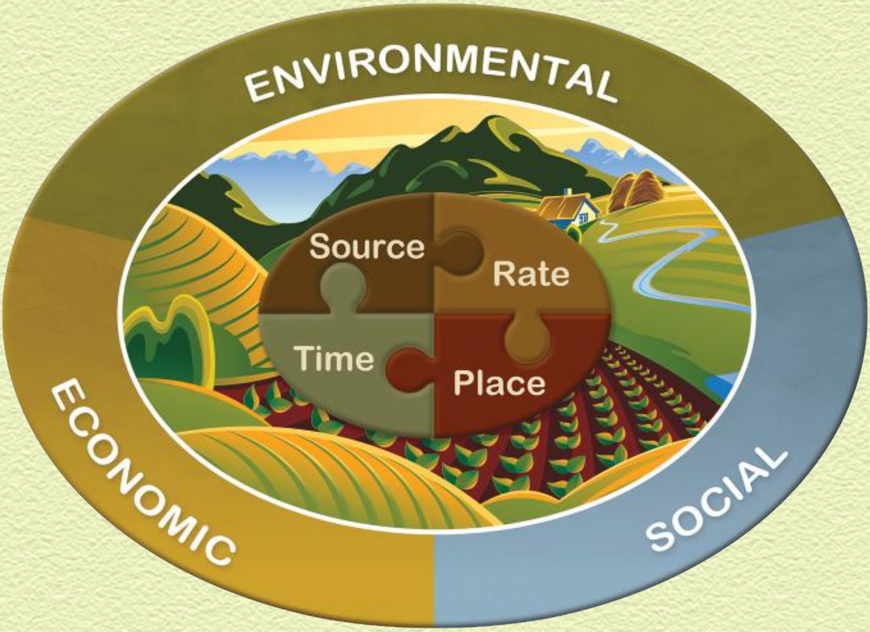
FERTILISER USE
AND
ENVIRONMENTAL QUALITY



ENSURING FOOD SECURITY

THE FERTILISER ASSOCIATION OF INDIA, NEW DELHI

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AND
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THE FERTILISER ASSOCIATION OF INDIA
NEW DELHI - 110 067

Fertiliser Use and Environmental Quality

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New Delhi - 110 067

Printed at Rakmo Press Pvt. Ltd., C-59, Okhla Industrial Area Phase-I,
New Delhi - 110 020

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PREFACE

India's self-sufficiency in food grain production parallels that of increase in fertiliser consumption. India is the second largest consumer of fertilisers in the world. However, per hectare fertiliser use is much lower than most of the developed and developing countries. Fertiliser use pattern reveals large inter- and intra- state variations. It is skewed in favour of nitrogen with distorted NPK use ratio. Imbalanced and inefficient use of applied nutrients by the crops makes vulnerable their leakage to the environment. Linkage of nitrous oxide emissions to the fertiliser-N consumption has been reported in few studies. Fertiliser-P linked eutrophication of waterbodies or cadmium build up in soils are non-existent in the country. Excessive potassium mining from soil without replenishment poses a threat to sustainable agriculture.

Conscious of importance of environment, we as a country are promoting sustainable agriculture. Best management practices, conservation agriculture, site-specific balanced application of nutrients incorporating the basic tenets of 4R principle, integrated nutrient management, customized and fortified fertilisers, water soluble fertilisers in high value crops are some of the steps being earnestly followed for enhancing use efficiency of applied nutrients and reducing their leakage to environment. Switching on to use of neem-oil coated urea is also part of the strategy to promote efficient use of fertilisers.

Ultimate mission of soil heath card scheme of the Government of India is also sustenance of soil heath and enhancing income of farmers through balanced use of soil test based fertiliser recommendations. Balanced and integrated use of nutrients has been part of advocacy efforts of FAI.

Country's dependence on fertilisers will increase to produce more and more from shrinking land and water resources. The current level of fertiliser use in India does not pose any threat to environmental quality. However, there is a need to monitor the situation in high fertiliser-consuming areas. Some misconceptions about the ill-effect of fertilisers have also come up which have no scientific evidence. FAI considered it prudent to bring out science based facts on fertiliser use and environmental quality.

This publication provides updated information of state of agriculture and environment, health of Indian soils, nutrient cycles operating in nature, consequences of fertiliser use on environmental quality, and strategies for enhancing use efficiency and minimizing environmental leakage of the applied nutrients. I hope that this publication will be useful to all those engaged in development of environmentally-benign sustainable agriculture.

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The Fertiliser Association of India

New Delhi
December, 2017

FERTILISER USE AND ENVIRONMENTAL QUALITY

Indian Agriculture and Soil Health

State of Indian Agriculture

Providing food and nutritional security to the rising population has driven the progress in Indian agriculture sector. Country became food-secure towards the end of 20th century. It is currently food-grain surplus, with production reaching record 275.68 million tonnes (Mt) in 2016-17 and is vigorously pursuing agenda of providing nutritional security to its people. Fruits, vegetables and pulses constitute the key ingredients in average Indian diets. Steady advances have been recorded in their production as well. India's horticulture (fruits and vegetables) output estimated to be 299.85 Mt in 2016-17 surpasses the total food grain production. Pulse production increased to 22.95 Mt during 2016-17. Boosting the production of crops like coarse cereals including millets; pulses; oilseeds; vegetables and fruits besides sustaining the productivity of Green Revolution crops is part of multi-pronged strategy for attaining nutritional security of large Indian population.

Progress in agriculture sector is no doubt impressive but the human population of India has witnessed steady rise; it grew to 1.21 billion in 2011 at a growth rate of 1.71% over 1.03 billion in 2001. Country faces a daunting task of meeting ever increasing demand of food and providing nutritional security to 17.5% of the global population. In addition, we have to meet the feed and fodder requirement of 11% of the world's livestock population. This has to come only from 2.3% of the land and only 4% of the fresh water resources. Per capita arable land in India has shrunk; it was 0.34 ha in 1950-51 and is expected to be 0.08 ha in 2025. Since 1970s, the net cultivated area has remained around 141±2 million hectares (Mha). Huge tracts of highly productive agricultural lands have been lost to urbanization, industrialization and other developmental activities.

Providing food and nutritional security to estimated 1.62 billion people by 2050 is quite challenging, particularly because more than

80% of Indian landholders are marginal (having agricultural land less than 1 ha) and small (having 1-2 ha) with very poor ability to cope with vagaries of nature. This is only possible through agricultural intensification brought about by growing fertiliser-responsive high yielding varieties under assured supply of production inputs and best management practices. At global and all India level, the share of fertiliser alone in increasing food grain production is estimated at 50%.

Health of the Indian Soils

The problem of soil health degradation is quite acute in our country. About 120.8 Mha country's land area constituting 36.5% of total geographical area (TGA) is degraded due to soil erosion, salinity/alkalinity, soil acidity, waterlogging, and some other complex problems (NBSS&LUP, 2008). Soil erosion due to water is the major cause of soil degradation (82.6 Mha) followed by chemical degradation (24.7 Mha). About 5.34 billion tonnes (Gt) of soil is eroded in India at an average rate of 16.3 t ha^{-1} yr^{-1}. While 61% of eroded sediments get redistributed on land, nearly 29% are lost permanently to the sea and the remaining 10% are deposited in reservoirs reducing their holding capacity by 1 to 2% annually. About 8 Mt of plant nutrients are also washed away along with eroded sediments. Degraded lands are the potential sources of soil erosion and flash floods. The extent of nutrient-wise deficiencies is: 89% N (63% low & 26% medium), 80% P (42% low & 38% medium), 50% K (13% low & 37% medium), 41% S, 43.4% Zn, 20.6% B, 14.4% Fe, 13% Mo, 7.9% Mn and 6.1% Cu (Rattan, 2013; Shukla and Pakhare, 2015). Sustenance of crop yields requires external application of the deficient nutrients through fertilisers.

Fertiliser Use in India

India has witnessed steady growth in fertiliser consumption. Nutrient ($N+P_2O_5+K_2O$) consumption increasd from 69,800 t in 1950-51 to 25.95 Mt in 2016-17. In terms of total nutrient consumption, India ranks second in the world after China and nutrient-wise, it stands 2nd in N and P_2O_5 consumption and 4th in K_2O consumption. Food grain production increased from 50.8 Mt in 1950-51 to 275.68 Mt in 2016-17. Nutrient consumption and food grain production exhibited a cumulative annual growth rate

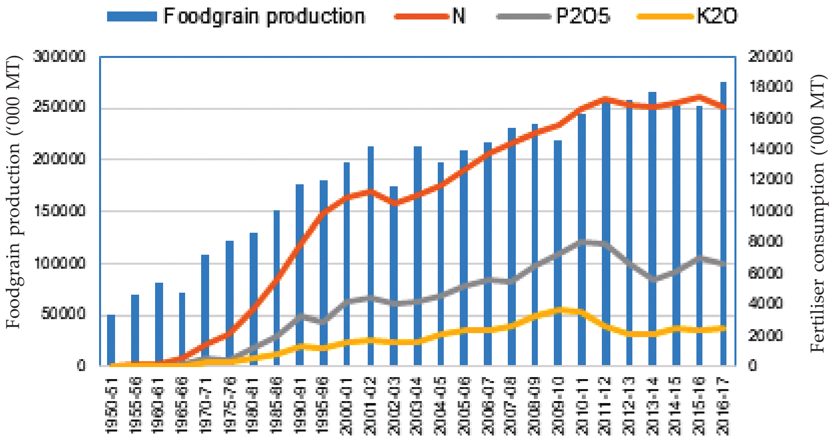


Figure 1. Foodgrain production *vis-a-vis* N, P_2O_5 and K_2O use on time scale (CAGR : FG = 2.60%, N=9.05%; P_2O_5 = 10.58%; K_2O = 9.58%; N+P_2O_5+K_2O = 9.38%)

Source : FAI (2016) and Annual Review of Fertiliser Production and Consumption (2016-17)

(CAGR) of 9.38 and 2.60%, respectively **(Figure 1)**; This accelerated use of fertiliser nutrients played a crucial role in making the country food- and nutritionally- secure.

Current NPK use ratio (employing K as base) of 6.7:2.7:1 for 2016-17 when measured against ideal NPK use ratio of 4:2:1 is tilted heavily towards N. This is not desirable both from crop need point of view or from sustainable productivity growth angle. The NPK use ratio, averaged for the whole world is 3.4:1.3:1. Regional disparities in the use ratio are more striking in the country, being widest in North (15.1:5.1:1) against lowest in South (4.2:1.9:1). These are 7.1:3.1:1 in West and 4.3:1.6:1 in East. The per hectare nutrient (NPK) use varied from 93.4 kg in West to 178.3 kg in North. Nutrient-wise, the use of K varied from 8.4 kg ha^{-1} in North and West to 24.0 kg ha^{-1} in South **(Table 1)**. Per hectare P use was maximum in South (46.8 kg) and minimum in West (25.7 kg). Nitrogen use was highest in North (127.3 kg ha^{-1}) and lowest in West (59.3 kg ha^{-1}). States differ widely in terms of nutrient consumption and nutrient use ratios. Per hectare nutrient (NPK) use was more than 200 kg in 4 states namely Haryana, Punjab, Andhra Pradesh and Telangana during 2016-17 **(Table 2)**. Per hectare NPK use varied from 55.9 kg in Rajasthan to 258.0 kg in Telangana among the major states. Nutrient-wise, per hectare K_2O

Table 1. Nutrient consumption in zones of India (2016-17)

Zone	Nutrient Consumption (Mt)				Nutrient Consumption (kg/ha)			
	N	P_2O_5	K_2O	Total	N	P_2O_5	K_2O	Total
East	2.43	0.93	0.57	3.93	79.7	30.6	18.6	129.0
	(14.5)	(13.9)	(22.7)	(15.1)				
North	5.57	1.86	0.37	7.80	127.3	42.6	8.4	178.3
	(33.3)	(27.8)	(14.7)	(30.1)				
South	3.39	1.59	0.81	5.79	99.8	46.8	24.0	170.6
	(20.2)	(23.7)	(32.3)	(22.3)				
West	5.35	2.32	0.76	8.43	59.3	25.7	8.4	93.4
	(32.0)	(34.6)	(30.3)	(32.5)				
Total	16.74	6.70	2.51	25.95	84.4	33.8	12.6	130.8

( ) = figures in parenthesis are per cent share

use varied from 0.6 kg in Rajasthan to 32.0 kg in West Bengal. Per hectare P_2O_5 use varied from 14.1 kg in Rajasthan to 62.3 kg in Andhra Pradesh. In case of N, it varied from 41.2 kg ha^{-1} in Rajasthan to 177.8 kg ha^{-1} in Punjab. The NPK use ratio was most distorted in Rajasthan, Punjab and Haryana due to very low per hectare use of K in these states. In general, K use per unit area is the highest in southern states and the lowest in northern states. Consequently, the

Table 2. State-wise nutrient consumption in India (2016-17)

State	N	P_2O_5	K_2O	Total	N	P_2O_5	K_2O	Total	NPK Use Ratio
	<———(000 tonnes.)——>				<——— —(kg/ha)—— —>				
Bihar	1053.0	308.9	146.7	1508.6	137.2	40.3	19.1	196.6	7.2:2.1:1
West Bengal	779.5	412.2	310.3	1502.0	80.4	42.5	32.0	155.0	2.5:1.3:1
Haryana	1008.2	291.8	42.8	1342.8	154.3	44.6	6.6	205.5	23.5:6.8:1
Punjab	1396.6	369.7	52.2	1818.5	177.8	47.1	6.6	231.5	26.8:7.1:1
Uttar Pradesh	2890.1	1133.5	237.5	4261.1	110.5	43.4	9.1	163.0	12.2:4.8:1
Andhra Pradesh	982.9	479.2	224.9	1687.0	127.8	62.3	29.2	219.4	4.4:2.1:1
Telangana	926.2	320.7	125.1	1372.0	174.3	60.3	23.5	258.1	7.4:2.6:1
Karnataka	876.3	510.7	241.2	1628.2	71.5	41.7	19.7	132.9	3.6:2.1:1
Tamil Nadu	513.8	231.7	163.0	908.5	85.7	38.6	27.2	151.5	3.2:1.4:1
Gujarat	1143.5	340.1	120.9	1604.5	89.5	26.6	9.5	125.6	9.5:2.8:1
Madhya Pradesh	1272.1	617.8	92.0	1981.9	53.4	25.9	3.9	83.2	13.8:6.7:1
Maharashtra	1542.2	799.4	464.5	2806.1	65.7	34.1	19.8	119.5	3.3:1.7:1
Rajasthan	998.3	340.7	15.7	1354.7	41.2	14.1	0.6	55.9	63.6:21.7:1
All India	**16735.4**	**6705.4**	**2508.3**	**25949.1**	**84.4**	**33.8**	**12.6**	**130.8**	**6.7:2.7:1**

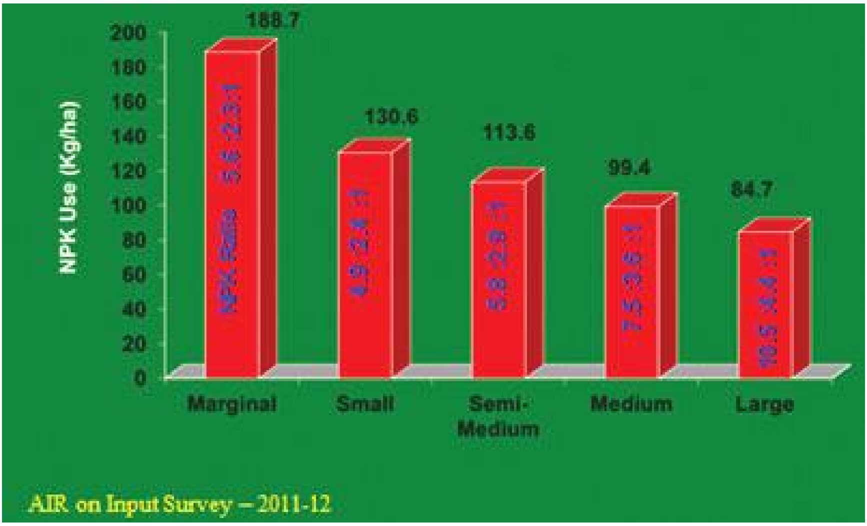


Figure 2. **Land holding-wise fertiliser use or intensity of fertiliser use by different categories of farmers**

Source : All India Report of Input Survey (2011-12)

NPK use ratio is narrow in southern states and wide in northern states.

Intensity of fertiliser use is determined by the farm size. Compared to the large scale farmers, small and marginal farmers use higher rates of fertilisers in more balanced proportions. As per All India Report of Input Survey (2011-12), average nutrient use was 84.7 kg ha^{-1} on large size farm holdings against 188.7 kg ha^{-1} on marginal size holdings **(Figure 2)**. The NPK use ratio was wider (10.5:4.4:1) in large farm size category compared to the small (4.9:2.4:1) and marginal (5.6:2.3:1) farm size category. Irrigation facilities also have impact on the quantum of fertiliser use. For example, total NPK use was 187 kg ha^{-1} in irrigated areas against 82 kg ha^{-1} in non-irrigated areas (**Figure 3**). Nutrient-wise use was 115.7, 51.9 and 19.4 kg ha^{-1} for N, P_2O_5 and K_2O in irrigated areas and in non-irrigated areas, per hectare use was 48.8 kg for N, 24.4 kg for P_2O_5 and 8.8 kg for K_2O.

Greenhouse Effect and Global Warming

Depending upon the ability to absorb the incident radiations, atmospheric gases are categorized as radiatively inert or active. Radiatively inert gases, which include nitrogen (N-N), oxygen (O-O) and hydrogen (H-H) are transparent and do not absorb any type of radiation whether short wave or long wave. Radiatively active

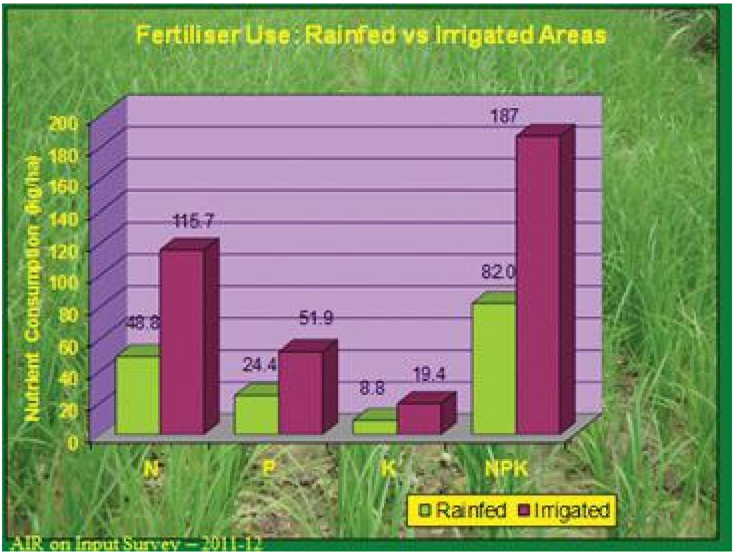


Figure 3. Per hectare nutrient use in rainfed and irrigated areas
Source : All India Report of Input Survey (2011-12)

gases include water vapour, carbon dioxide (CO_2), ozone (O_3), methane (CH_4) and nitrous oxide (N_2O). These have symmetric molecules (H-O-H, $\overset{\text{O}}{\overset{|}{\text{O}}}\text{-O}$, O-C-O, $\text{H-}\underset{\underset{\text{H}}{|}}{\overset{\overset{\text{H}}{|}}{\text{C}}}\text{-H}$, N-O-N) which are transparent to short-wave radiations coming from Sun but can absorb Earth's long-wave radiation being emitted into the space. Collectively termed as the greenhouse gases (GHGs), these warm

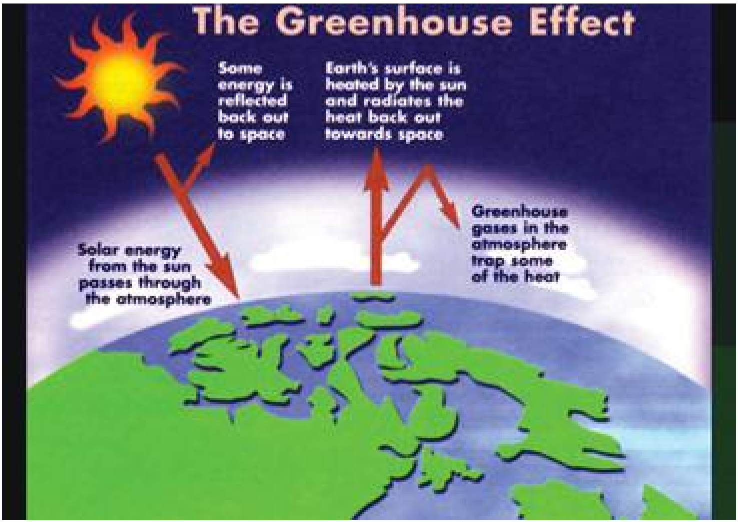


Figure 4. Schematic representation of greenhouse effect

Table 3. Sources of different gases in soil air of agroecosystems

Gas	Sources in soil air
CO_2	Decomposition of soil organic matter, application of manure and compost, green manuring, ploughing, root respiration, use of crop residue as mulch, biomass burning.
CH_4	Rice paddies and other anaerobic environments, application of biomass under anaerobic/wet soil conditions, use of fresh dung/manure, burning of buried biomass
N_2O	Use of synthetic nitrogenous fertilisers, denitrification under anaerobic conditions (low air porosity in soil), use of animal manure, biological N fixation by legumes and other processes.

Source : Lal (2015)

the earth by absorbing energy and slowing the rate of energy escape to space; and act like a blanket insulating the Earth. Greenhouse effect is depicted in **Figure 4**. Greenhouse effect has kept the earth planet warmer at 14 ^{O}C, which in its absence would have been -19 ^{O}C. *Greenhouse effect has thus been responsible for sustenance of life on earth in its present form*.

Carbon dioxide, methane and nitrous oxide are three important greenhouse gases (GHGs) arising out of agricultural intensification **(Table 3)**. Atmospheric concentrations of CO_2, CH_4 and N_2O in 2015 were 400 parts per million by volume (ppmV), 1845 parts per billion by volume (ppbV) and 328 ppbV against 278 ppmV, 722 ppbV and 270 ppbV in the year 1750, respectively which is considered to be the base year for the start of industrial revolution (**Table 4**). This was an increase of 144, 256 and 121% in concentration of CO_2, CH_4 and N_2O, respectively. As a result of increase in GHG concentrations, Earth's average temperature has arisen by about 0.6 °C since 1950, and is increasing at the rate of about 0.17 °C per decade (IPCC, 2013). The warming in India over the past 100 years (1901 to 2007) has been observed to be 0.51 °C with accelerated warming of 0.21 °C per every 10 years since 1970

Table 4. Atmospheric concentration of greenhouse gases

	CO_2	CH_4	N_2O
Concentration in 2015	400 ppmV	1845 ppbV	328 ppbV
Concentration in 2014	397.7 ppmV	1834 ppbV	327 ppbV
Concentration in 1750	278 ppmV	722 ppbV	270 ppbV
2015 abundance relative to year 1750	144%	256%	121%
2015 absolute increase over 2014	2.3 ppmV	11.0 ppbV	1.0 ppbV
2015 relative increase over 2014	0.58%	0.60%	0.31%
Mean annual absolute increase during last 10 years	2.08 ppmV yr^{-1}	6.0 ppbV yr^{-1}	0.89 ppbV yr^{-1}
Global warming potential	1	25	298
Mean residence time	120 yr	12 yr	11 yr

Source : WMO (2016)

(Krishna Kumar, 2009). When the rate of increase in Earth's temperature exceeds the threshold level of 0.1 °C per decade by human activities, it is called 'global warming'. Thus global warming, which is anthropogenic greenhouse effect, is real both for world as a whole as well as for India. Going by current practices of climate change, it is difficult to perceive the capping of rise in temperature to 2 ^{O}C by 2100 AD as envisaged in Paris 2016 deal.

Greenhouse Gas Emissions from Indian Agriculture

For computation of the atmospheric load of GHG emissions and allowing comparisons of the global warming impact of different gases, the concept of global warming potential (GWP) is used. The GWP is defined as a measure of how much energy the emission of 1 kg of a gas will absorb over a given period of time, relative to the emission of 1 kg of carbon dioxide (CO_2). The larger the GWP of a given gas, more it warms the Earth compared to CO_2 over that time period. The time period usually used for GWP is 100 years. Global warming potential for CO_2, CH_4 and N_2O taken as 1, 25 and 298, respectively, implies that CH_4 and N_2O are 25 and 298 times more lethal than CO_2. If atmospheric load of CO_2, CH_4 and N_2O each increases @ 1.0 Mt yr^{-1}, then the total annual increase in load of GHG emissions in CO_2 equivalent yr^{-1} will be = (1.0 Mt yr^{-1} CO_2) × 1 + (1.0 Mt yr^{-1} CH_4)×25 + (1.0 Mt yr^{-1} N_2O)×298 = 324 Mt CO_2eq yr^{-1}.

In India, out of total 406 Mt yr^{-1} of GHG emissions, enteric fermentation, manure management, rice cultivation, agricultural soils, and crop residue burning constituted 211 (52%), 27 (6.7%), 68 (16.7%), 94 (23.2%), and 6 (1.5%) Mt, respectively (Pathak et al. 2014). During 1970-2010, the GHG emissions from Indian agriculture increased by about 75%; enhanced use of fertilisers and other agri-inputs and the rising population of livestock were the major drivers for this increase in GHG emissions. Increase in N_2O emissions from 0.169 Mt in 1995 to 0.217 Mt in 2007 could be directly correlated with increased N fertiliser use. As per INCCA (2010) inventory on greenhouse gas (GHG) emissions for Indian agriculture, rice fields covering an area of 43.86 Mha emitted 3.37 Mt of CH_4 in 2007. The N_2O emissions from the Indian agricultural soils in 2010 were estimated at 0.30 Mt (Pathak *et al.* 2014). Field burning of agricultural residues in 2007 resulted in emission of 250,000 t of CH_4 and 6,500 t of N_2O. Carbon dioxide emissions from agricultural intensification as compared to other sources are almost insignificant.

Nitrogen and Environment

Nitrogen (N) is an essential element for life on earth and the fourth most abundant element (after C, O and H) in the biosphere. Most (>98%) of the Earth's N exists in lithosphere (1.64×10^{11} Mt). Rest 2% is distributed between hydrosphere (2.3×10^{7} Mt), biosphere (2.8×10^{5} Mt) and atmosphere (3.9×10^{9} Mt). In the atmosphere, N exists mostly as an inert and unreactive dinitrogen molecule (N_2). It constitutes 78% of the atmospheric gases and 1 m^2 of land surface is laden by 289.5 t of N_2. It requires very high energy to break the triple bond in N_2 which is either provided by micro-organisms (biological nitrogen fixation) or chemical means (chemical nitrogen fixation - as in the Haber-Bausch process). In fact, this has sustained life on Earth planet, because if breaking of triple bond of N_2 was easier, then most of N_2 would have yielded HNO_3 and this acid would have dissolved all the mineral matter. In hydrosphere, N occurs in dissolved organic or inorganic form and in biosphere it is present in different organic combinations. In nature, nitrogen exists in the myriad oxidation states ranging from +5 in the nitrate ion (NO_3^-) to -3 (NH_3 or NH_4^+) in ammonia.

NO_3^- [+5] « NO_2 (g) [+4] ! NO_2^- [+3] ! NO(g) [+2]! N_2O(g) [+1] ! N_2 [0]! NH_4^+ [-3].

Annual budget of N computed for the whole world and India is positive, hinting at the increased load of reactive N in the environment (Pathak, 2016). For example, nitrogenous fertilisers, animal manure and wastes, crop nitrogen fixation and deposition (including rain, irrigation water and grazing of animal) in 2010 contributed 16.6, 1.4, 1.4 and 2.7 Mt N, respectively (**Figure 5**). Removal of N by agricultural crops in the country

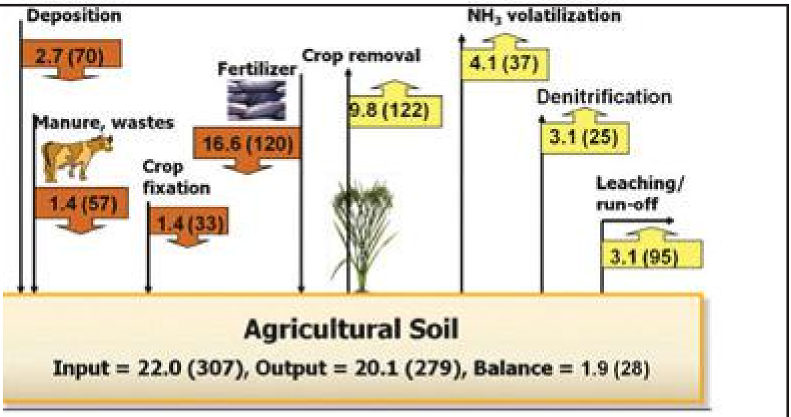


Figure 5. Annual budget of N (Mt) in agricultural soils of India and World (in parenthesis) during the year 2010
Source : Pathak (2012), unpublished; World values from Sutton et. al., (2013)

Table 5. Summary of environmental problems associated with nitrogen

Environmental issues	Causative mechanisms and impacts
	Human and animal health
Methemoglobinemia	Consumption of high-nitrate drinking waters and food; particularly important for infants because it disrupts O_2 transport system in blood
Cancer	Exposure to nitrosoamines formed from reaction of amines with nitrosating agents; skin cancer increased by greater exposure to ultraviolet radiation resulting from destruction of the O_3 layer
Nitrate poisoning	Livestock ingestion of high-nitrate feed or water
	Ecosystem damage
Groundwater contamination	Nitrate leaching from fertilisers, manures, sludges, wastewaters, septic systems, can impact both human and animal health, and trophic state of surface waters
Eutrophication of surface waters	Soluble or sediment-bound N from erosion, surface runoff, or groundwater discharge enters surface waters; direct discharge of N from municipal and industrial wastewater treatment plants into surface water; atmospheric deposition on water quality and biological diversity of fresh waters
Acid rain and ammonia evolution and redeposition	Nitric acid originating from reaction of N oxides with moisture in atmosphere is returned to terrestrial ecosystem as acidic rainfall, snow, mists, fogs (wet deposition) or as particulates (dry deposition); damages sensitive vegetation, acidifies surface waters, and, as with eutrophication, can unfavourably alter biodiversity in lakes, streams, bays; ammonia evolved from concentrated animal feeding operations can acidify soils and alter species diversity in nearby woodlands
Stratospheric ozone depletion and global climate change	Nitrous oxides from burning of fossil fuels by industry, automobiles, and from denitrification of nitrate in soils are transported to the stratosphere where O_3 destruction occurs; ultraviolet radiation incident on earth's surface increases, as does global warming

Source : Adapted from Keeney (1982)

during 2010 was 9.8 Mt. Besides, the losses of N included leaching and run-off (3.1 Mt), ammonia volatilization (4.1 Mt), and denitrification (3.1 Mt). This resulted in an accumulation of 2.0 Mt N in Indian agricultural soil-water system. Globally accumulation stands at a whopping 28 Mt N. This is a serious concern as N not utilized by the plant can adversely impact human and animal health **(Table 5)**.

Better understanding of the fate of N applied either through organics or fertilisers can be gauged through a glance at the N cycle operating in soil. Depicted schematically in **Figure 5**, nitrogen cycle, starting with dinitrogen (N_2), operates through the processes of fixation, mineralization, immobilization, nitrification, ammonia volatilization, denitrification, leaching, runoff, and plant assimilation. Different processes/ reactions in the soil operating in the N cycle are described below:

Nitrogen Fixation

Dinitrogen is fixed biologically as well as chemically.

Biological nitrogen fixation, involving nitrogenase enzyme, is described through the following reaction:

N_2+8H^++8e^-+16 Adenosine triphosphate (ATP) $\rightarrow$2NH_3 + H_2 + 16 Adenosine diphosphate (ADP) + 16 Pi ………. Eq. 1

Chemical nitrogen fixation, accomplished through Haber-Bosch process also involves reduction of N_2 to NH_3. In this process ammonia (NH_3) is synthesized by the reaction between H_2 and N_2 at an elevated pressure (200-1000 kg cm^{-2}) and temperature (400-450 °C) in presence of catalyst (Fe-oxide) and promoter (Al, K, Mg and Ca-oxides) as follows:

$3 H_2 + N_2 \rightarrow 2 NH_3$ ……….. Eq. 2.

Mineralization/Immobilization

Mineralization refers to the conversion of organic forms of N (proteins, chitins, amino acids, nucleic acids, etc.) to inorganic N as ammonium N, where organic N may be indigenous to the soils, or added as crop residues or wastes or organic fertilisers. Converse of mineralization is immobilization which is carried out by a myriad of heterotrophic organisms (bacteria, fungi, actinomycetes).

Mineralization/immobilization is viewed as:

$$\text{Organic-N (proteins, chitins, amino acids, nucleic acids etc.)} \underset{\text{Immobilization}}{\overset{\text{Mineralization}}{\rightleftarrows}} \text{Mineral N } (NH_4^+, NO_2^-, NO_3^-)$$

…….. Eq. 3.

Under anoxic conditions, end product of mineralization is NH_4^+ and in aerobic environments it leads to generation of NO_3^-.

Mineralization covers aminization, ammonification and nitrification.

i) Aminization

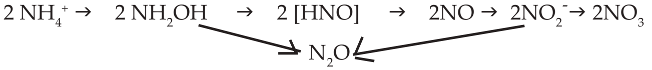
Organic N $\rightarrow$ Amino-N (R- NH_2) + $\uparrow$ CO_2 + Energy ……… Eq. 4

ii) Ammonification

Amino-N (R-NH_2) $\rightarrow$ R-OH + NH_3 + H_2O $\rightarrow$ NH_4^+ + OH^- …….. Eq. 5

iii) Nitrification

Overall nitrification is depicted schematically as:



$$2\,NH_4^+ \rightarrow 2\,NH_2OH \rightarrow 2\,[HNO] \rightarrow 2NO \rightarrow 2NO_2^- \rightarrow 2NO_3 \qquad (NH_2OH \rightarrow N_2O \leftarrow 2NO_2^-)$$

….. Eq. 6

Note: Possibilities of release of N_2O in the nitrification step are indicated. Nitrification is achieved in two steps *viz.,* oxidation of NH_4^+ first into NO_2^- and then NO_3^- by action of aerobic chemoautotrophic bacteria.

Step I. $2\,NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 2H_2O + 4\,H^+$ + Energy carried out by *Nitrosomonas, Nitrosospira* or *Nitrosococcus* ….. Eq. 7

Step II. $2\,NO_2^- + O_2 \rightarrow 2\,NO_3^-$+ Energy carried out by *Nitrobacter, Nitrospira* or *Nitrococcus* ….. Eq. 8.

Denitrification

Denitrification refers to the reduction of NO_3^- to gaseous forms of N (NO, N_2O and N_2) by soil microbes under conditions of low oxygen supply as shown in equation:

$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$ … Eq. 9.

Under anaerobic conditions certain bacteria use NO_3^- as an alternative to O_2 as the acceptor of electrons produced during decomposition of organic matter. Although end product of denitrification is evolution of N_2 with valence of N changing from +5 (in NO_3^-) to 0 (in N_2), depending upon the redox status and occurrence of oxidized and reduced zones/ pockets in soils give rise to the evolution of oxides of nitrogen, of which major concern is N_2O because of its role in global warming and destruction of stratospheric ozone.

Fate of Applied Nitrogenous Fertilisers in Soil

As per the Fertiliser Control Order (FCO, 1985), nitrogenous fertilisers in India are categorized as organic fertilisers (city compost, vermicompost, bio-enriched organic manure, phosphate rich organic manure, organic manure and bone meal (raw and steamed), biofertilisers (*Rhizobium, Azotobacter, Azospirillum, Acetobacter carrier based consortia and liquid consortia*) and mineral fertilisers [urea, diammonium phosphate (DAP), ammonium sulphate (AS), ammonium chloride (ACl) and host of complex fertilisers/mixtures containing N as one of the constituents). Organic fertilisers contain N in the organic combinations and undergo mineralization for their assimilation by plants. Mineral fertilisers contain N in the amide (urea – NH_2CONH_2) or NH_4 (ammoniacal fertilisers) or NO_3^- (nitrate fertilisers). Plants absorb N chiefly in NO_3^- form and some minor amounts (particularly in rice) may be absorbed as NH_4^+ form which implies that whole of organic fertiliser-N, urea-N and most of added ammoniacal-N has to convert to NO_3^- form for its absorption by crop plants. Unlike organic or mineral fertilisers, N-biofertilisers don't contain N but only fix atmospheric N in the root nodules of leguminous crop plants and other plant spp. Thus source of N, soil and environmental conditions determine the contribution of N as the nutrient and/or pollutant. A snap shot of nitrogen cylce-dynamic interechange among various N forms in the soil-crop-atmosphere system is illustrated in **Figure 6**.

Organic fertilisers or organic wastes or sewage sludges upon addition to the soil undergo mineralization, whose rate is determined by carbon:nitrogen (C:N) ratio of the added material, ambient temperature and soil water content. The C:N ratio of <20:1 and >30:1 indicates the net mineralization and net immobilization, respectively. Organic materials with wide C:N ratio cause net immobilization and may temporarily create the conditions of N deficiency in crops because microbes incorporate mineral N to build their bodies. Of course on the death of these microbes, immobilized N is released for plant use.

Upon addition to soil, urea meets the following fate. Being a completely water soluble neutral molecule, it may leach out of soil profile in coarse textured soils under excess water conditions. If applied in excessive quantities, it may prove toxic to the germinating seeds. Reaction of practical significance is hydrolysis of urea carried out by urease enzyme to yield NH_3 (Eq.10).

$$\underset{\text{Urea}}{NH_2\text{-}CO\text{-}NH_2} + H_2O \xrightarrow{\text{Urease}} \underset{\text{Ammonium carbamate}}{NH_2COONH_4} \rightarrow \underset{\text{Ammonia}}{2NH_3} + \underset{\text{Carbon dioxide}}{CO_2} \quad \text{.............. Eq. 10}$$

$$NH_3 + H_2O \rightleftarrows NH_4^+ + OH^- \quad \text{............... Eq. 11}$$

Depending upon the ambient temperature and moisture conditions, urea hydrolysis gets completed in 3-10 days giving rise to accumulation of ammonia gas. This large ammonia gas under the alkaline conditions aided by high wind velocity might escape to the atmosphere and that is called as ammonia volatilization. It may also react with water to yield NH_4^+ ion and in turn this NH_4^+ ion may either get absorbed by plant or held up in the soil as exchangeable NH_4^+ ion or irreversibly fixed in the clay lattice or

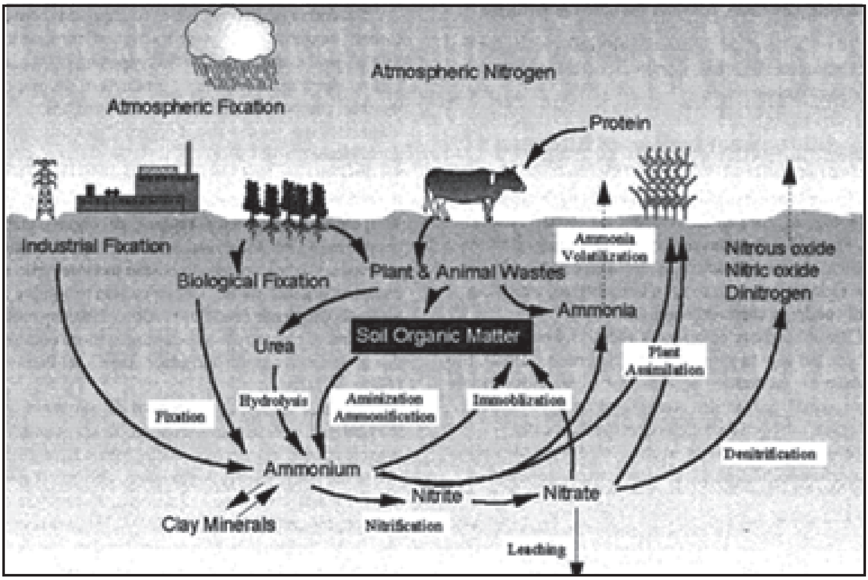


Figure 6. The nitrogen cycle - Dynamic interchange among various N forms in the soil-crop-atmosphere system

Source : Yadvinder Singh and Bijay-Singh (2015)

undergoes nitrification to yield NO_2^- and NO_3^- ions. Since NO_2^- and NO_3^- anions being negatively charged, are liable to be lost through leaching or denitrification, use has been made of urease inhibitors to slow down the rate of urea hydrolysis to have slower generation of NH_4^+ ions over a prolonged period of time, allowing evolved NH_4^+ ions to react with soil or undergo nitrification. Most widely used urease inhibitor is N-(n-Butyl) thiophosphoric triamide (NBPT) (commercial name Agrotain®), which converts to active N-(n-Butyl) phosphoric triamide (NBPTO) in soil. Dry concentrate of NPBT plus nitrification inhibitor DCD (commercial Agrotain Plus) has been developed to reduce volatilization losses of ammonia as well as N losses from denitrification and leaching. Super Urea® (Super U), a solid, pelleted urea, containing both DCD and NBPT has been developed but due to higher cost it has not found much acceptability. Other widely studied urease inhibitors include phenylphosphorodiamidate (PPD/PPDA) and hydroquinone. Ammonium thiosulphate and some metals can also inhibit urea hydrolysis.

Ammonium ions are generated in the soil through i) mineralization of organic N contributed by indigenous soil organic matter, crop and animal wastes, sewage sludges, etc., ii) hydrolysis of added urea, and iii) addition of ammoniacal fertilisers like DAP,

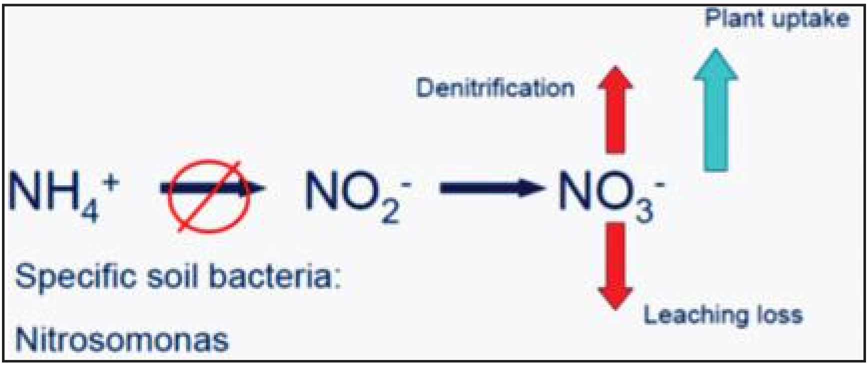


Figure 7. Nitrification inhibitors inhibit the activity of *Nitrosomonas* responsible for the conversion of NH_4^+ to NO_2^-

Source : Yadvinder-Singh and Bijay-Singh (2015)

monoammonium phosphate (MAP), ACl, AS, ammonium phosphate sulphate (APS) and different NPK mixtures having N in ammoniacal form. Apart from absorption by plants, volatilization loss as ammonia, and retention/fixation by soil, NH_4^+ ions undergo two-step nitrification yielding NO_2^- ions in the first step and NO_3^- ions in the second step. For providing NO_3^- ions to the plants over a prolonged time span, it is desirable to retard or inhibit the nitrification at the first step by reducing the activity of *Nitrosomonas*, *Nitrosospira* or *Nitrosococcus* bacteria (**Figure 7**) as NO_2^- and NO_3^- ions, both being anions, are susceptible to leaching losses. First step of nitrification has also been recently implicated with generation of nitrous oxide through the process termed as nitrifier-denitrifcation (Eq. 6).

Number of nitrification inhibitors like dicyandiamide (DCD), coated calcium carbide, N-serve and AM have been commercially exploited for enhancing N use efficiency and reducing emissions of nitrous oxides. Recognizing the potential of active principle azadirachtin as urease (probably) as well as nitrification inhibitor, Government of India has made it mandatory for the fertiliser industry to coat urea with 350 ppm *neem* oil. Coating of urea with *neem* oil offers the yield advantage of up to 10%, implying a saving on urea for sustenance of same yield levels. Enhanced N use efficiency with nitrification inhibitors helps in mitigation of N_2O emission by 10-40% (**Table 6**).

Nitrate ions generated through nitrification and added through nitrate-fertilisers are absorbed by the plants. Those not utilized by the plants are lost by one or more of the following mechanisms:

- Leaching out of the soil profile and finally charging the

Table 6. Efficiency of nitrification inhibitors in mitigating nitrous oxide emission in rice-wheat system

Nitrification inhibitor	Mitigation (%)
Dicyandiamide (DCD)	13-42
Neem cake	10-21
Neem oil	15-21
Nimin	25-35
Coated calcium carbide (CCC)	12-29
Thiosulphate	15-20

Source: Pathak et al. (2014)

ground-water particularly on coarse textured low organic matter soils fertilized with excessive doses of nitrogenous fertilisers, in particular nitrate-fertilisers.

- Loss through surface run-off leading to eutrophication of the waterbodies including lakes, etc.
- Denitrification under short supply of oxygen, in particular under waterlogged conditions in soils well supplied with decomposable organic matter. Since nitrate is the substrate for denitrification, conditions/factors favouring nitrification play a dominant role in controlling denitrification.

Fertiliser Nitrogen Use and Environmental Consequences

Use efficiency of fertiliser-N seldom exceeds 35% in lowland and 50% in the upland ecosystems. Situation becomes worse if whole soil-plant-human continuum is considered. Galloway and Cowling (2002) computed that out of 100 kg factory produced N by Haber-Bosch process, actually 14 kg goes into mouth in vegetarian diet and 4 kg in non-vegetarian diet (**Figure 8**). Unutilized-N is lost from the soil-plant system through processes of leaching principally

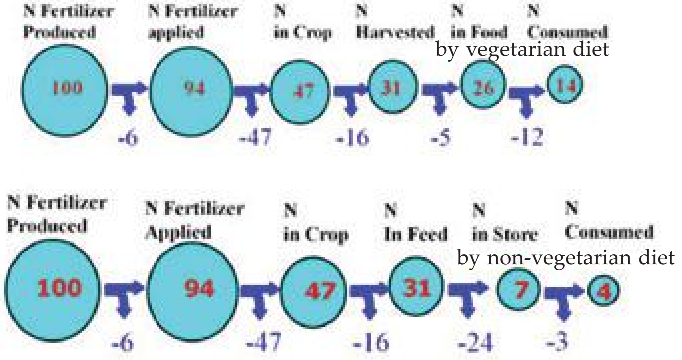


Figure 8. The fate of fertiliser-N produced by the Haber-Bosch process from the factory to the mouth for (a) vegetarian diet and (b) non-vegetarian diet

Source : Galloway and Cowling (2002) as NO_3^- and NO_2^- ions, and as NH_4^+ or -$CONH_2$ forms in minor quantities, volatilization as ammonia gas, denitrification as N_2O and N_2 gases, and surface run-off and erosion, besides getting immobilized in the organic pool. Impact of application of nitrogenous fertilisers on individual loss mechanism is discussed below:

Ammonia Volatilization

Ammonia is an intermediate form of N during the process in which urea is transformed to NH_4^+-N. Ammonia volatilization occurs when NH_4^+ in the soil is converted to NH_3 at pH above 7.0, which is then lost as a gas. Ammonia loss can be significant from the surface-applied fertilisers and organic manures containing NH_4^+-N or urea. On mega scale, more than 25% of fertiliser-N used in agriculture escapes to environment as NH_3 (Pathak, 2016). Ammonia emissions across the country vary from 1 to 22.8 kg N ha^{-1} depending upon soil, crop and fertiliser material (**Table 7**). These are non-existent in acid soils and increase rapidly with pH rising above neutrality. Generally, NH_3 losses increase linearly or exponentially with increasing N rate. Use of urea supergranules (USG) reduces the NH_3 emissions. Losses from urea broadcast, without rain/irrigation for at least a week after application, may range from 10 to 20% of the applied N. Ammonia volatilization losses are maximum on low

Table 7. Emission of ammonia from various land use types and locations of India

Location	**Crop**	**Org. C**	**pH**	**Texture†**	**N added (kg ha^{-1})**	**N source (%)**	**NH_3 emission (kg ha^{-1})**
New Delhi	Rice	0.48	7.7	SCL	120	Urea	10.1
New Delhi	Rice	0.48	7.7	SCL	120	USG	4.0
New Delhi	Wheat	0.41	8.2	L	100	Urea	8.0
Kalyani, WB	Rice	1.23	8.4	SiCL	90	Urea	15.6
Kalyani, WB	Rice	1.23	8.4	SiCL	90	*Neem*+ Urea	12.0
Kalyani, WB	Rice	1.23	8.4	SiCL	90	Urea + GM	7.2
Kerala	Rice	1.58	5.6	SL	90	Urea	0.4-5.0
Cuttack	Rice	0.70	6.0	SiL	90	Urea	2.9
Pantnagar	Rice	-	7.6	-	120	Urea	22.8
Pantnagar	Rice	-	7.6	-	120	USG	1.0
Cuttack	Rice	0.7	5.6	SCL	80	Urea	5.5
Ujjain, MP	-	0.45	CL	120	Urea	25.8	
Ujjain, MP	-	0.45	CL	120	DAP	4.3	

†Texture: SCL - Sandy clay loam; L - Loam; SiCL -Silty clay loam; SiL -Silty loam; S - Sandy; CL - Clay loam

Source : Sharma et. al. (2008)

organic matter, light textured alkaline or calcareous soils fertilized with urea and/ or anhydrous ammonia and the same get accentuated by the environmental conditions favouring high wind velocities. Application of urea to initially moist soils followed by drying conditions exacerbates the quantum of these losses. Ammonia losses are least with ammonium nitrate, ammonium chloride and ammonium sulphate, particularly on non-calcareous soils and these are negligible on acid soils. Volatilization can be minimized by incorporation of N fertilisers into soil, irrigation following urea application, deep placement and band placement of urea into the soil, and use of urease inhibitors (Yadvinder-Singh and Bijay-Singh, 2015). Placement of ammoniacal fertilisers at the 5-10 cm depth in rice-paddies prevents the escape of ammonia as its diffusive movement to the surface encounters aerobic layer which facilitates its nitrification.

Denitrifcation Losses as Nitrous Oxides

Denitrification is a microbially-facilitated process where nitrate is reduced and ultimately produces molecular nitrogen (N_2) through a series of intermediate gaseous nitrogen oxide products. Generation of nitrous oxide (N_2O) as a product of denitrification or nitrifier-denitrification has created a lot of environmental concern due to its role in global warming and depletion of stratospheric ozone shield. Conditions prevalent in submerged rice soils are congenial for denitrification as absence of oxygen triggers the use of NO_3^- as electron acceptor and easily decomposable organic C acts as an electron donor (Katyal et al., 2016). Denitrification can also occur even in saturated micro-sites of upland soils as the denitrifiers are largely facultative anaerobes (Firestone, 1982). End product of denitrification is N_2 and for the completion of this reaction, redox potential has to fall below -200 millivolts (mV). Conditions ideal for N_2O emission include conducive soil environment for nitrification leading to generation of NO_3^- ions - a substrate for the denitrifiers followed by moderate reducing conditions ideal for termination of denitrification at the N_2O generation stage.

Loss of fertiliser N through denitrification has been estimated to be as high as 50% (Aulakh and Bijay-Singh, 1996). Applied-N losses in lowland rice soils occur largely in the form of N_2 gas (Cady and Bartholomew, 1960) with proportion of N_2O to molecular N (N_2O/N_2) being inconsequential (Katyal et al., 2016). Park et al. (2012) reported sharp increase in N_2O emissions with increase in

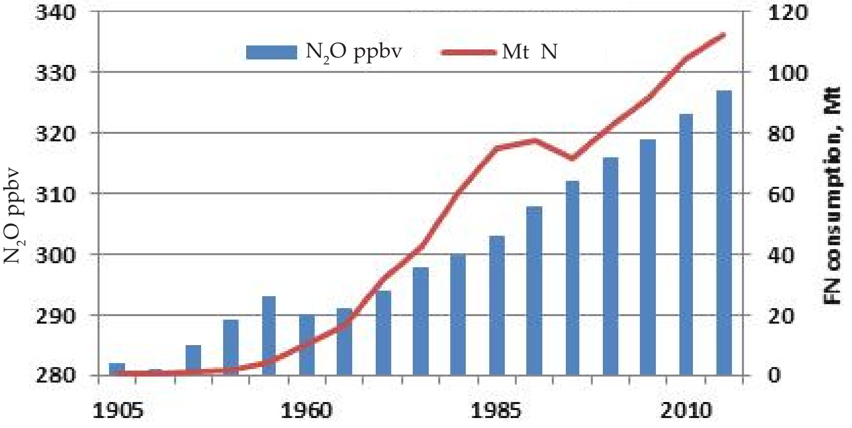


Figure 9. Dynamics of fertiliser consumption and N_2O emission
Source : Park et al. (2012)

fertiliser-N consumption, particularly since mid-1960s coinciding with the launch of Green Revolution (**Figure 9**). Emission of N_2O from Indian agriculture has also witnessed a rise. Pathak (2016) reported that emission of N_2O from all the sources of N including fertiliser, manure, crop residues, etc., which was only 0.06 Mt in 1970, increased by more than 320% by 2013; fertiliser-N alone accounted for 75% of these emissions. Conditions congenial for N_2O emissions from the applied N fertilisers include intermittent flooding and keeping soil water-saturated in rice and giving 3-5 irrigations in wheat; wheat crop environment provides both wet and dry zones and facilitates more emission of nitrous oxide (**Table 8**). Emission of N_2O, as percentage of applied fertiliser-N, is

Table 8. Emission of N_2O from agricultural fields in India

Crop	Fertiliser†	N dose (kg ha^{-1})	Irrigation‡	Duration (days)	N_2O emission (kg N ha^{-1})
Rice	Urea	140	CF	70	0.06
Rice	Urea	140	IF	90	0.16
Rice	AS	140	IF	90	0.23
Rice	Urea	120	SS	105	0.17
Rice	AS	120	SS	105	0.15
Rice	PN	120	SS	105	0.19
Rice	Urea	120	SS	90	0.74
Rice	Urea	120	IF	90	0.93
Wheat	Urea	140	3 irrig.	125	0.71
Wheat	Urea	120	5 irrig.	125	0.77
Wheat	Urea	120	5 irrig.	95	0.55

† Fertiliser: AS - Ammonium sulphate; PN - Potassium nitrate
‡Irrigation: CF - Continuously flooded; IF - Intermittently flooded; SS - Saturated soil
Source: Pathak et al. (2010)

Table 9. Nitrate leaching losses in various land use types and locations of India

Location	Crop	N added (kg ha^{-1})	NO_3^--N leached (%)
New Delhi	Rice	120	<20
Kalyani (West Bengal)	Rice	90	3.9
Ludhiana (Punjab)	Wheat	150	14.5
Ludhiana (Punjab)	Wheat	60	Negligible

Source: Pathak et al. (2009)

highest in pulses (0.67%) followed by oilseeds (0.55%), millets (0.43%) and cereals (0.40%) (Jain et al., 2016).

Nitrate Pollution of Groundwater

High rates of fertiliser-N application in conjunction with heavy irrigation regimes on light textured soils cause the leaching of nitrate out of the root zone to charge the ground water (**Table 9**). This might lead to rise of NO_3^- content in ground-water to more than 50 mg L^{-1}, upper safe limit fixed by the World Health Organization (WHO) for drinking water, to prevent the occurrence of blue baby disease syndrome or methemoglobinemia in infants. Khandare (2013) reported that the geological-N and manure-N were prominent sources of nitrate pollution across several regions in India. Higher levels of nitrate in some water samples could accrue from dumping of organic wastes and urban sewage rather than heavy use of N-fertiliser (Pathak et al., 2009). Citing different studies, Pathak (2016) summarized that in West Bengal, the average nitrate level was low in spite of high dosage of N fertiliser use whereas, leaching loss of N in *kharif* and *rabi* rice was of the order of 34.9 and 39.8% of the applied nitrogen fertiliser in the Indo-Gangetic plain region.

Strategies for Enhancing Use Efficiency and Minimizing Environmental Leakage of Nitrogen

Agriculture sans N-fertilisers is unthinkable. Leaving aside some intensively cultivated irrigated lands predominantly under rice-based and wheat-based cropping regions and some vegetable growing areas, there is a great scope for using more and more nitrogen. Average recovery efficiency or use efficiency of applied N in cereals (both direct and residual crops inclusive) in Asia on research farms is 50-57% (Ladha et al., 2005), with remaining N either incorporated into the soil or lost to the environment creating damages to humans or animals. The 4R Nutrient Stewardship promotes the use of right fertiliser source, at the right rate, at the

Table 10. Strategies and tools for enhancing nitrogen use efficiency, their economic feasibility and limitations

Tools/Tactics	Benefit: cost	Limitations
Site-specific N management	High	Has to be developed for every site, infrastructure required
Chlorophyll meter	High	Initial high cost
Leaf colour chart	High	Facilities need to be developed
Plant analysis	Low	Low profitability and lack of interest by industry
Controlled-release fertiliser	Low	Low profitability and lack of interest by industry
Nitrification inhibitors	High	Lack of equipment, labour-intensive
Fertiliser placement	High	Lack of equipment, risk involved
Foliar N application	Very High	A few varieties identified and tested
Breeding strategy N-fixation in non-legumes	High	Technology yet to be developed for field scale
Models and decision support systems	Medium	Tools are not available
Remote-sensing tools	Low	Technology needs to be fine-tuned
Geographic information systems	Low	Technology needs to be fine-tuned

Source : Adapted from Ladha et al. (2005)

right time, and in the right place. Best management practices (BMPs) evolved following the 4Rs can help increase yields, nutrient use efficiency and profitability while protecting the environment and improving sustainability. Fertiliser, soil, water, and crop management practices that maximize crop N uptake, minimize N losses and optimize indigenous soil N supply are sustainable BMPs for N (**Table 10**). Various approaches used for enhancing N use efficiency and minimizing environmental pollution are briefly discussed below:

Site-specific Nitrogen Management (SSNM)

The site-specific nitrogen management (SSNM) makes use of the assumption that use efficiency of applied N can be maximized by synchronizing the rate of N release from fertiliser with the crop N requirement. Real-time N management is a successful strategy under SSNM. Underlying assumption is that the leaf greenness determines the status and requirement of N of the crop. Greenness of the leaves of the growing crop relative to the greenness under optimal N supply is used as an index of N requirement. Tools used to measure greenness include leaf colour chart (visual), chlorophyll or SPAD

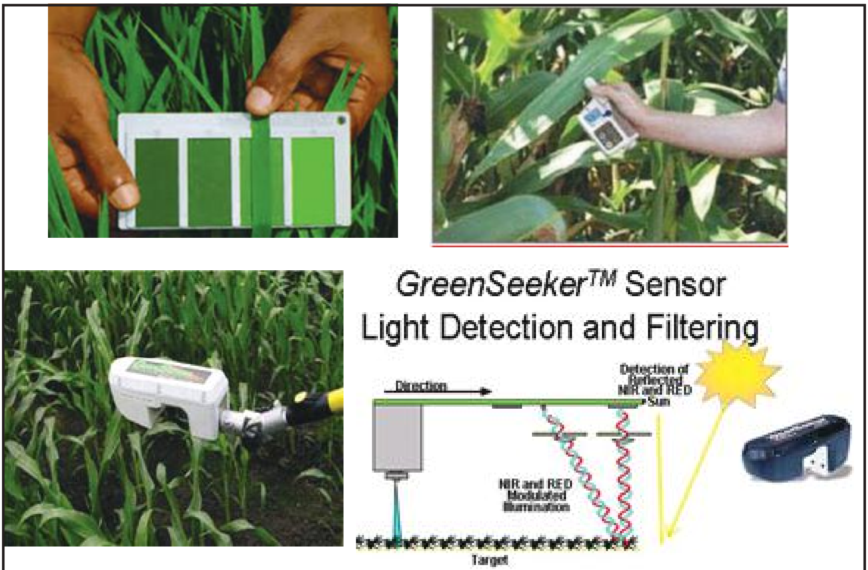


Figure 10. Gadgets used for measuring the greeness of plants for arriving at the topdressing dose of fertiliser nitrogen
Source : Yadvinder-Singh and Bijay-Singh (2015).

meter (chlorophyll content) or greenseeker (reflectance) (**Figure 10**) and the objective of using all these gadgets is to reduce the risk of yield-limiting N deficiencies and also avoid costly over-fertilization. Leaf colour chart developed at International Rice Research Institute (IRRI), Philippines is an inexpensive and simple tool to monitor leaf greenness and guide the application of fertiliser-N to maintain optimal leaf N content. A standardized plastic LCC with four panels, ranging in colour from yellowish green to dark green, is being currently used to determine the amount and timing of N fertiliser application in rice, wheat, maize and other crops. It economizes in terms of reduction in fertiliser-N rate without decrement in crop yields. For example, Varinderpal-Singh et al. (2007) reported that the LCC-guided N application helped in effecting a saving of 40 kg N ha^{-1} without any reduction in grain yield of rice in Punjab (**Figure 11**). One kg of N applied through urea on the basis of LCC produced 19 kg rice grains against 11 kg under conventional application (Yadvinder-Singh et al., 2007). The demand-driven N application using a leaf colour chart (LCC) could reduce nitrous oxide emission and global warming potential (GWP) by about 11-14% (Jain *et al.* 2013).

Product Development

Product development in N fertilisers has been in the form of slow

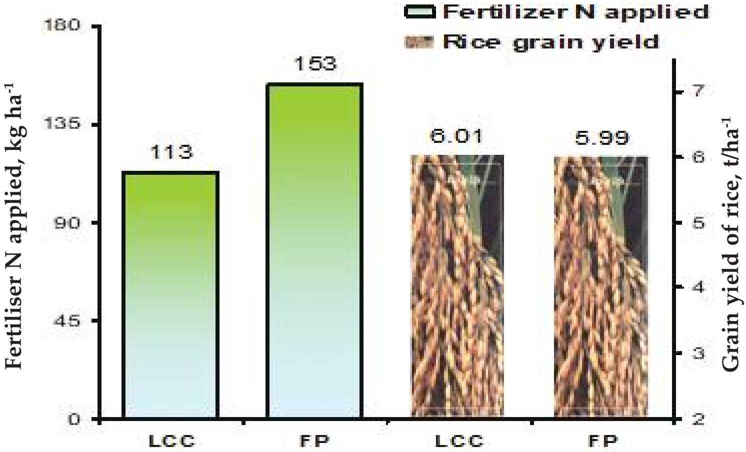


Figure 11. **Average fertiliser N applied and grain yield of rice in 107 on-farm trials comparing LCC based N management (LCC) with farmer's practice (FP) in Punjab**

Source : Varinderpal Singh et. al., (2007)

release fertilisers or controlled release fertilisers.

Slow Release N Fertilisers

Product modification has mostly been done with urea. One such modification was the development of urea supergranules (USG). Deep placement (5-10 cm depth) of USG is effective in enhancing NUE in rice but is not popular because of non-availability of product and higher application cost (Katyal et al., 2016). Slow release N fertilisers namely urea form, isobutylidene diurea (IBDU) and crotonaldehyde diurea (CDU) were developed with the objective of making N available during the entire crop duration,reducing N losses and enhancing NUE, decreasing labour costs and protecting the environment (Yadvinder-Singh and Bijay-Singh, 2015). Higher cost has come in way of their use. Prilled urea granules were coated with sulphur (sulphur coated urea, SCU) to prevent or control dissolution of urea. Microbial oxidation of S slowly released N into solution. Simple technology has not been adopted because of higher cost of sulphur.

Controlled Release N Fertilisers

Array of products, as mentioned earlier, have been developed as the urease and nitrification inhibitors. By way of regulating urea hydrolysis and nitrification at the first step, these help in slow generation of NH_4^+ and NO_3^- ions in soil solution offering more time for their absorption by the plants and reducing ammonia volatilization, nitrate leaching and nitrous oxide emissions. About 5-31% reductions in N_2O emissions in rice-wheat system and 7-29% in wheat crop have been recorded on alluvial soils of Indo-Gangetic plains with nitrification/urease inhibitors (Malla *et al.* 2005). Lower CH_4 and N_2O emission to rice paddy grain yield ratios, higher CH_4 production and oxidation potential, and lower soil denitrification activity (DEA) were recorded from '*Nimin*'-applied plot by Datta and Adhya (2014). With the exception of *neem* oil coated urea, other products did not become popular because of higher costs.

Indian fertiliser industry has taken some initiatives to develop value added / efficient fertiliser products. The development and use of neem coated urea has become a great success. The production and use of crop and area specific customised fertilisers including liquid fertilisers is being increasingly promoted to counteract the problem of expanding multinutrient deficiencies in Indian soils. The industry is promoting the use of some best management tools like laser land leveler, leaf colour chart (LCC), and water soluble fertilisers to improve nutrient use efficiency.

Agronomic Practices

From crop nutrition point of view, broadcasting and mixing of N-fertilisers is as effective as the band placement. However, surface broadcast of urea and ammoniacal fertilisers on moist alkaline soils triggers the ammonia volatilization. Irrigation of the field just after urea broadcast helps in moving urea-N from surface, reducing chances of ammonia volatilization (**Table 11**). Application of fertiliser-N in splits, with number and timing of split application synchronizing with the active N demand phases of plants is a sustainable practice of enhancing the NUE and reducing the loss to environment.

Table 11. **Influence of sequencing N top-dress and irrigation on yield and N loss**

Time of urea application	Grain yield (t ha^{-1})	Urea-N* recovery (%)	Urea N* loss (%)
Before irrigation	4.5	52	16
After irrigation	3.7	30	42

*Actual, since N^{15} labeled urea was top-dressed.
Source : Katyal et al. (1987)

Integrated Nutrient Management

Integrated nutrient management (INM) refers to the maintenance of soil fertility and of plant nutrient supply at an optimum level for sustaining the desired productivity through optimization of the benefits from all possible sources of organic, inorganic and biological components in an integrated manner. Nitrogen is central in planning experiments on INM because rates of application of different nutrient-sources are decided on the basis of relative contributions of N coming from them. Cultivation of mungbean (*Vigna radiata*) in rice-wheat cropping system and incorporating the mungbean residues after first picking of pods into the soil sustains the rice-wheat productivity, provides on an average 1 t mungbean seeds ha^{-1} and adds 40-120 kg N ha^{-1} to the soil. Bio-fertilisers contribute 15-30 kg N ha^{-1} yr^{-1} besides giving ancillary benefits like promoting plant growth, improving seed/ fruit quality and sustaining soil biological health (Prasanna et al., 2013). Balanced application of optimum NPK increased the crop NUE and addition of 5-15 t FYM ha^{-1} yr^{-1} over and above the optimum NPK further enhanced it (**Table 12**). Bhattacharyya et al.

Table 12. Apparent recovery efficiency (ARE) of nutrients in maize-wheat and rice-wheat systems as affected by long-term nutrient supply with and without FYM

Soil type	Location	Crop	Treatments			
			N	NP	NPK	NPK + FYM
		Apparent recovery efficiency of N (%)				
Inceptisol	Ludhiana	Maize	16.7	23.5	36.4	40.2
		Wheat	32.0	50.6	63.1	67.8
Alfisol	Palampur	Maize	6.4	34.7	52.6	63.7
		Wheat	1.9	35.6	50.6	72.6
Mollisol	Pantnagar	Rice	37.5	40.7	44.4	61.7
		Wheat	42.4	46.1	48.4	47.9
		Apparent recovery efficiency of P (%)				
Inceptisol	Ludhiana	Maize		10.3	21.4	26.3
		Wheat		20.6	30.7	34.8
Alfisol	Palampur	Maize		21.8	35.6	51.1
		Wheat		10.7	15.2	24.6
Mollisol	Pantnagar	Rice		18.2	23.3	53.0
		Wheat		11.2	10.4	23.3
		Apparent recovery efficiency of K (%)				
Inceptisol	Ludhiana	Maize			43.8	58.2
		Wheat			88.1	112.8
Alfisol	Palampur	Maize			23.0	38.9
		Wheat			22.6	66.8
Mollisol	Pantnagar	Rice			34.5	108.3
		Wheat			13.7	35.8

N: recommended N; NP: recommended N and P; NPK: recommended NPK to both crops; NPK+FYM: recommended NPK to both crops + FYM (15 t ha^{-1} yr^{-1} up to 2008-09 and 5 t ha^{-1} yr^{-1} thereafter) to *kharif* crop only.

Source : Singh et. al. (2012)

(2013) reported that super-imposition of FYM over and above NPK in 39 years of intensive rice-rice cultivation, improved significantly soil quality (higher soil labile C, N pools, soil enzymatic activities and microbial populations) but was associated with higher annual cumulative GHG emissions (CH_4, N_2O and CO_2 being 177.6, 1.28, 1407 kg ha^{-1}, respectively) and GWP.

Phosphorus and Environment

Phosphorus is the tenth most abundant element in the Earth's crust. Total P content in surface layer (0-15 cm) of Indian soils varies from 200 to 2000 kg ha^{-1}, with average content of 1000 kg ha^{-1}. Phytins, lipids and nucleic acids constitute the organic form of P in soil. These undergo mineralization to release P in soil solution as plant utilizable $H_2PO_4^-$ and/or HPO_4^{2-} forms. Phosphorus in soils mainly occurs as array of sparingly soluble compounds like strengite ($FePO_4.2H_2O$) and variscite ($AlPO_4.2H_2O$) in acid soils to apatites [$3Ca_3(PO_4)_2.CaX$], where X could be Cl^-, OH^-, F^- or CO_3^{2-}, in alkaline and calcareous soils. As depicted in **Figure 12**, soil solution P is buffered by absorbed (inorganic) phosphate and organic phosphate (rate of release of organic P being dependent on temperature and

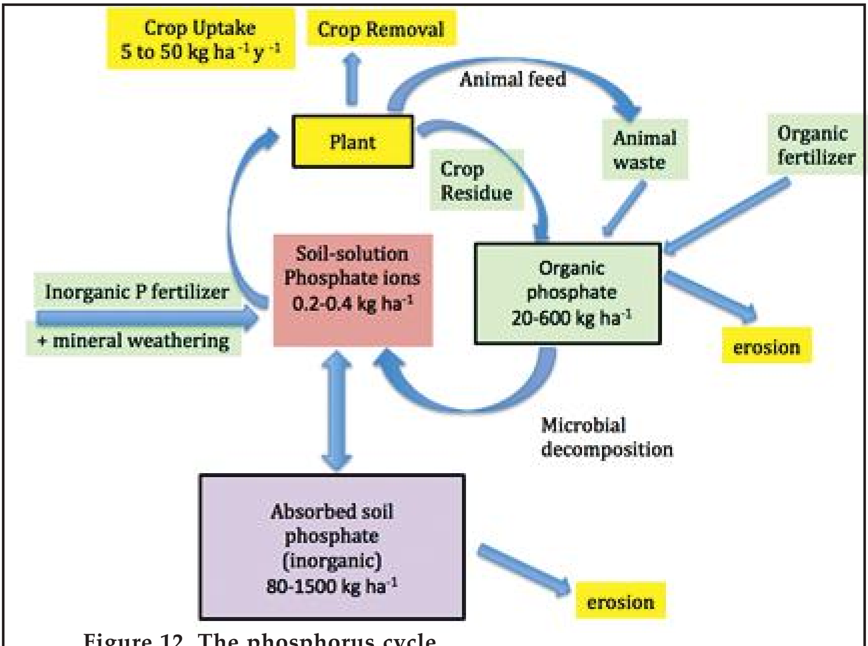


Figure 12. The phosphorus cycle
Source : Majumdar and Sanyal (2015)

moisture conditions). Crop residues, P-containing fertilisers and geological weathering of rocks and minerals also take part in P dynamics in soil-soil solution-plant continuum. Phosphates, being highly reactive, have limited mobility in soil and react with inorganic soil constituents to revert to form sparingly soluble phosphates of iron, aluminium and calcium depending on the pH and cationic environment. Coarse textured soils heavily fertilized with P-fertilisers are amenable to leaching of phosphates to ground-water. Discharge of surface run-off water laden with P-rich sediments raises P concentration in lakes and ponds etc., leading to eutrophication of these water bodies. Phosphate rocks (PRs), in particular the sedimentary PRs, are rich sources of heavy metals (Kongshaug et al., 1992). Sedimentary phosphate rocks are used for manufacture of phosphatic fertilisers. Concentrations of metals in PRs vary widely in different regions, with Cr content being highest and Hg the least (**Table 13**). During manufacture process these find way into finished P-fertilisers like SSP, TSP and DAP. Since metals have high residence time and are immobile in soils, these keep on accumulating in the soils continuously fertilized with P-fertilisers. Environmental concerns associated with P-fertiliser use include cadmium build up in the soil and eutrophication.

Phosphatic Fertilisers and Cadmium

Interest has centered mainly around Cd content of phosphate rocks

Table 13. Average heavy metal concentrations in phosphate rock (PR) deposits and estimated inputs in soil by P fertilisers

Phosphate rock deposit	**Heavy metal concentration (mg kg^{-1})**						
	As	**Cd**	**Cr**	**Pb**	**Hg**	**Ni**	**V**
Russia (Kola)	1.0	0.1	13.0	3.0	0.01	2.0	100
USA	12.0	11.0	109	12	0.05	37.0	82.0
South Africa	6.0	0.2	1.0	35.0	0.06	35.0	3.0
Morocco	11.0	30.0	225	7.0	0.04	26.0	87.0
North Africa	15.0	60.0	105	6.0	0.05	33.0	300
Middle East	6.0	9.0	129	4.0	0.05	29.0	122
Average of 91% of PR reserves	11.0	25.0	188	10.0	0.05	29.0	88.0
mg kg^{-1} of P	71.0	165	1,226	66.0	0.29	189	578
g ha^{-1} yr^{-1} of P applied through 20 kg P ha^{-1}	1.0	3.3	25.0	1.0	0.01	4.0	12.0
Tolerance limit in soil (mg kg^{-1})*	2.0	100	100	2.0	50.0	50.0	300

*Finck (1992) as cited in Mortvedt (1996)

Source: Kongshaug et al. (1992)

because of infamous Cd induced *itai-itai* disease in Japan (Mortvedt, 1996; Roberts, 2014). Cadmium occurs naturally in phosphate rock (PR). As per the IFDC report (van Kauwenbergh, 2001), igneous PR deposits in 9 countries had an average Cd concentration of 2 mg kg^{-1}, 7.5 times more enriched than the crustal abundance; sedimentary PR deposits were more concentrated source of Cd with mean and range of 21 and <1 to 150 mg kg^{-1} PR, respectively (**Table 14)**. Sedimentary PRs which are 69 times more concentrated with Cd than the sedimentary non-PRs have been used world-over for 85% production of the phosphatic fertilisers. During fertiliser-P manufacture,varying amounts of Cd in the phosphate rock move through the beneficiation and acidulation processes (Roberts, 2014). For ordinary (single) superphosphate (SSP) produced by reacting phosphate rock with sulphuric acid and triple super phosphate (TSP) produced by acidulation of the phosphate rock with

Table 14. Cadmium contents (mg kg^{-1}) of sedimentary and igneous phosphate rocks

Country	Deposit	Average Cd	Range
Sedimentary Deposits			
China		<2	
Israel	Zin	31	20-40
	Undifferentiated	24	20-28
	Arad	14	12-17
	Oron	5	-
Jordan	El-hasa	5	3-12
	Shidvia	6	-
Morocco	Undifferentiated	26	10-45
	Bou Craa	28	32-43
	Khouribga	15	3-27
	Youssoufia	23	4-51
Senegal	Taiba	87	60-115
Syria	Khneifiss	3	-
Togo		58	48-67
Tunisia		40	30-56
United States	Central Florida	9	3-20
	North Florida	6	3-10
	Idaho	92	40-150
	North Carolina	38	20-51
Other countries		13	<1 - 100
Overall sedimentary	*Averages*	*21*	*<1 - 150*
Igneous Deposits			
Brazil	Araxa	2	2-3
	Catalao	<2	-
South Africa	Phalaborwa	1	1-2
Russia	Kola	1	1-2
Other countries		1	<1-2
Overall igneous	*Averages*	*2*	*<1-4*

Source : van Kauwenbergh (2001)

phosphoric acid, all Cd present in the phosphate rock is transferred to the SSP or TSP. Depending on the phosphate rock source, SSP can contain from 2 to more the 40 mg kg^{-1} and TSP can have from <10 to over 100 mg kg^{-1} Cd content (van Kauwenbergh, 2001). In wet process phosphoric acid (WPA) Cd is transferred to the acid and gypsum by-product. About 55 to 90% of the Cd is transferred to the acid with the balance to the gypsum. Ammonium phosphates (*e.g.*, monoammonium phosphate [MAP] and diammonium phosphate [DAP]) produced from WPA can have their Cd content ranging from <1 mg kg^{-1} to >100 mg kg^{-1} depending on the source of phosphate rock used for manufacture. Extensive studies have shown that at the current rates of application of phosphatic fertilisers, there is no reason to worry. For example, Mortvedt (1987) reported that continuous annual Cd application of 0.3 to 1.2 g ha^{-1} yr^{-1} (assuming 5 mg Cd kg^{-1} of TSP) for more than 50 years in 9 experiments did not have any effect on Cd uptake by maize, soybean (*Glycine max* L. Merr.) and wheat leaves or grain, and timothy-grass (*Phleum pratense* L.). Application of single superphosphate (containing 70 ppm Cd) @ 137.3 kg P_2O_5 ha^{-1} yr^{-1} for 16 years although caused significant increase in Cd content in rice grain (0.11 ppm) over N alone (0.04 ppm) on black soil of Tamil Nadu (Parameswari et al., 2014), but contents were much lower than the upper safe level of 1.0 ppm in edible grains. Similar have also been the observations of Mulla et al. (1980) and Rothbaum et al. (1986).

Even if it is assumed that all the Cd contained in the P-fertiliser or phosphate rock keeps accumulating in the soil, their application at the current rates is not going to exceed toxicity limits for more centuries together. Using data from **Table 13,** Mortvedt *(1996)* illustrated the computation of the number of years required for a given heavy metal in P-fertilisers to reach the tolerable limit

*"Total soil Cd generally ranges from 0.1 to 1 mg kg^{-1}. The total amount of Cd in the surface 20-cm layer is 1.5 kg ha^{-1}, assuming an average Cd concentration of 0.5 mg kg^{-1}. The tolerable limit for Cd is 2 mg kg^{-1} which is equivalent to 6 kg ha^{-1}. Thus, Cd applications could total 4.5 kg ha^{-1} yr^{-1} to reach the tolerable limit. From the data in **Table 13**, it would take 1,300 years of P applications at a rate of 20 kg P ha^{-1} to reach the tolerable Cd limit (4.5 kg ha^{-1} divided by 3.3 g ha^{-1}). This calculation ignores other possible Cd inputs to agricultural soils, such as sewage sludges and aerial deposition, as well as Cd removal by crops. However, it illustrates the estimated time needed to reach some defined heavy metal limits for agricultural soils."*

Phosphatic Fertilisers and Eutrophication

Use efficiency of applied P-fertilisers in India seldom exceeds 20%. Majority of the unutilized fertiliser-P either undergoes transformation/reversion in the soil into sparingly soluble compounds like apatite (calcium phosphate), strengite (ferric phosphate), variscite (aluminium phosphate) etc., or gets irreversible fixed in soil through ligand exchange and keeps on accumulating in the soil. This excessively accumulated P undergoes mobilization and becomes amenable to loss through different mechanisms, most significant ones being P loss through soil erosion and surface run off to lakes and ponds or leaching in low organic matter highly percolating light textured soils or organic soils to ground-water (**Table 15**). Increased P levels in the surface water bodies like lakes and ponds have been implicated with eutrophication. According to United Nations Environmental Programme (UNEP) report, around 30–40% of lakes and reservoirs globally are affected by eutrophication (UNEP, 2005). Accumulation of excessive P has

Table 15. Factors influencing phosphorus loss in soil

Factors	**Description**
Site Management	
Soil P	As soil P increases, P loss in surface runoff and subsurface flow increases.
Applied P	The more P applied (mineral fertiliser or manure), the greater the risk of P loss.
Application method	P loss increases in the order; subsurface injection, ploughed under, and surface broadcast with no incorporation.
Application timing	The sooner it rains after P is applied, the greater the risk for P loss.
P source	The P in some fertilisers and manures is more soluble than in others and thus, more susceptible to runoff.
Transport	
Erosion	Total P loss is strongly related to erosion.
Surface runoff	Water has to move off or through a soil for P to move.
Subsurface flow	In sandy soil, organic, or P-saturated soils, P can be leached.
Soil texture	Influences relative proportions of surface and subsurface flow.
Connectivity to stream	The closer the field to the stream, the greater the chance of P reaching it.
Channel effects	Eroded material and associated P can be deposited or re-suspended with a change in stream flow. Dissolved P can be absorbed or desorbed by stream channel sediments and bank material.
Proximity of P-sensitive water	Some watersheds are closer to P-sensitive waters than others (*i.e.*, point of impact).
Sensitivity P input	Shallow lakes with large surface area tend to be more vulnerable to eutrophication.

Source: Shigaki et al. (2006)

been observed due to continuous application of phosphatic fertiliser in some intensively cultivated systems of north-western India. Indian Institute of Soil Science advocates that once the available P status upon continuous P application graduates to high-P category, then P dose can be reduced to half safely irrespective of the soil without any loss in yield (Singh et al., 2016). Farmers of Punjab, Haryana and Western Uttar Pradesh have been advised to follow the practice through their respective state governments. This strategy would not only reduce the burden on foreign exchequer but also reduce the cost of cultivation and intensity of P-linked eutrophication.

Potassium and Environment

Potassium exists in soil in four forms *viz.*, soil solution, exchangeable, non-exchangeable but useful [sodium tetra phenyl boron or borate (NaTPB) or boiling HNO_3 extractable], and mineral forms with their average contents being 10-50, 100-500, 100-3,000 and 10-10,000 kg ha^{-1}, respectively (**Figure 13**). Soil solution and exchangeable pools, in a state of dynamic equilibrium, constitute the readily available K. Available K is buffered by non-exchangeable pool. Mineral K, comprising of K-bearing primary and secondary minerals like feldspars and micas *viz.*, biotite and muscovite release K upon weathering. When plants remove K from soil solution, it is

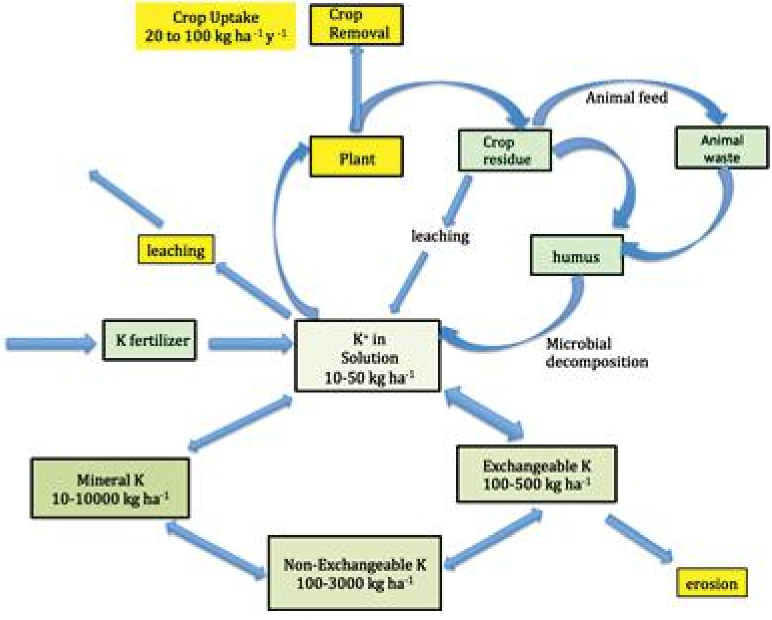


Figure 13. Schematic diagram of the potassium cycle
Source : Majumdar and Sanyal (2015)

replenished immediately by exchangeable K and non-exchangeable K pool slowly buffers both the solution and exchangeable K. Net result is that in spite of heavy withdrawal of K under intensive cropping systems, slight or no drop in available K (1*N* NH_4OAc-extractable K) occurs. Currently recommended rates of K application vary from 30 to 60 kg K_2O ha^{-1}. Experiments on the rice-wheat system in Indo-Gangetic alluvial plains have shown that application of even 75 kg ha^{-1} $crop^{-1}$ (600 kg ha^{-1} in 4 cropping years) is not able to arrest decline in exchangeable K, net K balance remains negative and contribution of non-exchangeable K to plant-K uptake is 95% (**Table 16**). Because of substantial contributions from non-exchangeable K, crops do not respond to fertiliser-K even on soils analyzing low in exchangeable K. Scientists erroneously conclude that potassium applications are not needed and omission of K helps in cutting on the import bill without any yield decrement. Indiscriminate application of NP fertilisers in the intensively cultivated North-western Indo-Gangetic Plains works as a shovel to mine higher and higher quantities of K from the inert mineral pools, virtually leading to the exhaustion of soil K reserves. Situation might develop where K-depleted soils will not respond to external K applications because the minerals which released K previously for crop uptake will preferentially fix the added K.

In 2015-16, Indian agriculture operated at a net negative balance of 2.3, 2.1 and 8.6 Mt of N, P_2O_5 and K_2O, respectively (**Figure 14**). On per hectare basis, these figures were -15.3, -9.4 and -42.2 kg and the net negative balance was highest in case of K_2O in all the crops and varied greatly among the crops (Tewatia et al., 2017). Neglect of K in fertilization schedule poses environmental problems like reduction in crop yields, crop quality, and recovery efficiency of N and P.

Use efficiency of K applied in conjunction with optimum NP

Table 16. K balance under different K application rates after 4 cycles of rice-wheat system

K rate (kg ha^{-1})	Total K applied (kg ha^{-1})	Total K uptake (kg ha^{-1})	Net K balance (kg ha^{-1})	Depletion of available K in 0-15 cm soil (kg ha^{-1})	Contribution from non-exchangeable - K (%)
0	0	883	-883	34	96
25	200	931	-731	28	96
50	400	932	-532	26	95
75	600	955	-355	33	95

Source : Meelu et al. (1995)

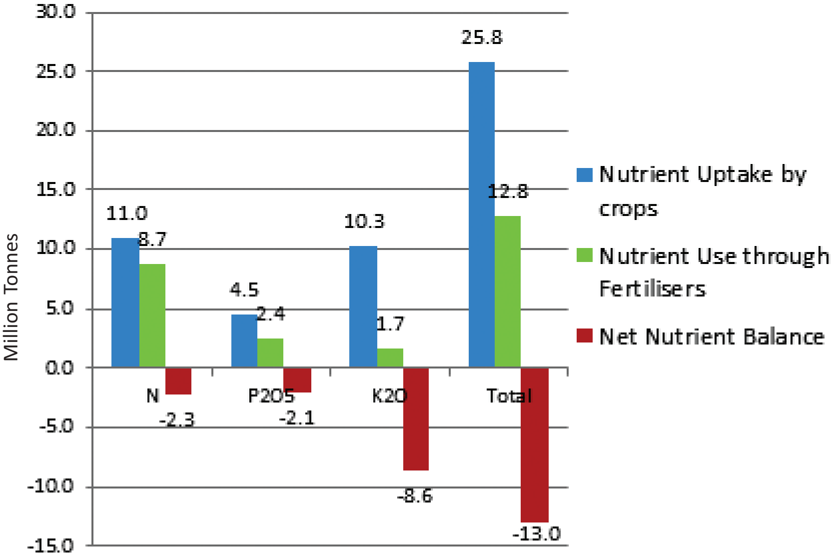


Figure 14. Net nutrient uptake, fertiliser use and gap (2015-16)
Source : Tewatia et al. (2017)

fertilisers is around 60%. In the Long Term Fertiliser Experiments (LTFEs), application of 5-15 t FYM ha^{-1} yr^{-1} along with optimum NPK increased the K use efficiency (KUE) by more than 50% in rice-wheat and maize-wheat systems. General practice is to apply whole of K as a basal dose. On light textured highly weathered acid soils dominated by kaolinite and amorphous minerals, split application of K maximizes the KUE (Dwivedi et al., 2017). Tube well water used for irrigation contains significant amounts of K and quantification of its contribution to crops is useful in adjusting the dose of fertiliser-K. Potassium is unique in that the economic produce (grain/seed) exports only 1/3rd to 1/4th of total K absorbed during the growing season, with rest left behind in the form of straw/stover residues. Buresh et al. (2010) reported that in rice-maize system (5 t ha^{-1} rice and 12 t ha^{-1} maize yield), retention of maize residues could markedly reduce the net K export, whereas residue removal failed to eliminate the deficit in K balance.

Fertigation is a process in which fertiliser is dissolved and distributed along with water in the drip or sprinkler (spray) irrigation system. Benefits accruing from fertigation include higher use efficiency of fertiliser as its supply can be synchronized with plant demand by controlling the timing of fertilization. Since drip supplies water and nutrient near the root zone, P and K (which are prone to fixation in soil), are positionally available to get absorbed by the plants, escaping fixation. Water soluble potassium sources used for fertigation include potassium chloride (MOP), potassium sulphate (SOP), monopotassium phosphate (MKP) and potassium nitrate (KNO_3). The KUE tending up to 100% can be achieved by fertigation leaving no K for loss to environment.

Organic Fertilisers and Heavy Metal Buildup in Soils

Organic fertilisers, particularly city compost, contain elevated levels of heavy metal contaminants because of their origin from urban and industrial wastes. Integrated nutrient management (INM), involving conjoint application of organic, bio- and mineral nutrient sources has been propounded as the eco-friendly strategy for improving/sustaining the health of the C-poor Indian soils. Agricultural intensification with more and more area coming under cultivation, replacement of draft power by the machinery and as a consequence drop in animal and livestock population, burning of crop residues, and competitive uses of animal manures as fuels have progressively reduced the C inputs to the soil. Use of the on- and off-farm generated wastes and also wastes generated from the urban settings (including sludges emanating from sewerage and industry) is being encouraged to improve soil health apart from substituting up to 25% of the mineral fertiliser-N. With a view to provide quality organic manures, the Government of India has included city compost, vermicompost, phosphate rich organic manure (PROM), organic manure, and bio-enriched organic manure in the Fertilizer (Control) Order 1985 specifying the minimum nutrient content for each source. Because of diverse sources used in manufacture of organic fertilisers, particularly those using the urban wastes, there is a possibility of these containing significant quantities of heavy metals like arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn). As per FCO, the maximum heavy metal content fixed in city compost, phosphate rich organic manure (PROM), organic manure and bio-enriched organic manure is: As as As_2O_3 10 mg kg^{-1}, Cd 5 mg kg^{-1}, Cr 50 mg kg^{-1}, Cu 300 mg kg^{-1}, Hg 0.15 mg kg^{-1}, Ni 50 mg kg^{-1}, Pb 100 mg kg^{-1}, and Zn 1000 mg kg^{-1}. For vermicompost metals specified are only Cd 5 mg kg^{-1}, Cr 50 mg kg^{-1}, Ni 50 mg kg^{-1}, and Pb 100 mg kg^{-1}.

In view of the accumulation of heavy metals and their long residence time in soils, different countries have developed guidelines to limit the application of metal-rich sludges. First simple approach developed was to allow land application of only those sewage sludges having Zn/Cd ratio of >100:1. Chumbley (1971) introduced the concept of zinc equivalent (ZN-E) of sewage sludge as Zn-E = [Zn] + 2 [Cu] + 8 [Ni] where [ ] represents the metal content (ppm) in sewage sludge. Assumption was that Cu was twice and Ni eight times more toxic than Zn and their effects were additive. Based on concept of zinc equivalent, the United Kingdom Government developed guidelines having following components: i) Land application of sewage sludge should be restricted to neutral or alkaline soils only, ii) amount and application schedule of sewage sludge should be such that the site receives a total Zn-E of 560 kg ha^{-1} over a period of say 30 years, and iii) application be terminated if the soil pH drops below 5.5. Subsequently it was discovered that there were more harmful metals/metalloids like Cd, Pb, Cr, Hg, etc., and their effects were not as simple as were thought to be in Zn-E. Country-specific guidelines have been developed across the world. Reproduced in **Table 17** are the United State Environmental Protection Agency (USEPA) guidelines limiting the application of biosolids. As per these guidelines, land application of biosolids must meet the ceiling concentrations and cumulative loading rates for nine trace elements. If the concentration limit of any one of the elements is exceeded, the biosolids cannot be land-applied. The application of biosolids will also be required to cease, if it is estimated that the cumulative loading limit is being approached.

Table 17. Heavy metal concentration limits and annual load limits of sewage sludges in USA (USEPA, 1993)

Element	Ceiling concentration limit (mg kg^{-1} dry weight)	Cumulative pollutant limit loading (kg ha^{-1})	Maximum annual load (kg ha^{-1} yr^{-1})
Arsenic (As)	75	42	2.0
Cadmium (Cd)	85	39	1.9
Copper (Cu)	4300	1500	75.0
Lead (Pb)	840	301	15.0
Mercury (Hg)	57	17	0.85
Molybdenum (Mo)	75	*	3.8
Nickel (Ni)	420	421	21.0
Selenium (Se)	100	100	4.9
Zinc (Zn)	7500	2805	140.0

Source : Mortvedt (1996) and Lu et al. (2012)

Imbalanced Use of Nutrients - Environmental Consequences

Imbalanced use of nutrients in the country is rampant as reflected in terms of $N:P_2O_5:K_2O$ ratio skewed heavily towards nitrogen and against potash, particularly in north and west zones. Long-term experiments have established that the NPK use efficiencies get optimized under optimal rates of their application (100% NPK) and improve further with application of 5-15 t farmyard manure ha^{-1} yr^{-1} as already given in **Table 12**. Accentuation of soil acidity with long-term use of urea and ammoniacal fertilisers on poorly buffered acid Alfisols is accompanied by reduction in crop yields. Under these situations, recovery efficiency (RE) of added N by crops drops to considerable extent and whole of added N is free for polluting the environment. With balanced and integrated use of nutrients, utilization of fertiliser-N by crops increases and leakage of fertiliser-N to the environment decreases. Multi-location studies in Indo Gangetic Plain (IGP) and adjoining rice-wheat growing areas show that RE of applied P and K drops if one is applied with the exclusion of the other (Dwivedi et al., 2017). Recovery efficiency of the primary nutrients is low on soils deficient in secondary (S) and micronutrients (Zn, B) and alleviation of their deficiencies is essential for enhancing the utilization of major nutrients. Thus, balanced application of primary, secondary and micronutrients is essential for getting higher yields, maximizing nutrient use efficiency, improving the economic benefits, and minimizing their leakage/escape to the environment.

Conservation Agriculture

Conservation agriculture (CA) is a resource-saving agricultural crop production striving to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment (FAO 2010). It is characterized by three interlinked principles namely, continuous minimal mechanical soil disturbance, maintenance of permanent organic soil cover, and adopting diversified crop rotations of annual crops and plant associations of perennial crops. It resembles a natural eco-system where soil is continuously covered. Build-up of soil organic carbon, less soil erosion, and reduction in use of energy (30-40%) are the benefits accruing from adoption of CA. The CA system involves extensive use of resource conservation technologies (RCTs) namely permanent raised beds (PRB), zero-tillage (ZT), furrow irrigated raised beds (FIRB), crop residue retention and laser land levelling. Since CA integrates use of on-farm generated organic nutrient sources, INM gets embedded into it. In addition to improving carbon sequestration and soil health, CA scales down the doses of mineral fertilisers due to more use of organic nutrient sources. On Typic Haplustepts of Western IGP, economic optimum rates of fertiliser N and P for wheat in the pigeonpea–wheat system were smaller (128 kg N and 28 kg P ha^{-1}) under PRB as compared to flat bed (FB) (152 kg N and 30 kg P ha^{-1}) owing to increased N and P supply, greater use efficiency and a better crop growth environment. The PUE was invariably higher under PRB (**Table 18**). Adoption of zero till along with residue retention in maize-wheat system enhanced the PUE and the phosphate solubilising bacteria (PSB) and arbuscular mycorrhizae (AM) inoculation further raised the PUE (Dwivedi et al., 2017). It indicates a strong possibility of using less of P-fertilisers in CA by making use of microbial inoculation.

Regulatory Environment

Fertiliser is a highly regulated commodity in India. Realising its role in national food security, fertiliser was declared Essential Commodity in 1957 under Essential Commodities Act (ECA), 1955. Government of India enacted Fertiliser (Control) Order to regulate quality, trade, price and movement of fertilisers. A number of committees including Committee on Fertilisers (Sivaraman Committee) – 1965; Fertiliser Pricing Committee (Marathe Committee) – 1977; High Powered Committee on Fertilizer Consumer Prices -1986; Task Force on Balanced Use of Fertilisers – 2005 were constituted by the Government of India

Table 18. Agronomic efficiency and recovery efficiency of P in wheat as influenced by fertiliser P rates and planting method (mean over 3 years)

Planting method	P rates (kg ha^{-1})				Mean
	0	13	26	39	
Agronomic efficiency of P (kg grain kg^{-1} P)					
FB	-	62.9	37.2	22.0	40.7
PRB	-	76.7	44.6	23.5	48.3
Recovery efficiency of P (%)					
FB	-	39.6	26.9	22.3	29.6
PRB	-	43.3	29.4	23.0	31.9
LSD ($p<0.05$)					

Agronomic efficiency of P Planting method (T)=3.67, P rates (P)=4.84, T×P=NS
Recovery efficiency of P Planting method (T)=1.24, P rates (P)=1.36, T×P=2.71
Source : Dwivedi et al. (2017)

to promote the increased and balanced use of fertilisers. Fertiliser policies formulated and implemented from 1960s to 1990s played an important role in growth of fertiliser consumption.

The introduction of Nutrient Based Subsidy (NBS) Scheme in April 2010 was aimed at promoting balanced use of nutrients. However, it covered only P&K fertilisers and urea was left out. Price of urea continued to remain controlled at almost same level as was in 2010. Simultaneously, the fixed subsidy on P&K fertilisers under NBS scheme was reduced substantially resulting in high retail price of these fertilisers (**Table 19**).

This distortion in price of urea *vis-à-vis* P&K fertilisers has affected the use ratio of N, P & K adversely because farmers prefer to buy more of low priced urea at the expense of high priced P&K fertilisers, oblivious of the fact that inadvertently they were inducing the imbalance in fertiliser use.

Imbalanced and inefficient use of plant nutrients exacerbated by present pricing policies may aggravate the problem of groundwater pollution and eutrophication of water bodies. Free water and power (in some states) coupled with heavily subsidized urea not only result in the inefficient use of N but also leave the farmers with lower crop yields and poor net economic returns. The present fertiliser pricing policy is not congenial for venturing into the area of value added / innovative products.

Conclusions

India made impressive strides in achieving self-sufficiency in food grain production by 2000AD and entered in 21st century with over-

Table 19. Impact of nutrient based subsidy (NBS) scheme on fertiliser prices and NPK use ratio

Year	Urea	DAP	MOP	Price ratio				NPK use ratio
	MRP (Rs./tonne)			DAP : Urea		MOP : Urea		
2009-10	4830	9350	4455	1.94	1	0.92	1	4.3:2.0:1
2010-11	5310	10150	5055	1.91	1	0.95	1	4.7:2.3:1
2011-12	5310	15525	9040	2.92	1	1.70	1	6.7:3.1:1
2012-13	5360	24000	17000	4.48	1	3.17	1	8.2:3.2:1
2013-14	5360	22500	16000	4.20	1	2.99	1	8.0:2.7:1
2014-15	5360	23700	16500	4.42	1	3.08	1	6.7:2.4:1
2015-16	5360	24000	16500	4.66	1	3.08	1	7.2:2.9:1

Source : Tewatia (2016)

flowing food granaries. During 2016-17, production of food grain (275.68 Mt) is going to be surpassed by that of horticultural (vegetables and fruits) production (299.85 mt). Improved fertiliser-responsive crop varieties, fertilisers, mechanization, expansion of irrigation facilities and innovative techniques like pressurized irrigation (drip and sprinkler), more effective plant protection measures, and better management practices made this possible. Fertiliser alone was responsible for 50% increase in this production, with nitrogen fertiliser accounting for the largest contribution.

While this impressive journey not only kept pace or performed better *vis-à-vis* population rise, run was confronted with emerging second generation problems in the post Green Revolution. These included a drop in partial factor productivity and nutrient response ratios per unit of fertiliser applied, impoverishment of soils of their indigenous nutrient reserves, reduction in the availability of farmyard manure due to animal-draft power getting replaced by farm machinery, accelerated emergence of the secondary and micronutrient deficiencies, rising water tables leading to development of waterlogging in canal irrigated area and secondary salinization, lowering of water tables in the tube-well irrigated tracts leading to more energy consumption in pumping the same amount of water, crop varieties becoming resistant to the plant protection chemicals at alarming rates and agricultural-intensification-induced global warming exacerbated by the burning of crop residues.

With respect to fertiliser use, low use efficiency of applied nutrients remains the main concern. Use efficiencies of the applied nutrients have remained abysmally low. As mentioned earlier, utilization of fertiliser nitrogen by crop seldom exceeds 35% under low-land and 50% under upland conditions. Inefficient use of N is linked to the NO_3-contamination of groundwater and excess NO_3^--carcinogenicity linked to its accumulation in leafy vegetables, NH_3-volatilization linked acid rains, and N_2O-induced global warming and catalytic reduction of stratospheric O_3 (which could be linked to enhanced UV radiations linked carcinogenicity). Nitrogen cycle is internally balanced leaving a little scope for its manipulation. There is a need to arrest ammonia volatilization, leaching of unutilized nitrate ions to ground-water and nitrous oxide emissions. Manipulation of conditions for reducing nitrous oxide emissions leaves nitrates to be vulnerable to leaching and vice-versa.

Use efficiency for other nutrients is : 15-25% for P, 50-60% for K, 8-12% for S and 2-5% for most of the micronutrients under best managed conditions. Small portion of unutilized P finds its way to water bodies leading to their eutrophication on coarse textured soils and under conditions facilitating run-off and water erosion, of course major part remaining in the soil. Heavy metal content of phosphatic fertilisers, in particular of cadmium, may create environmental concern. Of course, neither Cd toxicity nor P-induced eutrophication have come to light in any part of the country. Even if it is assumed that all the Cd contained in the P-fertiliser or phosphate rock keeps accumulating in the soil, their application at the current rates is not going to exceed toxicity limits for centuries together. Accelerated depletion of potassium in intensively cultivated soils due to its very low rate of or virtually non-existent application reducing the agronomic efficiency of the other fertiliser-nutrients is far more serious a problem and is going to assume gigantic proportions.

Government policy of retaining urea under price control and bringing P and K fertilisers under nutrient based subsidy (NBS) scheme, has made the farmers use more N on purely financial considerations, leading to wide $N:P_2O_5:K_2O$ ratios and imbalanced fertilization. There is wide variation in regional and inter-state fertiliser use and nutrient use ratios. Disparities in fertiliser use are also linked to irrigation facilities and farm size. Irrigated lands cultivated by small and marginal farmers receive higher fertiliser rates in more balanced proportions. Coarse textured acid red and lateritic soils of Eastern and Southern regions, being low in both P and K, receive more balanced application of nutrients.

Site-specific nutrient management coupled with the 4Rs (right source, right rate, right time and right place) principle of fertilization holds a promise in enhancing the use efficiency of applied nutrients leaving lesser and lesser amount of nutrients finding their entry to the environment. Real-time N management using simple gadgets like leaf colour chart, SPAD meter etc, in rice and wheat shows the use of this technology in maximizing NUE and minimizing N losses without any yield decrements. Simple agronomic practices like split application of N and also of K in the light textured low K-retentive acid soils, with each split synchronizing with active absorption stages can effect significant savings on fertiliser doses. Top-dressing of urea a day before irrigation increases the utilization of urea-N and decreases its losses.

The prevailing fertiliser pricing policy under which there is a huge distortion in urea *vis-à-vis* P&K prices goes against the concept of balanced fertilisation. It is harming the farmers, soils and the environment. Correction in pricing policy is a must to promote the balanced and efficient fertiliser use. Government is spending huge amounts on fertiliser subsidy. Need of the hour is that it should be used to promote balanced and efficient use of nutrients. Products and practices which encourage balanced fertilisation and give higher nutrient use efficiency need encouragement. Coating of urea with neem oil is a significant step in improving the nitrogen use efficiency (NUE). Use of chemicals inhibiting/prolonging urea hydrolysis (urease inhibitors) and nitrification (nitrification inhibitors), and development of slow release N fertilisers, and other simplified products like urea supergranules (USD) have shown a great promise but have not found acceptability because of lack of support under pricing and subsidy policy. Some policy decision is needed to bring these products within the purchasing power of the farmers.

The recent decision of the government to try direct benefit transfer (DBT) of subsidy to farmers in pilot districts and eventually replicating the model in the country is a step in right direction. It should be taken to its logical conclusion of transfering benefit to the farmers' accounts in a time bound manner. It will enable the industry to utilize its manpower and resources for developing more efficient fertiliser products and improving farmers' awareness on fertiliser best management practices (FBMPs).

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