Review/Synthesis

Efficient fertilizer use: The key to food security and better environment

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Received 11 April 2009; accepted 14 July 2009.

Abstract

Since the inception of Green Revolution there has been a race for increasing foodgrain (mainly cereals) production using chemical fertilizers in India. However, cereal production in the country increased only five fold, while fertilizer consumption increased 322 times during the 1950–51 to 2007–08 period, implying a very low fertilizer use efficiency. Large scale applications of fertilizer nitrogen (N) have also shown deleterious effects on groundwater quality, especially its nitrate content, which is harmful to health. Furthermore, gaseous losses of N as NH_3 and NO_x resulting from N fertilization have adverse effects on the environment. Therefore, the goal of Indian agriculture has to be to "increase food-grain production with the minimum and efficient use of chemical fertilizers". This calls for a sincere effort on the part of agricultural scientists including extension workers to increase the efficiency of fertilizers applied in the farm fields. An effective nutrient management involves development of site specific nutrient recommendations including balanced NPK doses, timely application of fertilizers using appropriate methods, development and production of slow-release N fertilizers and indigenous nitrification inhibitors, and developing and practicing an integrated plant nutrient supply system (IPNS) using chemical fertilizers, organic manures, crop residues, and biofertilizers. In addition to proper nutrient management, other aspects of soil and crop management including the use of high yielding, nutrient-efficient cultivars, correcting soil physical and chemical problems and water management, disease and pest management (IPM), and post-harvest care and safe storage are important to achieve high fertilizer use efficiency.

Keywords: Fertilizer use efficiency, Nutrient use efficiency, Agronomic efficiency, Crop response ratio, Nitrification inhibitors, Slow-release fertilizers, Site specific nutrient management, Integrated plant nutrient supply, N-balance.

Introduction

India has only 2.5% of the world's geographical area but has about 17% of its population. This places considerable pressures on land for food production. Providing two meals a day to each person has been India's perpetual problem due to its ever increasing population. India's population increased from 361 million in 1951 to 1131 million in 2007: a three-fold increase in a span of a little over 50 years. According to FAO (2003), globally there are about 963 million undernourished people, out of which approximately 21% are in India. As of today, there is sufficient food for everyone in the country, yet its availability to each citizen remains a problem due to lack of purchasing power. To quote Mahatma Gandhi 'God continues to be bread' to poor children, men, and women in some parts of the country. Parikh (2002) stated that 0.9% people in rural areas and 0.5% in urban areas, totalling to about 10 million, do not get two square meals a day throughout the year. Launching of the 'National Food for Work Programme' by Dr. Manmohan Singh, Honorable Prime Minister of India in 150 most backward districts of the country on 14 November 2004 is a landmark in this respect (Prasad, 2006a). By 2020, India will need about 294 Tg (1 Tg or tera gram = 10^{12}g =1 million tonne) foodgrains (i.e., 268 Tg cereals + 26 Tg pulses; Kumar, 1998). However, only 230.67 Tg was produced in 2007–08 (FAI, 2008), implying that about

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63 Tg additional foodgrains have to be produced from the same or even lesser land area, for which fertilizers will play a major role (Prasad, 1999).

Fertilizer was considered an important tool to augment food production in India since independence. For instance, in 1947, Dr. A.B. Stewart of the MaCaulay Institute of Soil Research, Scotland (UK) was invited to advise the Government of India (GOI) on this aspect. He suggested two sets of experiments to study fertilizer responses of crops, namely, simple trials on farmers' fields and complex experiments at a few selected research centres (known as Model Agronomic Experiments; Stewart, 1947). These fertilizer experiments were also encouraged by Dr. Frank W. Parker from USA, Agriculture Adviser to GOI in the 1950's and the simple on-farm fertilizer trials rapidly expanded under the Technical Cooperation Mission (Randhawa, 1980). Besides generating crop response data on NPK, these on-farm trials also served as demonstrations on the use of chemical fertilizers for increasing crop yields; until then fertilizers were applied only to commercial crops such as sugarcane and cotton.

The true role of fertilizes in augmenting food production in India was realized only with the introduction of high yielding dwarf varieties of wheat (and other cereals) during 1966–68, the 'Green Revolution' era. Fertilizer consumption almost doubled from 0.78 Tg to 1.54 Tg during 1965–66 to 1967–68 with a concomitant increase in wheat production from 10.4 Tg to 16.5 Tg and the total cereal production from 62.4 Tg to 82.9 Tg. As can be seen from Table 1, there was a five-fold increase in cereal production, i.e., from 42.4 Tg in 1950–51 to 215.6 Tg in 2007–08.

Although the data in Table 1 show a continuous increase in fertilizer consumption and food production, there have been a few hiccups in recent years. The annual growth rate of fertilizer consumption was negative (–0.02%) during 1996–97 to 2003–04, as compared to 2.89% during 1988–89 to 1996–97. As a consequence, the annual rate of growth in cereal production was only 0.02% during 1996–97 to 2004–05 against 2.23% during 1990–91 to 1996–97, and 3.15% during 1980–81 to 1989–90. Fortunately during 2004–05 to 2006–07, the rate of annual growth in fertilizer consumption was 6.2% (Ramesh Chand, 2008), which reflected in increased cereal production from 185.2 Tg in 2004–05 to 215.6 Tg in 2006–07 (FAI, 2008). The production of pulses, however, was only 15 Tg during 2007–08 and has remained at 13±2 Tg during the last two decades or so creating a protein malnutrition problem in some parts of the country (Prasad, 2003). With a consumption of 14.4 Tg N, 5.5 Tg P_2O_5, and 2.6 Tg of K_2O in 2007–08, India now occupies the second position (neck to neck with

Table 1. Cereal production and fertilizer consumption in India.

Year	Cereal production (Tg)			Fertilizer consumption (Tg)			
	Rice	Wheat	Total	N	P_2O_5	K_2O	Total
1950–51	20.6	6.5	42.4	0.055	0.009	0.006	0.07
1960–61	34.6	11.0	69.3	0.21	0.05	0.03	0.29
1965–66	30.6	10.4	62.4	0.57	0.13	0.08	0.78
1966–67	30.4	11.4	65.9	0.74	0.25	0.11	1.10
1967–68	37.6	16.5	82.9	1.03	0.33	0.17	1.54
1970–71	42.2	23.8	96.6	1.21	0.38	0.17	1.76
1980–81	53.6	36.3	119.0	3.68	1.21	0.62	5.51
1990–91	74.3	55.1	162.1	8.00	3.22	1.33	12.55
1995–96	77.0	62.1	168.1	9.82	2.90	1.55	13.87
2000–01	85.0	69.7	185.7	11.31	4.38	1.67	17.36
2005–06	91.8	69.3	195.2	12.72	5.20	2.41	20.33
2007–08	96.4	78.4	215.6	14.42	5.51	2.64	22.57

Source: FAI (2008).

USA) after China in N and P consumption. In K consumption, India occupies the fourth position. India also occupies the second position in fertilizer N production (10.9 Tg in 2007–08) and third position in phosphate fertilizer production (3.7 Tg in 2007–08; FAI, 2008). However, fertilizer use efficiency in India is rather low. This paper gives an overview on fertilizer use, fertilizer use efficiency, and its most important determinants from the food production and environmental security perspectives.

Defining Fertilizer/Nutrient Use Efficiency (NUE)

In general, four terms are used in relation to NUE. These are: Agronomic Efficiency (*AE*), Recovery Efficiency (*RE*), Physiological Efficiency (*PE*), and Partial Factor Productivity of Fertilizers (*PFPf*). The following expressions are used for determining these:

$$AE \text{ (kg grain·kg nutrient}^{-1}\text{ applied)} = \frac{Yf - Yc}{Na}$$

$$RE \text{ (\% of nutrient taken up by a crop)} = \frac{NUf - NUc \times 100}{Na}$$

$$PE \text{ (kg grain·kg nutrient}^{-1}\text{ taken up by a crop)} = \frac{Yf - Yc}{Nuf - NUc}$$

$$PFPf \text{ (kg grain·kg nutrient}^{-1}\text{ applied)} = \frac{Yf}{Na}$$

In the above expressions, *Yf* and *Yc* are the yields (kg·ha^{-1}) in fertilized and control (no fertilizer) plots, respectively. *NUf* and *NUc* are the amounts of nutrients taken up by a crop in fertilized and control plots, respectively and *Na* refers to the amount of nutrient applied (kg·ha^{-1}). *AE* is the same as "crop response ratio" or productivity index used by FAO (1989) and can be determined for a single nutrient (N, P, or K) or for a combination of nutrients (NP, NK, PK, or NPK), or for a fertilizer material *per se*. *PFPf* can also be determined for a single or a combination of nutrients or for a fertilizer *per se*. *PFPf* which was recently introduced does not ask for a 'no-fertilizer control' plot yield. This term permits comparison of fertilizer use efficiency in different countries or in different regions of a country. The term is useful in comparing the advantages of fertilizer use in experiments on tillage, irrigation, weed control etc., where a 'no fertilizer control' is typically not provided. Most discussion in this paper uses *AE* or *PFPf*. *RE* and *PE* on the other hand are determined for specific nutrients. Further, *RE* may be apparent recovery efficiency (*RE*) or true recovery efficiency (*REt*). *REt* is determined with the help of ^{15}N for N and ^{32}P for P. *RE* is used by soil and environment scientists in finding out the part of nutrient taken up by crop and the part causing environmental pollution. *PE* is used by plant physiologists and plant breeders in studying the efficiency of different crops or cultivars of a crop in utilizing the absorbed nutrients. *PE* is actually *AE/RE*. In this paper term *NUE* is used for nutrient use efficiency for all nutrients, while subscripts *n, p, k, npk* are used to refer to efficiencies of individual or a combination of nutrients. Also the term *NiUE* is used for nitrogen use efficiency.

AE or Crop Response Ratio

In the pre-Green Revolution era tall rice and wheat varieties were grown, which used to lodge when high rates of fertilizers were applied. Consequently, the rates of application of $N/P_2O_5/K_2O$ were low. Data from on-farm trials conducted under the Simple Fertilizer Trials Scheme of ICAR (Table 2) show that response ratio was the highest for N (11.6 to 16.7 kg grain·kg N^{-1}), followed by P (5.5 to 12.5 kg grain·kg $P_2O_5^{-1}$), and the least for K (3.6-6.2 kg grain·kg K_2O^{-1}). Furthermore, response to NP, NK, or NPK was not additive of their individual responses, which made the farmers to apply mostly N alone. Data from on-farm trials of the same project (renamed as All India Coordinated Agronomic Experiments Scheme or AICAES) with high yielding varieties of wheat after Green Revolution are in Table 3. The rate of nutrient application in these trials was high (120 kg N + 60 Kg P_2O_5 + 60 kg K_2O) and although the increase in yield due to fertilizer was much higher (1.1 to 2.6 Mg·ha^{-1} compared to 0.47 to 1.25 Mg·ha^{-1} for tall wheats), the response ratio to NPK application was not much and ranged from 4.7 to 10.9 kg grain·kg nutrient^{-1}. On-farm trials conducted under the aegis of FAO during 1961–86 in 48 developing countries of Asia, Africa, and Latin America also showed low

Table 2. Yield increase and crop response ratios in rice and wheat due to NPK fertilization in on-farm trials during pre-Green Revolution era.

Crop	Soil	Trials (numbers)	Yield (100 kg·ha^{-1})						
			Control	N	P	K	NP	NK	NPK
Rice	Alluvial	933	12.2	3.1 (13.8)	2.0 (8.9)	1.2 (5.3)	4.1 (9.1)	2.5 (5.6)	5.6 (8.3)
	Black	180	13.6	2.7 (12.0)	2.1 (9.4)	0.8 (3.6)	3.0 (6.7)	3.0 (6.7)	4.5 (6.7)
	Red	726	15.2	3.3 (14.7)	2.8 (12.5)	1.7 (7.6)	5.1 (11.4)	4.0 (8.9)	7.0 (10.4)
	Laterite	239	15.2	3.0 (13.4)	1.7 (7.6)	1.0 (4.5)	3.7 (8.2)	3.2 (7.1)	5.4 (8.0)
	All India	2833	13.8	3.0 (13.4)	2.2 (9.8)	1.4 (6.2)	4.4 (9.8)	3.3 (7.4)	6.1 (9.1)
Wheat (irrigated)	Alluvial	1294	14.1	3.8 (16.7)	2.2 (9.8)	1.3 (5.8)	5.3 (11.8)	4.2 (9.4)	7.2 (10.7)
	Med. Black	23	9.5	1.8 (8.0)	1.0 (4.5)	0.1 (0.4)	1.8 (4.0)	2.4 (5.3)	4.7 (7.0)
	Red	192	10.2	3.7 (16.5)	2.3 (10.3)	1.9 (8.5)	5.7 (12.7)	4.8 (10.7)	8.4 (12.5)
	Laterite	35	8.5	3.3 (14.7)	1.3 (5.8)	0.6 (2.7)	3.9 (8.7)	3.0 (6.7)	4.2 (6.2)
	All India	1916	13.0	3.7 (16.5)	2.3 (10.3)	1.4 (6.2)	5.3 (11.8)	4.4 (9.8)	7.3 (10.9)
Wheat (rainfed)	Alluvial	210	9.2	2.7 (12.0)	1.3 (5.8)	0.9 (4.0)	3.5 (7.8)	2.9 (6.5)	4.8 (7.1)
	Hill	237	9.5	2.7 (12.0)	1.5 (6.7)	0.9 (4.0)	3.5 (7.8)	3.1 (7.1)	5.5 (8.2)
	All India	518	9.2	2.6 (11.6)	1.3 (5.8)	0.9 (4.0)	3.6 (8.0)	2.9 (6.5)	4.9 (7.3)

All nutrients applied @ 22.4 kg·ha^{-1}; Figures in parentheses are response ratio in kg grain·kg nutrient^{-1}.
Source: Panse and Khanna (1964).

response ratios of 4–12 kg grain·kg nutrient^{-1} (FAO, 1989). Again the percent contribution of NPK in AICAE was in the same order (N>P>K) as in earlier trials. More recent data from this project (renamed as Project Directorate of Cropping Systems Research, PDCSR), however, showed much higher response ratios (9.6 to 20.6 kg grain·kg nutrient^{-1}; Hegde, 1998).

Recovery Efficiency (RE)

Data on true recovery efficiency (*REnt*) from some experiments in India showed that in rice the values ranged from 26 to 35.8%, while in wheat these ranged from 25.6 to 44%. Rice-wheat cropping system is the backbone of food security in India (Prasad, 2005a) and the values of apparent recovery efficiency of N (*REn*) averaged over some rice and wheat experiments at the Indian Agricultural Research Institute, New Delhi are in Table 4 and the global average values for rice, wheat, and maize are in Table 5. Data in Table 4 clearly show that the values of all the terms associated with N use efficiency (*NiUE*) declined as the rate of N applied increased. At N levels similar to those in Table 4, values of all *NiUE* terms in rice were lower in India compared to the global values (Table 5). On the other hand, values of all terms of *NiUE* in wheat were higher in India than the global values,

Table 3. Yield increase and response ratio of irrigated wheat to N, P, and K in on-farm trials conducted during 1971–82 in different states of India.

State	Trials (numbers)	Control	Yield increase due to NPK	Response ratio (kg grain·kg nutrient^{-1})	Percent contribution		
		(Mg·ha^{-1})			N	P	K
Himachal Pradesh (1)	85	1.41	2.37	9.9	46	28	26
Punjab, U.P., Bihar	1400	1.77	2.62	10.9	61	23	16
Part Madhya Pradesh, Orissa	882	1.11	1.71	7.1	44	33	23
Part Madhya Pradesh, Maharashtra	1145	1.38	1.48	6.2	58	22	20
Karnataka	250	1.26	1.13	4.7	44	28	28
All India	3768	1.45	1.95	8.1	56	25	19

(1) At 120 kg N + 60 kg P_2O_5 + 60 kg K_2O per ha.
Source: AICARP (1985).

Table 4. Estimates of N use efficiency in rice and wheat in experiments at IARI, New Delhi.

N Rates (kg·ha^{-1})	PFPn (kg grain·kg N^{-1} applied)	AEn (kg grain·kg N^{-1} applied)	REn (%)	PEn (kg grain·kg N^{-1} taken up by crop)
Rice				
40–60	84.3	22.0	36.1	44.4
61–120	47.7	16.2	40.2	37.7
121–180	32.8	13.1	31.3	40.4
Wheat				
40–60	83.7	28.8	73.8	47.8
61–120	50.2	20.1	57.7	42.8
121–180	31.3	15.9	61.8	24.0

Source: Prasad et al. (2000).
PFPn = Partial Factor Productivity of N; AEn= Agronomic Efficiency of N; REn= Recovery Efficiency of N; PEn= Physiological Efficiency of N.

showing that in India N is more efficiently utilized for wheat than rice. Thus in rice there is considerable scope to increase *NiUE*. Some data on apparent recoveries of P and K in rice and wheat are in Table 6. *RE* of P varied from 20–37%, while that of K varied from 40–56% in the rice-wheat cropping system. These data suggest that the generally perceived 60—80% *RE* of K (Tandon, 2004) is probably on the higher side.

Table 5. Global estimates of nitrogen use efficiency in cereals.

Crop	N Rates (kg·ha^{-1})	PFP (kg grain·kg N^{-1} applied)	AEn (kg grain·kg N^{-1} applied)	REn (%)	PEn (kg grain·kg N^{-1} taken up by crop)
Maize	123	72.0	24.2	65	36.7
Rice	115	62.4	22.0	46	52.8
Wheat	112	44.5	18.1	57	28.9
Average		20.6	51.6	55	40.6

Source: Ladha et al. (2005).
See Table 4 for abbreviations.

Table 6. Apparent recovery of P and K in rice-wheat cropping system (RWCS).

Centre	Phosphorus (%)			Potassium (%)		
	Rice	Wheat	RWCS	Rice	Wheat	RWCS
Sobour	29	27	28	60	51	55
Palampur	24	21	22	42	40	41
Ranchi	25	17	21	50	36	43
R.S. Pura	22	18	20	47	44	46
Ludhiana	31	29	30	54	47	51
Faizabad	31	30	31	55	38	47
Kanpur	38	36	37	47	47	47
Modipuram	32	28	30	45	35	40
Varanasi	28	24	26	59	53	56
Mean	29	26	27	51	44	47

Source: Singh et al. (2008b).

Ways to Increase Fertilizer/Nutrient Use Efficiency

Crop yield directly or indirectly is the numerator in all the terms of *FUE/NUE* and the crop, soil and agronomic factors that increase crop yield may therefore increase *FUE/NUE*. Before a discussion on management factors it is therefore desirable to have a look at the potential and realizable yields of crops in different parts of the country. Some data on potential yield, on-station, and on-farm yields in the regions where research station are located are summarized in Table 7. It shows a gap of 37–52% between potential and on-station yields and a 35–70% gap between potential and on-farm yields. The gap between on-station and on-farm yields varied from 6–44%. In general the gaps are wider in rice than in wheat. The available farm technology can at least

Table 7. Potential, on-research station and on-farm yields of rice and wheat in different zones of Indo-Gangetic Plains (IGP).

IGP Zone	Site	Potential[1] yield (A)	On-station yield (B)	On-farm yield (C)	Yield gap (%)		
		(Mg·ha^{-1})			100(A–B)/A	100(A–C)/A	100(B–C)/B
Rice							
2	Ludhiana	10.7	5.6	5.6	47.6	47.6	0
2	Karnal	10.4	6.8	3.8	34.6	63.5	44.1
3	Kanpur	9.5	4.5	2.8	52.1	70.5	37.8
3	Pantnagar	9.0	5.5	4.2	38.9	53.2	23.6
4	Varanasi	9.2	4.1	3.2	55.4	65.2	21.9
4	Faizabad	9.1	4.2	2.8	53.8	69.2	33.3
Wheat							
2	Ludhiana	7.9	4.7	4.3	40.5	45.6	6.3
2	Karnal	7.3	4.6	3.6	37.0	50.7	21.7
3	Kanpur	7.0	4.6	2.8	34.3	60.0	39.1
3	Pantnagar	6.5	3.9	4.2	40.0	35.4	–0.07
4	Varanasi	7.0	3.8	3.2	45.7	54.3	15.8
4	Faizabad	6.7	3.4	2.8	49.2	58.2	17.6

Source: [1] Aggarwal et al. (2000) and all others from Ladha et al. (2003).

reduce on-station–on-farm gap and this can increase rice and wheat production by 15–20%. What is heartening to note is that in rice the on-station–on-farm gap is zero in Ludhiana region of Punjab and in wheat it is even slightly negative in Pantnagar, Uttaranchal. This shows that the farmers have already applied the available technology in these regions. Thus with good extension efforts it can be replicated in other parts of the country. Information on benefits of improved technology as compared to farmers' practices in increasing crop yield is also available for oilseeds (Hegde and Babu, 2008) and pulses (Ali et al., 2002).

Crop varieties and cropping systems

The Green Revolution in India was initiated with the introduction of high yielding fertilizer responsive dwarf varieties of wheat (Swaminathan, 2006), which not only gave higher yields but also higher *NUE*. The introduction of rice hybrids (Chang et al., 1988; Siddiq, 2006) promises one tonne additional yield over that obtained with current high yielding varieties and an increase in *AEn* and *REn* (Kumar and Prasad, 2004; Kumar et al., 2007). Large benefits are expected from genetically modified (GM) crop plants (Gupta, 2008) and *Bt* Cotton is an excellent example (Singh and Kaushik, 2007). Likewise, carefully selected cropping systems result in increased fertilizer use efficiency as determined by crop equivalents or net returns (Gill and Ahlawat, 2006).

Soil management

Both chemical amendments such as lime and gypsum and physical management involving tillage are important for increasing crop yields and in doing so, they improve *NUE*.

- *Liming acid soils*: Nearly 51 million ha of soils in India have pH 5.5 or less (Mahapatra and Pattanayak, 2008). Long-term fertilizer experiments from Ranchi (Nambiar, 1994) further show that over a period of 13 years, maize yield was higher under NPK + lime compared to no-lime treatments. Continuous application of FYM also maintained reasonably good yields (71.7% of that obtained with NPK + lime).
- *Gypsum application in sodic soils*: Crop yields are low on sodic soils and can be largely increased by gypsum application. Data from Karnal (Singh and Abrol, 1988) illustrated that *PFPnpk* in wheat almost doubled following gypsum application.
- *Tillage*: Puddling rice paddies reduces percolation of water and leaching of fertilizers, especially N, besides helping in weed control. The net result is increased rice yield and *PFPn* (Dwivedi et al., 2003). Several new tillage implements such as laser aided land leveller, mechanical rice transplanter, and drum seeders have recently become available (Tomar et al., 2006) and their use in rice cultivation will increase *NUE*.
- Zero-till machines have become particularly relevant in rice-wheat cropping system, where wheat sowing is generally delayed if the conventional method of pre-sowing irrigation and land preparation are adopted (Mehla et al., 2000). It is now possible to sow wheat soon after rice harvest without primary cultivation, which permits timely sowing, besides ensuring increased grain yields and *PFPnpk* (Yadav et al., 2005; Singh et al., 2008a). Advantage of zero tillage has also been reported for maize after rice in Telangana region of Andhra Pradesh (Reddy and Veeranna, 2008). In arid regions, off-season tillage can help in storing soil moisture, which increases crop yield and *PFPnpk* (Samra, 2003).

Agronomic management

- *Timely sowing/transplanting*: Delayed transplanting of rice reduces grain yield and *PFPnpk* as is obvious from the data from Bhubaneswar (Nayak et al., 2003). Late sown wheat in rice-wheat cropping system results in16–24% less grain yields and 21.9 to 16–19.4% lower *PFPnpk* (Tripathi et al., 2002).
- *Plant population*: Sub-optimal plant population is one factor that reduces crop yields in India more than any other factor. Lower seed rates associated with wider spacing and fewer seedlings per hill in the case of rice and seedling mortality due to diseases and pests are the major factors that affect plant population in other crops. In rice transplanting

two seedlings is advantageous from the viewpoint of grain yield as well as *PFPnpk* (Nayak et al., 2003). Increasing seed rate from 100 to 125 $kg{\cdot}ha^{-1}$ increased rice yield by 240 $kg{\cdot}ha^{-1}$ and *PFPnpk* by 2% (Tripathy and Mohapatra, 2007). Further increase in seed rate, however, reduced grain yield and *PFPnpk*. A large volume of data exists on seed rate, spacing, thinning etc. on most crops in India but it has not been linked with NUE.

- *Weed Control*: Weeds compete with crop plants for nutrients, water, and sunlight and as a consequence reduce crop yield and NUE. Examples are the menace of *Phalaris minor* in wheat in India (Sharma, 2007) and weedy rice (a natural hybrid of *Oryza sativa* and wild rices *O. rufipogon* and *O. nivara*) in South and Southeast Asia (Anonymous, 2007). Considerable information exists in India on effective weed control through mechanical methods and herbicides (Gupta, 1984), albeit it is not linked with *NUE*. Saha et al. (2007), however, showed that effective weed control in rainfed rice in Cuttack raised grain yield by 1.34 $Mg{\cdot}ha^{-1}$ and *PFPnpk* by 11.2%.
- *Water management*: Water management involving proper irrigation scheduling (irrigated areas) and moisture conservation (rainfed agriculture) is highly correlated with *NUE*. For example, in wheat, irrigation at 1.0 *IW/CPE* increased grain yield by 0.41 $Mg{\cdot}ha^{-1}$, water use efficiency by 7.5 $kg{\cdot}ha^{-1}{\cdot}cm^{-1}$ and *PFPnpk* by 1.7 kg grain·kg NPK^{-1} over irrigation at 0.8 *IW/CPE* (Verma and Singh, 2008). Similarly, construction of water harvesting structures such as tanks with open dug wells in the upper reaches and shallow ditches in the lower reaches of a drainage line to re-harvest the seepage water from the tanks for irrigation are potential mechanisms in rainfed agriculture to increase grain yield as well as *PFPnpk* (Pali et al., 2007).

Fertilizer materials and their methods of application

Materials: Nitrogen fertilizers are highly soluble and this leads to considerable leaching losses under upland conditions and de-nitrification losses under low-land situations. Efforts have therefore been made to develop slow-release nitrogen fertilizers. These are of two kinds: the coated conventional fertilizers such as sulphur coated urea, polymer coated urea, neem coated urea, and the inherently less soluble materials, which are mostly urea-aldehyde products, such as ureaform (urea-formaldehyde), isobutylidene diurea (IBDU), and crotonaldehyde diurea (CDU). However, the cost of N in these materials is twice or thrice or even more than the conventional fertilizers, making them beyond the reach of common farmers. They are generally referred to as specialty fertilizers and are used in golf courses, lawns, and floriculture. During 1995–96, 562,000 Mg of slow-release fertilizers were produced in USA, Europe, and Japan. Of this 40% was ureaform, 19% sulphur coated urea, 15% IBDU, and 24% polymer coated urea (Trenkel, 1997). Another approach has been to use nitrification inhibitors to retard nitrification of applied NH_3 or urea-N and to reduce leaching and de-nitrification losses (Prasad, 2005b). The most widely tested and used nitrification inhibitors are Nitrapyrin or N-Serve, AM (2-amino-4-chloro, 6-methyl pyridine), and dicyandiamide. Some researchers have suggested the use of urease inhibitors for reducing NH_3 volatilization losses and the most widely tested urease inhibitor is NBTPT or NBPT (Hendrickson, 1992).

In India, Prasad and Prasad (1980) developed the neem cake coated urea (NCCU), which was shown to have nitrification inhibiting properties (Thomas and Prasad, 1982a). It increased yield in rice (Sudhakara and Prasad, 1986) and rice-wheat cropping systems (Prasad et al., 1981). In rice-wheat cropping system, NCCU was as good as sulphur coated urea; the major factor responsible for N regulation was nitrification inhibition by the triterpenes in neem (Devakumar and Mukherjee, 1985). Since coating of urea with neem cake was industrially not feasible due to the large volumes involved (e.g., 20% w/w of urea), a neem oil micro-emulsion technique was developed (Prasad et al., 1999a). This technique or its modification is currently being used by the National Fertilizes Ltd., Indo-Gulf Fertilizers, and Shriram Fertilizers and Chemical Ltd. and about 0.4 Tg of neem coated urea (NCU) are being manufactured in India. Furthermore, on-farm trials in Delhi, Punjab, Haryana, and Uttar Pradesh have shown that NCU results in 6 to 11% increase in rice yield. *PFPn* for NCU ranged from 41 to 43% compared to 36 to 41% for prilled urea (Prasad, 2007).

Another product that needs to be mentioned is the urea super granules (USG), which are ~1 cm diameter granules/pellets weighing ~1 g. USG was tested at research centres as well as on farmers' fields during the 1980's and the results were very encouraging on most soils except the highly porous coarse textured soil. Yield benefits with USG over prilled urea varied from 0.2 to 1.2 $Mg \cdot ha^{-1}$at the same level of N (Kumar et al., 1989). Thomas and Prasad (1982b) have reported that in addition to the advantage of N placement, which reduces volatilization losses, placement of such a high amount of urea at a micro-locus produced very high concentrations of NH_3, inhibiting nitrification. Production of USG in India, however, did not take off. Nonetheless, it was well received by the rice farmers of Bangladesh (Balasubramanian et al., 2004).

There has been not much research on slow-release P and K fertilizers. As regards to phosphate fertilizers, the phosphate rock is insoluble but on acid soils it can be directly used.

Time of application: Under irrigated conditions split application of N is a well accepted method of increasing *NiUE* and plenty of literature is available on the subject (Prasad, 2007 and many others). Split application of N is highly desirable since crop plants take up very small amounts of N $ha^{-1} \cdot day^{-1}$. For example, Prasad (2006b) reported that rice removed just 1–1.2 kg N $ha \cdot day^{-1}$. Excess N not used by crops is subject to various mechanisms of losses (Prasad et al., 1999b; Adhya et al., 2007; Pathak et al., 2008). Recent research has shown that for determining the proper time of post transplant/sowing application of N, use of new tools such as chlorophyll meters and leaf colour charts holds promise (Pathak and Ladha, 2007; Bijai-Singh, 2008).

Most P and K are applied at sowing/transplanting, although it is reported that in wheat P may be applied after the first irrigation, in case it is not available or applied at sowing (Singh, 1985). Likewise, some reports on the advantage of split application of K in rice are available (Meena et al., 2002).

Method of application: Considerable data exist in India on the advantage of deep placement of P for increasing its efficiency for crops other than rice (Rao et al., 2003 and many others). However, only in areas where agriculture is mechanized, deep placement of P is practised; elsewhere, it is still broadcast depriving the farmers the full benefits of P fertilization. Regarding N also, deep placement increases *NiUE* considerably. Panda et al. (2007) reported that band furrow placement of N doubled *NiUE* compared to its broadcast application in rainfed lowland rice. This is one of the advantages associated with USG. Lately, the International Fertilizer Development Centre, USA has developed a machine for deep placement of urea, which is performing well in Bangladesh (Sharma, 2008). Placement of N has definite advantages in dryland crops such as oilseeds, as well (Hegde, 1995).

Foliar application of N is desirable in dryland agriculture, because the farmers in these areas apply fertilizers only when rains come, and these are often delayed. Under such conditions foliar application of N is the best choice. Thanunathan et al. (2004) recommended foliar application of N and K in flooded rice, while Kumar and Kumar (2007) recommended foliar application of K in banana. Foliar application of KNO_3 in addition to soil K application was recommended for potato at Ludhiana (Brar and Kaur, 2006).

Balanced NPK Fertilization and Site Specific Nutrient Management

Balanced NPK fertilization has received considerable attention in India (Hegde and Babu, 2004; Prasad et al. 2004; Ghosh et al., 2004 and many others). Farmers, specially the marginal and dryland farmers, generally, tend to apply only N. However, the *AEn* of applied N can be largely increased by adequate P and K fertilization (Table 8). About 45% of Indian soils are also deficient in S (Biswas et al., 2004) and 48% in Zn (Gupta et al., 2007). The soils in eastern India are particularly deficient in B (Shrotriya and Phillips, 2002).

Table 8. Effect of balanced NPK fertilization on *AEn* of nitrogen.

Crop	Control yield ($kg{\cdot}ha^{-1}$)	N applied ($kg{\cdot}ha^{-1}$)	*AEn* (kg grain or cane·kg N^{-1})		Increase in *AEn* due to PK application (%)
			–PK	+ PK	
Rice (*kharif*)	2740	40	13.5	27.0	100
Rice (*boro*)	3030	40	10.5	81.0	671
Wheat	1450	40	10.8	20.0	85
Pearl millet	1050	40	4.7	15.0	219
Maize	1670	40	19.5	39.0	100
Sorghum	1270	40	5.3	12.0	126
Sugarcane	42200	150	78.7	227.7	189

Source: Prasad (1996).

Adequate application of S and Zn in the soils deficient in these nutrients automatically increases the *AEnpk* (Sakal et al. 1998; John et al. 2006). Widespread deficiencies of S, Zn, and B have led to the evolution of site specific nutrient management (SSNM; Singh et al., 2008b). Simply put, SSNM involves analyzing the soils for all essential plant nutrients and developing fertilizer recommendations based on soil analysis. SSNM increases the *AE* of all nutrients applied.

Integrated Plant Nutrient Supply System (IPNS)

IPNS is an approach, which adapts plant nutrition to specific farming systems and particular yield targets, with consideration of the resource base, available plant nutrient source, and the socioeconomic background (Dudal and Roy, 1995). Further, since plant nutrients are transferred in cyclical processes, IPNS involves monitoring all pathways of flow of plant nutrients in agricultural production systems to maximize profit so that farming as a profession can be sustained, which is the only way to produce food (Ange, 1997). Thus IPNS demands a holistic approach to nutrient management for crop production and it involves judicious combined use of fertilizers, biofertilizers, organic manures (FYM, compost, vermicompost, biogas slurry, green manures, crop residues etc.), and growing of legumes in the cropping systems (Prasad, 2008). IPNS also encompasses balanced fertilization and SSNM. Considerable research on IPNS has been done in India (Rao et al., 2002; Katyal and Rattan, 2003; Gupta et al., 2006). Moreover, long-term fertilizer experiments have shown that addition of organic manures in addition to NPK (add-on series) results in high yields over a long period of time as compared to a decline in yield over time when only inorganic fertilizers were applied (Swarup, 2002). Sarkar and Singh (2002) reported that for soybean-wheat cropping system in the acidic soils of Ranchi (pH < 5.4), soybean yield (averaged over 28 years) was 0.33 $Mg{\cdot}ha^{-1}$ and wheat yield, 0.43 $Mg{\cdot}ha^{-1}$ for plots receiving N alone as compared to 1.59 $Mg{\cdot}ha^{-1}$ in soybean and 2.65 $Mg{\cdot}ha^{-1}$ in wheat when NPK was applied. Application of FYM with NPK increased the soybean yield to 1.86 $Mg{\cdot}ha^{-1}$ and that of wheat to 3.19 $Mg{\cdot}ha^{-1}$. Further, the effects of NPK + FYM were at par with NPK + lime, implying that in acid soils continuous application of FYM can also partially offset soil acidity.

Data from 'replacement series' trials under the PDCSR reveal that in most cropping systems especially rice-wheat and rice-rice cropping systems, application of 50% N through green manure, FYM or crop residues, and 50% of the recommended dose of fertilizer (RDF) to *kharif* rice and 100% RDF to *rabi* crop (rice/wheat) gave the same yield as obtained with 100% RDF to both *kharif* and *rabi* crops (Hegde, 1998). These results show that 25% NPK applied to the cropping system can be saved. However, most inferences in such studies are based on crop yields and the results are reported without accounting for NPK added through organic manures and the interaction effects also have not been studied.

Green manure crops have the intrinsic potential to recycle considerable quantities of organic materials and nutrients. Data in Table 9 show that *Sesbania* adds/ recycles much more NPK as compared to other green manures and FYM. On the other hand, wheat straw adds the least amount of NPK. The most important finding was that *Sesbania* or cowpea (*Vigna unguiculata*) and mungbean (*Vigna radiata*) residue incorporation produced the same grain yield of rice + wheat without any N application to rice, as obtained with 120 kg N ha^{-1} applied to rice in the control plot. Further, productivity of rice-wheat cropping could be raised by 1.2 $Mg{\cdot}ha^{-1}$ with 80 kg N ha^{-1} applied to rice over 120 kg N ha^{-1} applied in control plots (no green manure, residue, or FYM). FYM and *Leucaena* loppings were, however, inferior to *Sesbania* or cowpea green manure, or mungbean residue incorporation. Although incorporation of wheat straw was the least effective, it still produced more grain than in the control.

Legumes are the most important component of IPNS. They may be grown as a green manure, grain crop, or as a dual purpose crop (grain as well as green manure) in cropping systems. Soil restoring capacity of legumes has been known in India since historic times (Nene, 2006) even when their capacity to fix N was not known. Legumes fix 50–500 kg N ha^{-1} depending upon the crop and its growth period, and leave a residual N varying from 30–70 kg N ha^{-1} to the succeeding crop (Venkatesh and Ali, 2007). Sharma et al. (1996) reported a saving of 5.6 to 39.1 kg N ha^{-1} in wheat following mungbean or uridbean (*Vigna mungo*). The N-saving in wheat decreased as the level of N application was increased. It is estimated that in India legumes fix about 2.4 Tg of N annually (Ahlawat and Gangiah, 2004).

Green manures contribute 60–120 kg N ha^{-1} to the succeeding crop (Sharma et al., 1996; Palaniappan et al., 1997). In a study on a sodic soil (pH 8.7; ESP 18) at Karnal, a green manured rice crop supplied with 75 kg N + 30 kg P_2O_5 +25 kg K_2O ha^{-1} produced same grain yield as the one receiving 180 kg N + 90 kg P_2O_5 + 75 kg K_2O + 5kg Zn ha^{-1} (Yaduvanshi and Sharma, 2007–08), showing that benefits of green manuring are not limited to N only. Despite such encouraging results, the area under green manure crops has been declining especially in northern India (Prasad, 2008), mainly because of the non-remunerative nature of these crops. A better alternative is a dual purpose legume such as cowpea (John et al., 1989) or mungbean (Sharma and Prasad, 1999; Sharma et al., 2000). When mungbean is grown as a summer catch crop in the rice-wheat cropping system

Table 9. Integrated effects of organic manures/ crop residues and levels of N on the total grain production of a rice-wheat cropping system (data pooled over 3 years).

Treatments	Amount applied ($Mg{\cdot}ha^{-1}$)	Amount of NPK added/recycled ($kg{\cdot}ha^{-1}{\cdot}yr^{-1}$)			Grain yield ($Mg{\cdot}ha^{-1}$) under different doses of N applied to rice[1]			
		N	P	K	0	40	80	120
Sesbania green manure	5.5	143.0	22.0	121.0	8.1	8.9	9.3	9.3
Cowpea green manure	3.5	59.5	15.7	25.2	7.9	8.9	9.2	9.4
Mungbean residues (after picking pods)	1.9	28.9	4.0	14.1	8.2	8.5	8.8	9.1
Leucaena	2.0	48.4	5.4	28.0	7.7	8.4	8.9	8.9
Wheat straw	5.0	20.0	0.5	55.0	6.9	7.7	8.3	8.4
FYM	10	42.0	25.0	51.0	7.8	8.6	9.1	9.3
Control	0	0	0	0	6.3	7.1	7.7	8.1
CD (0.05)					0.3			

[1]N doses are in $kg{\cdot}ha^{-1}$. The succeeding wheat crop received 30 kg N ha^{-1}. Both rice and wheat received 20 kg P ha^{-1} as single super phosphate and 30 kg K ha^{-1} as muriate of potash.
Source: Misra and Prasad (2000).

and its residue is incorporated in the soil after one picking of pods (giving about 0.5 $Mg \cdot ha^{-1}$ grain), it contributes N equivalent to 60–90 $kg \cdot ha^{-1}$ to the cropping system. Organic manures also supply small amounts of micronutrients (Mishra et al., 2006) and when applied regularly over a long time can help to avoid micronutrient deficiencies. Application of organic manures also improves the soil physical, chemical, and biological properties (Misra and Saha, 2008; Vineela et al., 2008).

Biofertilizers [*Rhizobium, Azotobacter, Azosprillum*, blue green algae (BGA), azolla, phosphate soluibilizing organisms (PSO, PSB, PSF), vescicular arbuscular mycorrhyza (VAM)] can become an important component of IPNS (Swarnalakshmi et al., 2006; Tewatia et al., 2007) specially under low-land rice cultivation and dryland agriculture, where only low levels of fertilizers are applied. Organisms accelerating the decomposition of crop residues also have a role (Sharma and Prasad, 2002).

Fertilizer Use Efficiency and Environment

There is global concern on the effect of overuse of fertilizers, especially N fertilizers on the environment (Peoples et al., 1995; Laegreid et al., 1999). Part of applied fertilizer N is lost as NH_3, N_2, and NO_x gases, which adversely affect the environment. NH_3 after oxidation to NO_3 also contributes to soil acidity, while other NO_x are involved in depletion of the stratospheric ozone layer. Part of applied fertilizer N leaches down as NO_3 and contaminates the groundwater resources (Bijai-Singh et al., 1995), which leads to health hazards such as methaemoglobinemia or the blue baby syndrome. An epidemiological study in Rajasthan revealed severe methaemoglobinemia (7–27% of Hb) in all age groups of the population, especially in < 1 year age group (Gupta et al., 2000). The WHO safe limit for drinking water is 10 mg NO_3–$N \cdot L^{-1}$. Malik (2000), however, reported that of the total 822 groundwater samples from Punjab and Haryana, 3.3% had NO_3–N in the 0–10 $mg \cdot L^{-1}$ range, 15% with 10–20 $mg \cdot L^{-1}$, and 58% contained > 22 $mg \cdot L^{-1}$.

According to Agrawal (1999), irrigation without artificial drainage increases NO_3 pollution of groundwater in the poorly drained flat plains of Punjab and Haryana, which comprises of a thick pile of unconsolidated and permeable Late Quaternary – Holocene alluvial sediments. Datta et al. (1997) reported < 0.22 to 159 mg NO_3–$N \cdot L^{-1}$ in Delhi groundwaters. NO_3 pollution of groundwater is a serious problem in Karnataka too and the districts worst affected are Tumkur, Mysore, Kolar, Raichur, Mandya, Devangere, Chamrajnagar, and Chitrangda (Nagaraj and Chandrashekhar, 2005). Again, this has been reported from Andhra Pradesh (Rao, 1998), Tamil Nadu (Rangerajan et al., 1996), and Maharashtra (Deshpande et al., 1999). Although fertilizer N does contribute to NO_3 in groundwater, other sources such as animal excreta, sewage effluent, decomposition of soil organic matter, and natural soil nitrates are important in this respect.

Estimates of NH_3 volatilization losses in India vary from 2.86 to 25.80% of applied N, while N_2O losses due to denitrification are estimated at 4 to 1600 g N ha^{-1} depending on the source of N, soil, crop, water management (in rice), and the use of a nitrification inhibitors (Prasad et al., 1999b; Adhya et al., 2007; Pathak et al., 2008). In 2000–'01, 177 Tg of N was

Table 10. Annual budget of N in agriculture in the world and India (2000–01).

Inputs	Quantity (Tg)	Outputs	Quantity (Tg)
World (Mosier et al., 2004)			
Fertilizer	84	Crop removal	85
Manure	20	NH_3 volatilization	21
Biological Fixation	33	Leaching	37
Deposition	24	Denitrification	22
Crop residue	16		
Total	177	Total	165
India (Pathak et al., 2008)			
Fertilizer	10.8	Crop removal	7.7
Manure	1.4	NH_3 volatilization	2.3
Biological fixation	2.4	Leaching	2.3
Deposition	2.3	Denitrification	3.1
Crop residue	0.1		
Total	17.0	Total	15.4

introduced in agriculture globally and 165 Tg was the accountable output (Mosier et al., 2004). N import in Indian agriculture in the same year was 17 Tg and the accountable output, 15.4 Tg (Table 10). Needless to add that reduction of N losses from soil leads to increased nitrogen use efficiency.

Conclusions

Fertilizer consumption increased 322 times in India during the 1950–51 to 2007–08 period. However, fertilizer use efficiency has been very low in Indian agriculture. Large applications of fertilizer N not only impair groundwater quality but also have profound deleterious effects on the environment through gaseous emissions of NH_3 and NO_x. An effective nutrient management involves development of site specific nutrient recommendations including balanced NPK doses, timely application of fertilizer using appropriate methods, development and production of slow-release nitrogen fertilizers and indigenous nitrification inhibitors, and developing and practicing an integrated plant nutrient supply system (IPNS). Organic manures, legumes including green manures, and biofertilizers have a key role in organic agriculture which is gaining ground in response to the increasing demand for organic foods.

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