$ 2-3 t^{-1} urea. Increase in rice yield with neem micro-emulsion coated urea (NMCU) so made varies from 6.1 to 11.9 % over urea (Fig. 1). Superiority of NMCU over prilled urea was also reported from Punjab (Thind *et al*. 2010). This product using a technique similar to ours is being manufactured in India and is generally known as Neem Coated Urea (NCU).

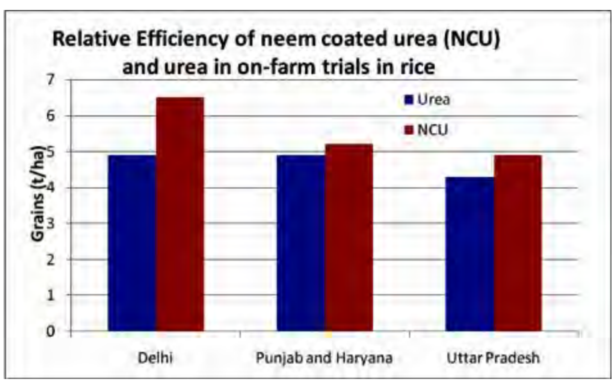

Fig. 1: Relative efficiency of neem coated urea (NCU) and urea in on-farm Trials (@ 120 kg N/ha)

(d) Polymer Coated Urea

Polymer or polyolefin coated urea (PCU) is the latest addition. It requires in a smaller quantity (3-6%) unlike sulphur or neem cake, which are needed in larger quantities. Salman (1998) reported that the PCU has slower dissolution rate than urea and reduces ammonia volatilization (Blaise and Prasad 1995) and leaching losses of N (Blaise and Prasad 1997). In a field experiment although PCU did not give a significant increase in yield, it recorded higher agronomic efficiency and apparent recovery of applied N (Blaise and Prasad 1996). In Japan substantial quantity of PCU is used and performs better than urea (Fashola *et al*. 2002).

(e) Urease Inhibitors

Urease inhibitors reduce the rate of hydrolysis of urea to ammonium and can reduce loss of N due to ammonia volatilization when urea is surface applied (Sarkar *et al*. 1991). A number of urease inhibitors have been reported which include phenyl phosphorodiamide (PPD/PPDA), N-(n-butyl) thiophosphorictriamide (NBPT or NBTPT), thiophosphoryltriamide (TPT), cyclohexyl phosphoric triamide (CHTPT), cyclohexyl phosphoric triamide (CNPT), phosphoric triamide (PT), hydrquinone (HQ), amino thiosulphate (ATS), and hexaamidocyclotriphosphazine (HACTP) (Trenkel 1997, Kiss and Simihaian 2002). The PPDA and NBTP have been tested for rice and the results did not show their advantage in increasing grain yield (Buresh *et al*. 1988, Raju *et al*. 1989).

(f) Urea Super Granule (USG)

The USG was developed taking a lead from the mud-ball technique of application of fertilizer N. In this technique a small amount of fertilizer N is placed in the centre of a mud ball and the balls are sealed with mud. Mud balls are then dried in the shade and are deep-placed in rice field. The USG in rice on medium to heavy soils can increase the NUE by 10-20%. The data in Table 3 shows that same yields of rice can be obtained with 26-59% less N with USG (Tandon 1989). Increased rice yield and NUE with USG has been reported from Indonesia (Pasandaran *et al*. 1999) and Bangladesh (Balasubramanian *et al*. 2004). During 2008 USG were used in 500,000 ha, which increased rice productivity by 268,000 Mt in Bangladesh and reduced country's urea import by 50,000 Mt saving US$ 22 million in fertilizer imports (IFA 2009). The USG was, however, not found to have an advantage in light sandy soils of Ludhiana, Punjab (Bijai-Singh and Katyal 1987). The USG has the built-in advantage of deep placement of N. In addition, ammonia concentration in the vicinity of USG is high enough to inhibit nitrification for some time (Thomas and Prasad 1982).

Table 3: Nitrogen required as USG (kg N/ha) to produce same yield of rice as prilled urea taken as 100

Targetted yield (t/ha)	Bhubaneswar	Coimbatore	Cuttack	Hyderabad	Pantnagar
4	60	39	41	52	55
5		46	74	49	64
6				54	63

Source: Tandon (1989b)

(g) Fertilizer Nitrogen and Environmental Pollution

When leached, fertilizer N enriches groundwaters with nitrates leading to health hazards such as methaemoglobinemia (blue baby syndrome) and several other ailments (discussedlater) and when lost as ammonia it contributes to acid rain. When lost as N_2, N_2O or NOx, it is responsible for Ozone layer depletion. Global estimates of gaseous emissions of NH_3, N_2O and NO from fertilizer is at 11.2, 0.9 and 0.6 million tonnes of N/yr, respectively (Peoples *et al*. 2004). The Indian estimates of gaseous emissions of NH_3 and N_2O+NO_x are at 2.3 and 3.3 million tonnes N/yr (Pathak *et al*. 2009). Agricultural activities in India account for more than 80% of the total N_2O emissions, 60% from the fertilizers and 12% from the burning of agricultural residues (Bijai-Singh *et al*. 2008). Enhancing nitrogen use efficiency (NUE) is a benign way to reduce the pollution of surface and ground waters and associated health hazards as well as environmental pollution.

Of the 104.6 million tonnes (Mt) of N consumed globally in 2010, 32.6 Mt (31.2%) was consumed in China and 16.5 Mt (15.8%) in India (FAI 2012). Thus 47% or nearly half of the fertilizer N consumed globally is used in Asia. Caraco and Cole (Caraco and Cole 1999) estimated that 601, 495, 276 and 144 kg N/yr is transported to sea from Ganges, Yangtze, Huang He and Mekong rivers, respectively, while Zheng *et al*. (2002) estimated that the riverine discharge of dissolved inorganic N in Asia was 6.8 Mt in 2000 and is likely to increase to 9.6 Mt in 2030. Thus nearly one-third of the N discharge from rivers to the sea in Asia is from the agricultural fields. Globally 20 million tons (Mt) of N/year (Seitzinger and Kroez 1998) is transported by rivers to the ocean leading to the eutrophication of the marine waters. One of the most studied cases is the eutrophication of Gulf of Mexico due to N and P discharges from the Mississippi and Atchafalaya rivers (Snyder 2008). Eutrophication of fresh and marine waters leads to noxious algal blooms which cause hypoxia (< 2mg/L dissolved oxygen) (Burkart and James 1999) that causes the mortality of fish and other marine organisms and also a foul odour, which is bad from the aesthetic sense.

(h) Fertilizer Nitrogen and Health

One of the most widely reported symptoms of nitrate toxicity is methaemoglobinemia (MHGN) or Blue Baby Syndrome in infants. In the presence of nitrates the ferrous ion of haemoglobin gets oxidized to ferric form and results in the formation methaemoglobin (Benz 2001), which cannot transfer oxygen. Once the methaemoglobin in blood exceeds 10% of the total methaemoglobin it manifests as clinical cyanosis and causes anoxia (Gangolli *et al*. 1994).

Most cases of nitrate toxicity in infants occur with nitrate level of 90 mg nitrate/L or more (Jaffe 1981). Recently, MHGN has been reported in all age groups (Gupta *et al*. 2000). Nitrate toxicity could also lead to diarrhoea (Gupta *et al*. 2001). Formation of nitroso compounds due to excess nitrate has been reported (Terblanche 1991). These are formed after the reduction of nitrates to nitrites, which react with amines and amides to form nitroso compounds. About 20% of injested nitrate is reduced to nitrite by nitrate reducing flora present in saliva (Eisenbrand *et al*. 1980), mostly at the base of the tongue (Walker 1995). Nitroso compounds are carcinogenic in nature. The data from a number of epidemiological studies are at most only suggestive relating nitrates to carcinogenicity in humans (WHO 1996). For a more detailed discussion on nitrate toxicity and human health reference may be made to a review by Gupta *et al*. (2007).

5. Conclusion

Nitrogen is the key nutrient for food production; however, its use efficiency is quite low, because about one-third of applied N is lost to the atmosphere or groundwater. An all-out effort is needed to increase nitrogen use efficiency. In addition to best agronomic management practices, more efficient nitrogen fertilizers need to be developed.

References

Abrol I, Yadav J and Massoud F Soil affected soils and their management. *FAO Soils Bulletin* **39** (1988)

Amberger A and Guster R Umsatz und wirkung von hornstoff-dicyandiamide-sowie ammoniumsulfat-dicyandiamide-production zu weidelgras und reis *Z Planzen Bodenk* **141** (1978) 553-566

Amberger A and Vilsmeier K Hummung der nitrification de gullestickstoff durch dicyandiamide. *J Agronomy & Crop Sci* **148** (1979) 239-246

Arora R, Sachdev M, Sud Y, Luthra V and Subbiah B Fate of fertilizer nitrogen in a multiple cropping system *Panel Proceedings Series* (1980) 3-22

Aulakh M, Doran J and Mosier A Soil denitrification-significance, measurement, and effects of management. *Advan Soil Sci* Springer (1992) 1-57

Aulakh M S and Bijay-Singh Nitrogen losses and fertilizer N use efficiency in irrigated porous soils *Nutr Cycl Agroecosyst* **47** (1997) 197-212

Aulakh M S, Khera T S, Doran J W and Bronson K F Denitrification, N_2O and CO_2 fluxes in rice-wheat cropping system as affected by crop residues, fertilizer N and legume green manure *Biology and Fertility of Soils* **34**(6) (2001) 375-389

Balasubramanian V, Alves B, Aulakh M, Bekunda M, Cai Z, Drinkwater L, Mugendi D, van Kessel C and Oenema O Crop, environmental, and management factors affecting nitrogen use efficiency *Agriculture and the Nitrogen Cycle SCOPE* **65** (2004) 19-33

Banerjee B, Pathak H and Aggarwal P Effects of dicyandiamide, farmyard manure and irrigation on crop yields and ammonia volatilization from an alluvial soil under a rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) cropping system *Biology and Fertility of Soils* **36**(3) (2002) 207-214

Benz E Hemoglobinopathies *Harrison's Principles of Internal Medicine* **1** (2001) 666-673

Bhat J A, Kundu M C, Hazra G C, Santra G H and Mandal B Rehabilitating acid soils for increasing crop productivity through low-cost liming material *Science of the Total Environment* **408**(20) (2010) 4346-4353

Bijai-Singh Crop demand driven nitrogen application in rice and wheat-some related areas *Indian J Agronomy* **53** (2008) 157-166

Bijai-Singh and Katyal J Relative efficacy of some new urea-based nitrogen fertilizers for growing wetland rice on a permeable alluvial soil *The J Agricultural Sci* **109** (1987) 27-31

Bijai-Singh and Singh Y Balanced Fertilisation for Environmental Quality Punjab Experience *Fertiliser News* **49**(4) (2004) 107-114

Bijai-Singh, Tiwari M K and Abrol Y P Reactive nitrogen in agriculture, industry and environment in India. IGBP-WCRP-SCOPE. New Delhi, Indian National Science Academy: 42 (2008)

Biswas P and Sharma P A new approach for establishing fertilizer response ratio - the Indian scenario *Indian J Fertilizers* **4**(4) (2006) 59-62

Blaise D, Amberger A and Von Tucher S Influence of iron pyrites and dicyandiamide on nitrification and ammonia volatilization from urea applied to loess brown earths (luvisols) *Biology and Fertility of Soils* **24**(2) (1997) 179-182

Blaise D and Prasad R Effect of blending urea with pyrite or coating urea with polymer on ammonia volatilization loss from surface-applied prilled urea *Biology and Fertility of Soils* **20**(1) (1995) 83-85

Blaise D and Prasad R Relative efficiency of modified urea fertilizers in wetland rice (Oryza sativa) *Indian J Agron* **41**(3) (1996) 373-378

Blaise D and Prasad R Dynamics of N-release from differently coated fertilizers under flooded soil conditions *Proc Indian National Science Academy, Section B* **63** (1997) 73-78

Buresh R, De Datta S, Padilla J and Samson M Field evaluation of two urease inhibitors with transplanted lowland rice *Agronomy J* **80**(5) (1988) 763-768

Burkart M R and James D E Agricultural-nitrogen contributions to hypoxia in the Gulf of Mexico *J Environmental Quality* **28**(3) (1999) 850-859

Caraco N F and Cole J J Human impact on nitrate export: an analysis using major world rivers *AMBIO: A J Human Environment* **28**(2) (1999) 167-170

De R A review of fertilization of crops in India *Fertiliser News* **16**(12) (1971) 77-81

Devasenapathy P and Palaniappan S Band placement of urea solution increases N use efficiency in transplanted lowland rice *International Rice Research Notes* **20** (1995)

Eisenbrand G, Spiegelhalder B and Preussmann R Nitrate and nitrite in saliva *Oncology* **37**(4) (1980) 227-231

FAI (2012). Fertilizer Statistics 2011-12. New Delhi, The Fertiliser Association of India.

FAO (1989). Fertilizer and Food Production. Rome, The FAO Fertilizer Programme.

FAO (2010). The State of Food Security in the world-Addressing food in protracted crises. Rome, FAO.

Fashola S S, Hayashi K and Wakatsuli T Effect of water management and polyolefin coated urea on growth and nitrogen uptake of indica rice *J Plant Nutrition and Soil Sci* **25** (2002) 2173-2190

Gangolli S D, van den Brandt P A, Feron V J, Janzowsky C, Koeman J H, Speijers G J, Spiegelhalder B, Walker R and Wishnok J S Nitrate, nitrite and nitroso compounds *European Journal of Pharmacology: Environmental Toxicology and Pharmacology* **292**(1) (1994) 1-38

Glenn J, Gordon T, Florescu E and Starke L The State of the future, 2008 Millenium project. New York, World Federation of of the United Nations Association (2008)

Goring C A Control of nitrification by 2-chloro-6-(trichloro-methyl) pyridine *Soil Sci* **93**(3)(b) (1962ab) **211** 431-439

Goswami N, Prasad R, Sarkar M and Singh S Studies on the effect of green manuring in nitrogen economy in a rice-wheat rotation using a 15N technique *The J Agricultural Sci* **111**(3) (1988) 413-417

Gupta N and Chandrasekharan H Status of nitrate contamination in groundwater near Delhi: A case study *Spec Publ R Soc Chem* **237** (1999) 240-249

Gupta S, Gupta R and Gupta A Nitrate toxicity and human health. New Delhi, IK International Publishing House (2007)

Gupta S K, Gupta R, Gupta A, Seth A, Bassin J and Gupta A Recurrent acute respiratory tract infections in areas with high nitrate concentrations in drinking water *Environmental Health Perspectives* **108**(4) (2000) 363

Gupta S K, Gupta R C, Gupta A B, Seth A K, Bassin J K, Gupta A and Sharma M L Recurrent diarrhea in children living in areas with high levels of nitrate in drinking water *Archives of Environmental Health: An International J* **56**(4) (2001) 369-373

Humphreys E, Chalk P M, Muirhead W A and White R J Nitrogen fertilization of dry-seeded rice in southeast Australia *Fertilizer Res* **31** (1992) 221-224

IFA (2009) Urea deep placement increasing agricultural production and protecting the environment. Fertilizer & Agriculture. Paris, International Frtilizer Industry Association: 6-10

IFPRI (2011) Global Food Policy Report. 2011: 114

IPCC (2000) Climate Change Group: The Science of Climate Change (XII) Cambridge

Jaffe E Methaemoglobinaemia *Clinics in Haematol* **10**(1) (1981) 99

Jepson I Plant expressed cellulases Proceedings of the University Industry Consortium, October 29-30, 2008, Research Triangle Park, NC

Joseph P and Prasad R The effect of dicyandiamide and neem cake on the nitrification of urea-derived ammonium under field conditions *Biology and Fertility of Soils* **15**(2) (1993) 149-152

Kamboj V Presidential address 76th Annual Session, National Academy of Sciences, India. Mumbai, National Academy of Sciences, India (2006)

Katsura K, Maeda S, Lubis I, Horie T, Cao W and Shiraiwa T The high yield of irrigated rice in Yunnan, China: 'A cross-location analysis' *Field Crops Res* **107**(1) (2008) 1-11

Katyal J, Singh B, Vlek P and Buresh R Efficient nitrogen use as affected by urea application and irrigation sequence *Soil Science Society of America J* **51**(2) (1987) 366-370

Katyal J, Singh B, Vlek P and Craswell E Fate and efficiency of nitrogen fertilizers applied to wetland rice. II. Punjab, India *Fertilizer Res* **6**(3) (1985) 279-290

Khan M, Alam M, Hossain M, Rashid M, MIU, Quddas M, Mial M, Sikder M and Ladha J Validation and delivery of improved technologies in the rice ecosystem in Bangladesh. Integrated Crop Resource Management in Rice-Wheat System of South Asia. L. Y. S. O. JK, Erenstein; B, Hardy. Los Banos, Philippines, International Rice Research Institute, Los Banos, Philippines (2009)

Kiss S and Simihaian M Improving efficiency of urea fertilizers by inhibition of soil urease activity, Kluwer Academic Pub (2002)

Kumar N and Prasad R Effect of levels and sources of nitrogen on concentration and uptake of nitrogen by a high yielding variety and a hybrid of rice *Archives of Agronomy and Soil Sci* **50**(4-5) (2004) 447-454

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

McAllister C H, Beatty P H and Good A G Engineering nitrogen use efficient crop plants: the current status *Plant Biotechnology J* **10**(9) (2012) 1011-1025

Mohanty S, Singh U, Balasubramanian V and Jha K Nitrogen deep-placement technologies for productivity, profitability, and environmental quality of rainfed lowland rice systems *Nutrient cycling in agroecosystems* **53**(1) (1998) 43-57

Nishihara T and Tsunyoshi T The effect of some nitrification inhibitors on the avilability of basic fertilizer nitrogen by rice plants on dry paddy fields *Bulletin, Faculty of Agriculture, Kagoshima University, Japan* (1969) 133-141

Novoa R and Loomis R Nitrogen and plant production *Plant and Soil* **58**(1-3) (1981) 177-204

Pandey P, B P S, Gautam R and Lal P Evaluation of modified urea forms for increasing N use efficiency in irrigated transplanted rice. New Delhi, Indian Farmers Fertilizer Cooperative (IFFCO) (1989)

Pasandaran E, Gultom B, Adiningsih J S, Apsari H and Rochayati S Government support for technology promotion and adoption: A case study of urea tablet technology in Indonesia. Los Banos Kluwer Academic, Netherlands & International Rice Research Institute, Philippines (1999)

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

Pathak H, Mohanty S and Prasad R Fate of nitrogen in Indian agriculture, environmental impacts-quantification and uncertainties-A review *Proceedings National Academy of Sciences, India Sect B* **79** (2009) 322-335

Pathak H, Timsina J, Humphreys E and Godwin D Simulation of rice crop performance and water and N dynamics, and methane emissions for rice in northwest India using CERES Rice model *Technical Report CSIRO Land and Water* **23**(4) (2004) 111

Patrick Jr W H, Peterson F and Turner F T Nitrification inhibitors for lowland rice *Soil Sci* **105**(2) (1968) 103-105

Peoples M B, Boyer E W, Goulding K W, Heffer P, Ochwoh V A, Vanlauwe B, Wood S, Yagi K and Van O Cleemput Pathways of nitrogen loss and their impacts on human health and the environment *Agriculture and the nitrogen cycle: assessing the impact of fertilizer use on food production and the environment* (2004) 53-69

Ponnamperuma F and Deturck P A review of fertilization in rice production *Bulletin de la Commission Internationale du Riz* (1994) 42

Prasad R Fertilizer urea, food security, health and the environment *Current Sci* **75**(7) (1998) 677-683

Prasad R Protein-Energy Malnutrition and Fertiliser Use in India *Fertiliser News* **48**(8) (2003) 13-26

Prasad R Research on nitrification inhibitors and slow-release fertilizers in India — A review *Proceedings National Academy of Sciences, India Sect B* **75** (2005) 149-157

Prasad R Strategy for increasing fertilizer use efficiency *Indian J Fertilizers* **3**(11) (2007) 53-62

Prasad R Integrated plant nutrient supply system (IPNS) for sustainable agriculture *Indian J Fertilizers* **4**(12) (2008) 71-90

Prasad R Efficient fertilizer use: The key to food security and better environment *J Tropical Agriculture* **47**(1-2) (2009) 1-17

Prasad R 4 Aerobic Rice Systems *Advances in Agronomy* **111** (2011) 207

Prasad R, Devakumar C and Shivay Y Significance in increasing fertilizer nitrogen efficiency. Neem Research and Development. N. R. B. Parmar. New Delhi, Pesticide Society of India (1993)

Prasad R, Kumar D, Sharma S, Gautam R and Dwivedi M Current status and strategies for balanced fertilization *Fertiliser News* **49**(12) (2004) 73-80

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

Prasad R, Rajale G and Lakhdive B Nitrification retarders and slow-release nitrogen fertilizers *Adv Agron* **23** (1971) 337-383

Prasad R, Sharma S N, Prasad M and Reddy R N S Efficient utilization of nitrogen in rice-wheat rotation. Indian Society of Agronomy National Seminar. Hisar (Haryana), India, *Indian Society of Agonomy* **34** (1981)

Prasad R, Sharma S N, Singh S, Devakumar C, Saxena V S and Shivay Y S Neem coating of urea for environment and agriculture *Fertiliser News* **47**(6) (2002) 63-67

Prasad R, Singh R, Rani A and Singh D Partial factor productivity of nitrogen and its use efficiency in rice and wheat *Fertiliser News* **45**(5) (2000) 63-65

Rajale G and Prasad R Nitrification inhibitors and slow-release nitrogen fertilizers for rice (*Oryza sativa* L.) *The J Agricultural Sci* **80**(3) (1973) 479-487

Rajale G B and Prasad R Mineralization of slow-release nitrogen fertilizers at varying moisture levels *Fertiliser News* **15**(5) (1970) 38-39

Raju R, Reddy K and Husain M Urease-inhibitors and coated urea fertilizers *Indian J Agricultural Sci* **59**(12) (1989) 817-819

Raun W R and Johnson G V Improving nitrogen use efficiency for cereal production *Agronomy J* **91**(3) (1999) 357-363

Reddy R and Prasad R Studies on the mineralization of urea, coated urea, and nitrification inhibitor treated urea in soil *J Soil Sci* **26**(3) (1975) 304-312

Reddy R and Prasad R Effect of variety, rates and sources of nitrogen on growth characters, yield components and yield of rice *Riso* **26** (1977) 217-223

Roberts T The role of fertilizer in growing the world's food *Better Crops* **93**(2) (2009) 12-15

Salman O A Polymer coating of urea prills to reduce dissolution *J Agriculture & Food Chemistry* **36** (1998) 616-621

Sarkar M C, Banerjee N K, Rane D S and Uppal K S Field measurement oa ammonia volatilization loss of urea applied to wheat *Fertiliser News* **36**(11) (1991) 25-28

Schnier H, De Datta S, Fagi A, Eaqub M, Ahmed F, Tejasarwana R and Mazid A Yield response of wetland rice to band placement of urea solution in various soils in the tropics *Fertilizer Res* **36**(3) (1993) 221-227

Seck P A Feeding the world in 2050 *Rice Today* **10**(4) (2011) 12-13

Seitzinger S P and Kroez C Global distrbution of nitrous oxide production and nitrogen inputs in fresh water and coastal marine ecosystems *Global Biogeochemical Cycles* **12** (1998) 93-113

Sekhon G Fertilizer-N use efficiency and nitrate pollution of groundwater in developing countries *J Contaminant Hydrology* **20**(3) (1995) 167-184

Sharma N and Batra P A study on fertilizer response ratios for various crops and cropping sequences. New Delhi, Indian Agricultural Statistics Research Institute (2011)

Sharma S and Prasad R Effect of crop-residue management on the production and agronomic nitrogen efficiency in a rice-wheat cropping system *J Plant Nutrition and Soil Sci* **171**(2) (2008) 295-302

Shaviv A Advances in controlled-release fertilizers *Advances in Agron* **71** (2001) 1-49

Shihua T and Wenquiang F Nitrogen management in the rice-wheat cropping system in the Yangtze river flood plain. Soil and Crop Management Practices for Enhanced Productivity of the Rice-Wheat Cropping System in the Sichuan Province of China. P. H. R. Gupta. New Delhi, *Rice-Wheat Consortium for the Indo-Gangetic Plains* 24-32 (2000)

Snyder C Nutrients and Hypoxia in the Gulf of Mexico – An Update on Progress, 2008 *Better Crops* **92**(2) (2008) 16-22

Sohlman M (ed) Nobel Lectures, Chemistry: 1922-1941, Elsevier (1966)

Sudhakara K and Prasad R Relative efficiency of prilled urea, urea supergranules (USG) and USG coated with neem cake or DCD for direct-seeded rice *The J Agril Sci* **106** (1986) 185-190

Suri I, Prasad R and Devakumar C Neem coating of urea-present status and future trends *Fertiliser News* **49**(8) (2004) 21-24

Swarup A Lessons from long-term experiments in improving fertilzer use efficiency and crop yields *Fertiliser News* **47**(12) (2002) 9-12

Tandon H L S Nitrogen recommendations for higher fertilizer efficiency *Fertiliser News* **34**(12) (1989a) 63-77

Tandon H L S Urea supergranules for increasing nitrogen efficiency in rice - an overview *Soil fertility and fertilizer use* **3** (1989b) 10-22

Terblanche A Health hazards of nitrate in drinking water *Water S A* **17**(1) (1991) 77-82

Thannunathan K, Kandasamy S, Vaiyapuri V, Imayavambram V and Singarvel R Conjunctive use of N and K through foliage for augmenting the flood affected rice *J Potassium Res* **20** (2004) 116-117

Thind H, Pannu R, Gupta R, Vashistha M, Singh J and Kumar A Relative performance of neem (*Azadirachta indica*) coated urea *vis-a-vis* ordinary urea applied to rice on the basis of soil test or following need based nitrogen management using leaf colour chart *Nutrient Cycling in Agroecosystems* **87**(1) (2010) 1-8

Thomas J and Prasad R On the nature of mechanisms responsible for the higher efficiency of urea supergranules for rice *Plant and Soil* **69**(1) (1982) 127-130

Thomas J and Prasad R Mineralization of urea, coated urea and nitrification inhibitor treated urea in different rice growing soils *Zeitschrift für Pflanzenernährung und Bodenkunde* **146**(3) (1983) 341-347

Thomas J and Prasad R Relative efficiency of prilled urea, urea sper granules, sulphur coated urea and nitrification inhibitor N-Serve blended urea for direct seeded rice *J Agronomy & Crop Sci* **15** (1987) 302-307

Tilman D, Balzer C, Hill J and Befort B L Global food demand and the sustainable intensification of agriculture *Proc National Academy of Sci* **108**(50) (2011) 20260-20264

Trenkel M Controlled-Release and Stabilized Fertilizers in Agriculture; International Fertilizer Industry Association: Paris, 1997. Paris: 151 (1997)

UN-DESA (2011) Development Report. New York, United Nations

Verma S and Singh S Enhancing wheat production through appropriate agronomic management *Indian Farming* **58**(5) (2008) 15-18

Verma U N and Srivastava V C Balanced fertilization use for increased food production in eastern India, Phosphate and Potash Institute of India (1995) 23-24

Walker R (1995) The conversion of nitrate into nitrite in several animal species and man. Health aspects of nitrate and its metabolites (particularly nitrite). Proceedings of an international workshop, Bilthoven (Netherlands), 8-10 November 1994

Watts D, Hergert G and Nichols J Nitrogen leaching losses from irrigated orchardgrass on sandy soils *J environmental quality* **20**(2) (1991) 355-362

WHO (1996) Toxicological evaluation of certain food additives and contaminants. 44th Meeting of the Joint FAO/WHO. Geneva, WHO

Wohler F Ueber Kusliche bildung des hornstaff *Annalen der Physik und Chemie* **88**(2) (1828) 253-256

Yadav D, Shukla R and Kumar B Effect of zero tillage and nitrogen level on wheat (*Triticum aestivum*) after rice (*Oryza sativa*) *Indian J Agron* **50**(1) (2005) 52-53

Yadvinder S and Bijai-Singh Need based field specific nitrogen management in rice for high fertilizer use efficiency *National Academy of Agricultural Sciences (NAAS) News* **8**(1) (2009) 9-12

Zeigler R Monitoring an inconvenient divergence *Rice Today* **10**(4) (2011) 4

Zhang F, Zhang W, Fan M and Wang J Improving fertilizer use efficiency through management practices - Chinese Experience. The Fertilizer Association of India Annual Seminar, New Delhi, India, The Fertiliser Association of India (2007)

Zheng X, Fu C, Xu X, Yan X, Huang Y, Han S, Hu F and Chen G The Asian nitrogen cycle case study *AMBIO: A J Human Environ* **31**(2) (2002) 79-87.