Fertilizer Use in Indian Agriculture and its Impact on Human Health and Environment

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Abstract

Fetilizer is one of the vital inputs required for enhancing agricultural production and the farmers' income in India. India ranks second in the world and first among the South Asian Association of Regional Cooperation (SAARC) countries in terms of total fertilizer consumption. However, the average fertilizer application per hectare of about 145 kg in India during 2019-20 was much below than that in the SAARC countries of about 174 kg ha^{-1}. There are huge inter-state and inter-regional variations in fertilizer use. The changes in government policies pertaining to fertilizer distribution and use have impacted significantly the nutrient use ratio. Overuse or misuse or imbalanced application of fertilizer nutrients and sheer negligence in the application of secondary and micronutrients have been responsible for the lower utilization of applied nutrients, leading to the accumulation of fertilizer nutrients in the soil and/or leakage to the environment, and thus causing environmental degradation and climate change. The compounded harmful effects of imbalanced fertilizer use are not only intensifying soil and atmospheric pollution but also impacting water bodies (eutrophication) and causing threat to biodiversity and human health. The increased use of fertilizer-N has direct bearing on higher total N_2O emission and low N use efficiency (15-30%). As per estimates, India emits about 6.24 Tg yr^{-1} of reactive nitrogen (Nr), though contribution from agricultural fields is not really alarming. Adoption of the best crop and fertilizer management practices namely, use of *neem* oil coated urea, growing of nutrient efficient genotypes, balanced nutrient application, adoption of preventive strategies and organic farming practices facilitated by the enabling policies can achieve 20-30% reduction in the fertilizer use. Ministry of Agriculture and Farmers Welfare, Government of India is making holistic efforts to ensure the balanced use of fertilizers for the major agricultural, horticultural, and medicinal crops. India has to put in place a well defined comprehensive system that enforces stringent policies on balanced fertilizer use, besides facilitating integrated nutrient management with locally available organic manures/crop residues and cultivation of efficient crop genotypes.

Key words: Fertilizer use, agriculture, soil health, environmental degradadtion, human health

Introduction

Agriculture is the livelihood source for around 50% human population of India. With 29 states and 7 Union Territories it is home to 2nd largest (1.38 billion) human population in the world. With the current levels of about 309 million tonnes (Mt) of food grain production (wheat & rice among major ones), country has to produce more than 400 Mt of food grains by 2050 to feed 1.68 billion people. India has one of the largest national agricultural systems in the world, comprising of 104 ICAR Institutes and 71 Agricultural Universities, hosts of Krishi Vigyan Kendras (KVKs), and numerous non-governmental and autonomous institutions. Independent India made strong strides, powered by Green Revolution in mid-1960s, increasing its food grain production by 5.6 times, horticultural crops by 10.5 times, fish by 16.8 times, milk by 10.4 times and eggs by 52.9 times during last seven decades. With current $ 2.1 trillion economy, country is the major exporter of raw cotton, wheat, rice, fruits, vegetables, spices, meat and chemicals; largest producer of milk, pulses and jute; second largest producer of rice, wheat, sugarcane, groundnut, vegetables, fruits and cotton; and is a leader in the production of spices, fish, poultry, livestock and plantation crops. Agriculture accounts for 23% of gross domestic product (GDP) and offers employment to 59% of the country's total workforce.

Fertilizer accounts for 50% increase in the country's food grain production. Fertilizer consumption in India increased by about 13 times during 1970 to 2020 (FAI, 2020; Bijay-Singh, 2016); fertilizer use remained skewed in favour of N. Disproportionately higher use of fertilizer nitrogen (N) increased loss of reactive N (Nr) to environment by about 5 times. Excessive use of two key nutrients, namely, N and phosphorus (P), has led to the alteration of N cycle, amplifying annual budget of Nr compounds from atmospheric dinitrogen (N_2), resulting in the reduced nitrogen use efficiency (NUE) of the Indian food system (30%) (Adhya et al., 2010). The fertilizer P use recovery is very low (15%) leading to the deposition of P unutilized by the plants in soil and loss to water bodies either through leaching down to groundwater or runoff to surface water

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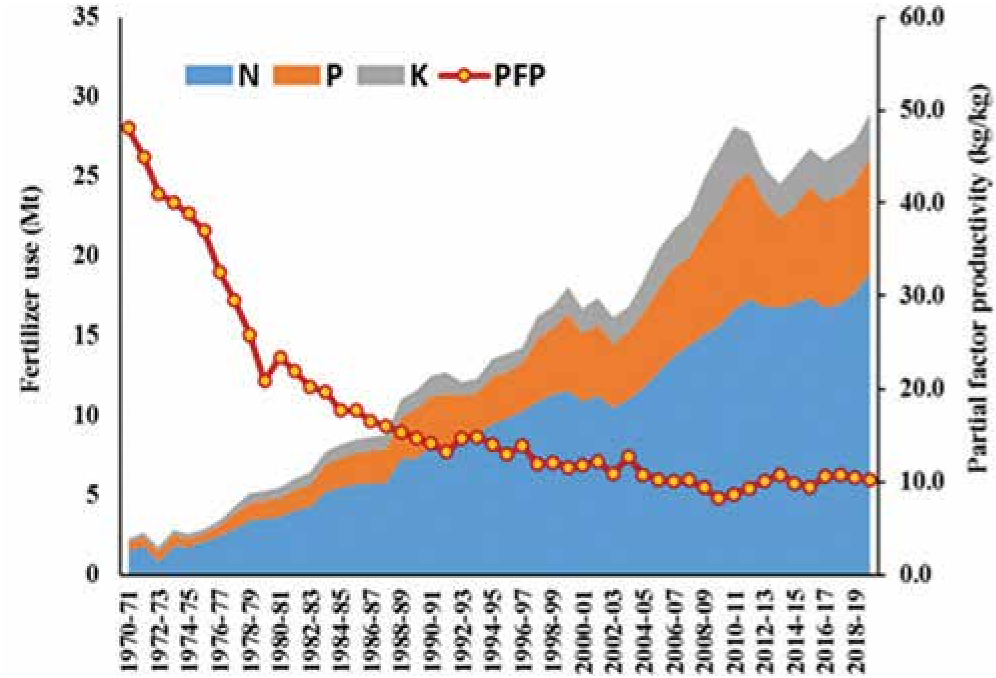

Figure 1. Use of NPK fertilizers and partial factor productivity after Green Revolution (Source : FAI, 2020)

bodies. Harmful effects associated with excessive use of N and P include soil and atmospheric pollution, eutrophication (a reduction in dissolved oxygen in water bodies caused by an increase of mineral and organic nutrients) of rivers and lakes, threat to biodiversity and the health of native plant species and natural habitats, formation and release of nitrous oxide (N_2O) – a highly harmful greenhouse gas (GHG), etc.

There is a need to i) regulate and optimize the use of fertilizers involved in food and horticultural production by incentivizing healthy and sustainable consumer choices, ii) model the crop management practices that reduce GHG emissions, iii) have balanced nutrient consumption, v) adopt ecosystem-based approaches, vi) and strengthen the policies which have minimal or negligible impact on animal/ human health and environment.

Fertilizer Consumption in India

Fertilizer manufacturing industry in India is second most important core sector after steel industry in terms investment, developments, quantity and the types of fertilizers produced, the technologies used, and the feedstock employed. With ushering into the Green Revolution era in mid-1960s through the introduction of fertilizer-responsive high-yielding varieties of rice and wheat, fertilizer consumption in India witnessed a spectacular rise. For example, nutrient consumption rose in 2019-20 to 28.97 million tonnes (Mt) against 2.26 Mt in 1970-71 (**Figure 1**). However, fertilizer use exhibited inter-state and inter-region variations. While the North and South zones had a consumption of more than 100 kg N + P_2O_5 + K_2O ha^{-1}, in the East and West zones the consumption was less than 80 kg ha^{-1}. Among the major states, the per-hectare consumption was more than 100 kg in West Bengal (122 kg), Haryana (167 kg), Punjab (184 kg), Uttar Pradesh and Uttarakhand (127 kg), Andhra Pradesh (138 kg) and Tamil Nadu (112 kg). In the remaining states, the consumption per hectare is lower was than the all-India average. The overall NPK consumption in India grew 11.84 times from 1970-71 to 2018-19. Consumption of fertilizer products increased from 50.6 Mt in the year 2009 to 61.4 Mt in 2020 with compound annual growth rate of 2.0%. However, the partial factor productivity (kg food grain produced per unit of fertilizer nutrient used) exhibited a decline from 28 kg kg^{-1} in 1970-71 to 10 kg kg^{-1} in 2019-20 (**Figure 1**). Total nutrient consumption (NPK) shot up from 2.26 Mt in 1970-71 to 28.97 Mt in 2019-20, while food grain production during the corresponding period increased from 108.4 Mt to 297.5 Mt. In terms of total fertilizer nutrient consumption ($N+P_2O_5+K_2O$), India ranks second in the world with 28.97 Mt, next only to China (52.50 Mt).

However, per hectare consumption of fertilizer in

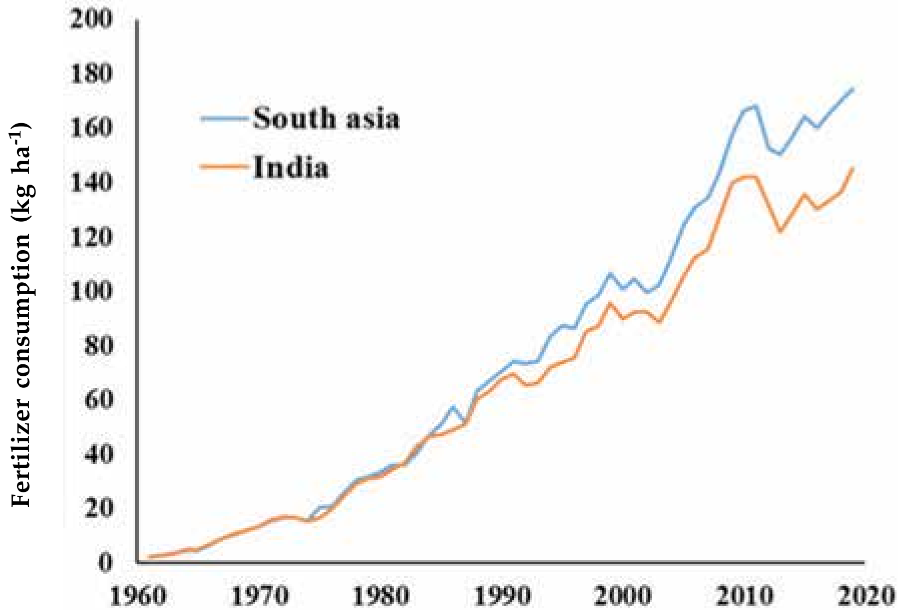

Figure 2. Comparison of per hectare average fertilizer nutrients (NPK) consumption in India and South Asia (Adapted from World Fertilizer Trends and Outlook, FAO, 2020)

India is relatively low when compared to many other countries, including our neighborhood countries (**Figure 2**). The current average fertilizer nutrients ($N+P_2O_5+K_2O$) use per hectare in SAARC countries in 2019-20 was much higher (~174 kg ha^{-1}) than India (~145 kg ha^{-1}) (FAI, 2020; FAO, 2020). Fertilizer use pattern is highly skewed towards N consumption. Fertilizer-N consumption in India during 1970 to 2020 increased by about 13 times, whereas the crop N uptake increased by 4 times, leading to 5 times more loss of reactive N. In addition to application through N-containing fertilizers, N inputs also accrue through the biological N-fixation (BNF) process. As per the conservative estimates, N contribution through BNF in Indian agriculture varies from 5.20 Tg N to 5.76 Tg N, making roughly 9.5%-10.6% of the global agricultural BNF, with cereals contributing 32% and grain legumes accounting for 43%. Phosphorus consumption in India increased from 0.54 Mt during 1970-71 to 1.21 Mt during 1980-81, 3.22 Mt in 1990-91, 4.80 Mt in 2000-01, 7.28 Mt in 2010-11 and 7.50 Mt in 2019-20. Thus, P consumption recorded more than 14 times increase during 40 years (1970-71 to 2010-11). Consumption of K which was very meagre at 0.24 Mt in 1970-71 increased 11-fold to 2.64 Mt in 2019-20.

Policy Framework for Optimum Use of Fertilizers

In India, fertilizer was brought under Essential Commodities Act 1955 and Government of India (GoI) regulated the sale, price, and quality of fertilizers under Fertiliser (Control) Order (FCO) 1957, which was revised several times till 1985. Revised version is known as Fertiliser (Control) Order 1985. Urea is the only controlled fertilizer, which is sold at the statutory notified uniform sale price. The phosphatic (P) and potassic (K) fertilizes are decontrolled and are sold at indicative maximum retail prices (MRPs). The most important factors which influence fertilizer use are prevailing fertilizer price policy and various subsidy schemes implemented by GoI. Five major historical policy decisions which guided the fertilizer use in the country included: i) Retention Price Scheme (RPS) (Marathe Committee) (cost plus pricing subject to some efficiency norms)-1977; ii) Economic Reforms and Joint Parliamentary Committee (JPC) during 1991-92 and decontrol of P&K fertilizers as on 25th August 1992; iii) Expenditure Reforms Commission (Geethakrish-nan Committee)-2000 and group based new pricing scheme for urea in 2003; iv) Nutrient Based Subsidy (NBS)-for P&K fertilizers in 2010 -selective implementation of the scheme on 2010; and v) Promotion of *neem* coated urea-2015 **(Table 1)**. The NPK use ratios are also given in the Table. The cheaper price of fertilizer N and government subsidy have rendered fertilizer use highly skewed in favour of N across the length and breadth of the country. Abolition of retention price-cum-subsidy scheme on P&K fertilizers and their decontrol in 1992 severely distorted the NPK ratio to 9.5:3.2:1in 1992-93 as compared to 5.9:2.4:1 in 1991-92. Further, India announced the nutrient-based subsidy policy in 2010 to ensure application of fertilizers in a balanced approach; however, selective implementation of the scheme on P and K fertilizers led to a decrease in their use. The immediate effect of NBS was a sharp rise in prices of P and K fertilizers, which increased on an average from 10,000 t^{-1} before the introduction of NBS

Table 1. Fertilizer policy induced changes in ratio of NPK use in India

Fertilizer scheme	Year	$N:P_2O_5:K_2O$ ratio
Before RPS	1976	7.7:2.0:1
Retention price cum subsidy scheme (RPS) on all fertilizers	1977	5.8:1.9:1
Before decontrol of P&K fertilizers	1991	5.9:2.4:1
Abolition of RPS on P and K fertilizers and their decontrol	1992	9.5:3.2:1
Before uniform MRP of P&K fertilizers	1996	10.0:2.9:1
Uniform MRPs of P&K fertilizers (except SSP)	1997	7.9:2.9:1
Group based new pricing scheme for urea, 25% and 50% ECA allocation	2003	6.1:2.2:1
Before NBS scheme on P&K fertilizers	2009	4.3:2.0:1
NBS scheme and price decontrol on P and K fertilizers	2010	4.7:2.3:1
After NBS scheme	2013	8.2:3.2:1
Introduction of *neem* coated urea	2015	7.0:2.7:1
After *neem* coated urea	2016	6.7:2.7:1

Note: RPS- retention price cum subsidy scheme, GoI – Government of India, NBS-nutrient based subsidy.

to Rs. 25,000 t^{-1} in 2013. The immediate outcome of this was a sharp decline in the use of P and K fertilizers and disproportionately larger increase in the urea-N consumption at the cost of P&K fertilizers.

Although urea prices remained administered, the surge in sale for urea meant that there had been more demand by the farmers because of disparity in MRP of urea *viz-a-vis* P&K fertilizers. As a result, NPK ratio distorted from 4.3:2.0:1 in 2009-10 to 8.2:3.2:1 in 2012-13. Government directive on 100% urea coating with *neem* oil (NOCU) had positive impact on fertilizer N use efficiency; consumption of fertilizer N remained constant till 2018-19 with NPK ratio of 6.6:2.6:1 (FAI, 2020). As against the ideal ratio of 4:2:1 (approximately 57% of N, 29% of P and 14% of K), the actual ratio has always been distorted due to fluctuations in fertilizer policies. As a result, NPK use changed to 68.4, 23.0 and 8.6% in 2013-14 and 65.1, 25.8 and 9.1% in 2019-20 as against 58.9, 28.6 and 12.5% in 2010-11 (**Figure 3**). Inappropriate fertilizer use leads to deterioration of soil health, degradation of environmental quality, and strain on the country's economy caused by the burgeoning fertilizer subsidy bill. Biggest challenge is to change the fertilizer use pattern, which involves not only revamping and re-energizing the extension services but also changing the NBS suitably to remove the price distortion caused by it. Since fertilizer prices follow the trends of prevailing international petroleum prices, the only way to reduce the subsidy bill is to reduce the dependence on imports and increase the domestic production. While rationalizing fertilizer subsidy across nutrients may be the short-term but the need of the hour is to have a policy framework that incentivizes domestic production of fertilizers.

Types of Fertilizers Used in Agricultural Production Systems

Currently, an array of fertilizer products are being used to grow crops to produce enough food to feed the burgeoning human population. Urea, ammonium sulphate (AS)/ammonium chloride (ACl) diammonium phosphate (DAP), single superphosphate (SSP), muriate of potash (MoP), NP/NPK complex fertilizers dominate the Indian market

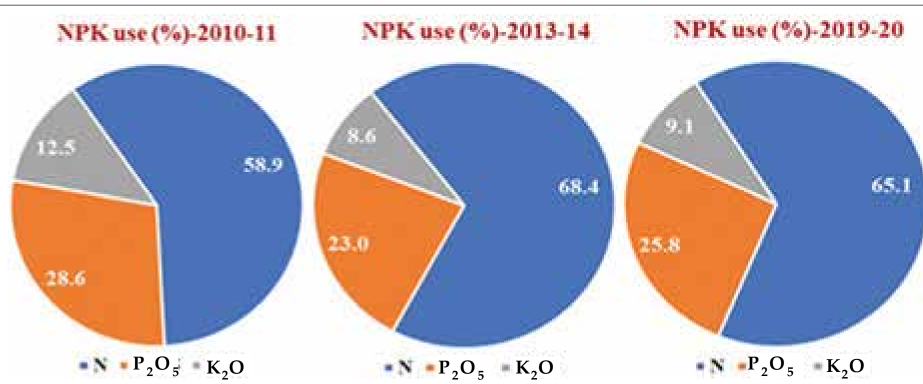

Figure 3. Relative changes in NPK use over the years due to implementation of price decontrol and nutrient based subsidy scheme (Source : FAO, 2020)

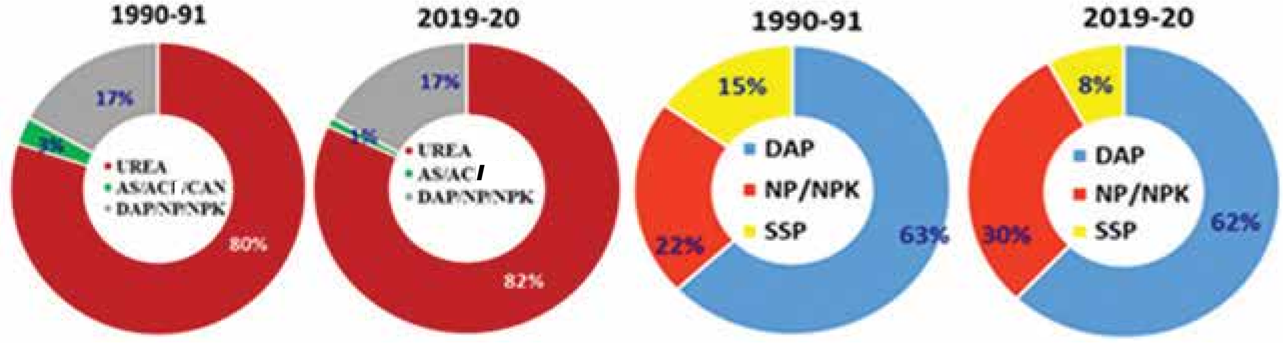

Figure 4. Share of N and P containing fertilizer products in total consumption (Soruce : FAI, 2020)

as carriers of N P and K. In 2019-20, the total nutrient ($N+P_2O_5+K_2O$) consumption was 28.97 Mt; with individual consumption of N, P_2O_5 and K_2O being 18.86, 7.46 and 2.64 MT, respectively (FAI, 2020).

Supply of individual nutrients has been highly skewed in favour of urea and DAP. Of the total fertilizer products consumed in Indian agriculture during 2019-20, the share of urea at 54.6% was highest followed by DAP (16.5%), NP/NPK (15.5%), SSP (6.9%), MoP (4.6 %), and AS/ACl (1.4%), respectively (FAI, 2020). Share of consumption of micronutrient-containing products to the total fertilizer products was very little (<0.50%). Urea has been the major N fertilizer consumed in India; its share to total N fertilizer supply was 82% during 2019-20 against 80% in 1990-91 (**Figure 4**). Diammonium phosphate has been the most preferred P source. Share of NP/NPK complex fertilizer to P nutrition increased from 22% in 1990-91 to 30% in 2019-20, while supply of P through SSP decreased from 15% to 8% during the same period. Other straight N fertilizers, such as AS, and ACl account for less than 2%. Use of high analysis fertilizers like DAP, urea and MOP, devoid of sulphur (S) and micronutrients, has led to emergence of secondary and micronutrient deficiencies in the country. Out of the total fertilizer nutrients applied in Indian agriculture, 67.1% goes to food crops followed by 9.6% to oilseed crops, 8.7% to cotton, 5.6% to sugarcane, 3.1% to vegetables and only 2.0% to fruit crops (**Figure 5**). As per recent estimates on micronutrients consumption, the use of zinc sulphate fertilizer was the highest at 1,89,579 t followed by iron sulphate (38,624 t), boric acid/borax (27,166 t), manganese sulphate (17,241 t) and copper sulphate (4,564 t) during 2020-21 (FAI, 2021). Of the total zinc (Zn) used, 70% goes to the field crops and remaining 30% finds use in vegetable and fruit crops, while the reverse is true for manganese (Mn), iron (Fe) and copper (Cu). Of the total borax fertilizer used, about 60% goes to vegetable and fruit crops and the remaining 40% is consumed by food and oilseed crops (Shukla et al., 2021).

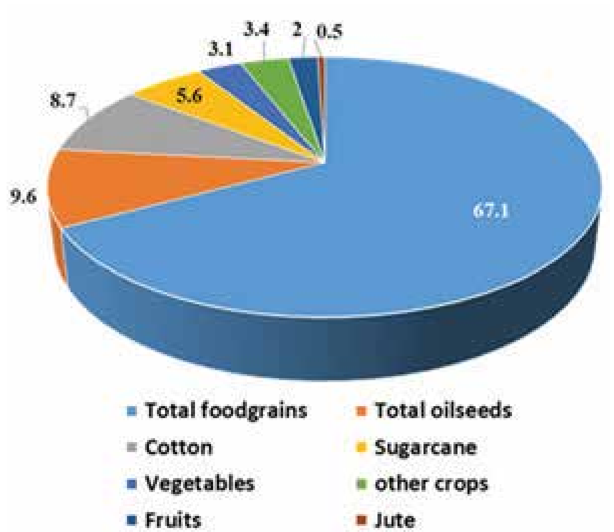

Figure 5. Share of usage of fertilizer NPK by different crops (Source : FAI, 2020)

Best Management Practices for Fertilizers

In addition to weather, cultivars, spacing, crop rotation, tillage practices, now famous 4Rs (method, rate, time and source) involved in fertilizer application have direct bearing on utilization of applied nutrients by the crops (Majumdar et al., 2014). Efficient nutrient management is a must to minimize the loss/leakage of applied nutrients from the soil-plant system to the environment. Enhancing recovery efficiency of applied N (which continues to be low at 30-50% by the first crop) continues to pose major challenge. Rest of the applied N either remains in the soil, the recovery of which in the following crops is very limited, or escapes from the soil-plant system, causing serious disruptions in ecosystem functions (Ladha et al., 2005). Large number of best management practices (BMP) have been developed for optimum use of nutrients by enhancing nutrient use efficiency (NUE) and reducing the losses across the country.

Some of the important BMPs are summarized as under:

(1) Balanced fertilization using fertilizer nutrients as

per soil test and crop response function is first and foremost BMP. Agronomic efficiency parameters measured in different cropping systems are higher under balanced NPK fertilization. Such an improvement in NUE is attributed to the increased indigenous nutrient supplying capacity of soil under balanced NPK fertilization (Yadav, 2001).

(2) Promotion of the micronutrient application in adequate amounts guided by the existing deficiency status. Application of micronutrients not only ensures improved use efficiency of major nutrients like NPK, but also improves the micronutrient content in the edible plant parts, which helps in combating micronutrient malnutrition in the country.

(3) Integrated plant nutrient supply (IPNS) involving conjoint use of different nutrient sources is a sustainable strategy for realization of high yields, restoration of soil health, and improvement in fertilizer use efficiency as a whole (including NUE). Important ingredients of IPNS, namely fertilizers, organic manures, green manures, crop residues (CRs), industrial wastes and by-products, sewage-sludge, and bio-fertilizers have to be used in balanced, judicious and effective manner.

(4) *In situ* burning of crop residues by farmers in North-West India causes serious environmental implications besides causing loss of nutrients. Conservation agriculture (CA) has the potential to make available about 141 Mt of cereal residues for nutrient cycling and soil health improvement.

(5) Site-specific and precision nutrient management refers to management strategies which encourage better utilization of applied nutrients, enhance the NUE, and minimize N losses to the environment. Use of leaf colour chart (LCC), chlorophyll meter for synchronizing N application with crop N requirement, and use of micronutrients kriged maps of 640 districts prepared by ICAR-All India Coordinated Research Project on Micronutrients offer important tools to execute site-specific nutrient management and precision nutrient management at a mega scale. Fertilizer N application guided by the critical LCC values have helped in optimizing the grain yield and enhancing the NUE of rice and wheat crops. Considering AEN of 20 kg kg^{-1} N and REN of 50% as optimum NUE for rice, LCC ≤3 for Basmati, LCC ≤4 for inbred (Saket 4), and LCC ≤5 for hybrid (PHB 71) rice were evolved as the standard values (Shukla et al., 2004). Fertilizer N-scheduling based on LCC proved to be superior to conventional practice, *i.e.*, application of 120 kg N ha^{-1} in three-splits (Bijay-Singh et al., 2003; Shukla et al., 2004). In certain cases, even a saving of fertilizer N (up to 30 kg N ha^{-1}) was recorded with the use of LCC.

(6) Inclusion of legume-based crop rotation in existing cropping pattern helped in restoring atmospheric N lost through denitrification or other processes.

(7) The nutrient use efficiency could be optimized by bringing in precision management following '4R' principle, which implies right fertilizer source, right rate, right time, and right method of placement. The application of fertilizer as per 4R principle, enhanced the fertilizer nutrient recovery efficiencies (RENs) in researcher-managed experiments for major grain crops to the range from 46% to 65% against the on-farm RENs of 30-40%.

Adverse Impacts of Fertilizer Use on Soil, Water, Environment, Food Chain and Human Health

Heavy Metal Accumulation

Some mineral/chemical fertilizers contain heavy metals and even radionuclides, albeit in low quantities, and their excessive use in agriculture has a potential of creating environmental problems. Heavy metal contents in fertilizers and FYM used in India are given in **Table 2**. Perusal of data shows that the heavy metal impurities are more in SSP, DAP and FYM as compared to urea and MOP. The fertilizer samples contain heavy metals as impurities, which vary in different grades

Table 2. Average heavy metal content (mg kg^{-1}) in different fertilizers and FYM used in India (Source: Adhikari et al., 2019)

Fertilizer/Manures	Pb	Cr	Ni	Cd	Co
Single super phosphate	10.84 ± 3.6	11.13 ± 6.6	9.75 ± 1.8	14.1 ± 5.7	4.06 ± 1.0
Diammonium phosphate	8.16 ± 2.6	13.02 ± 1.9	14.76 ± 7.7	6.29 ± 2.9	8.16 ± 9.0
Urea	1.76 ± 1.8	2.81 ± 1.0	2.65 ± 1.0	0.25 ± 0.2	0.16 ± 0.1
Farmyard manure	8.93 ± 1.5	10.10 ± 7.0	23.60 ± 7.9	0.75 ± 0.4	8.81 ± 3.8
Muriate of potash	2.41 ± 2.6	6.09 ± 1.7	6.12 ± 4.9	0.22 ± 0.2	0.80 ± 0.4
Zinc sulphate	7.13 ± 2.1	8.21 ± 3.1	9.76 ± 3.7	0.61 ± 0.1	2.56 ± 2.1

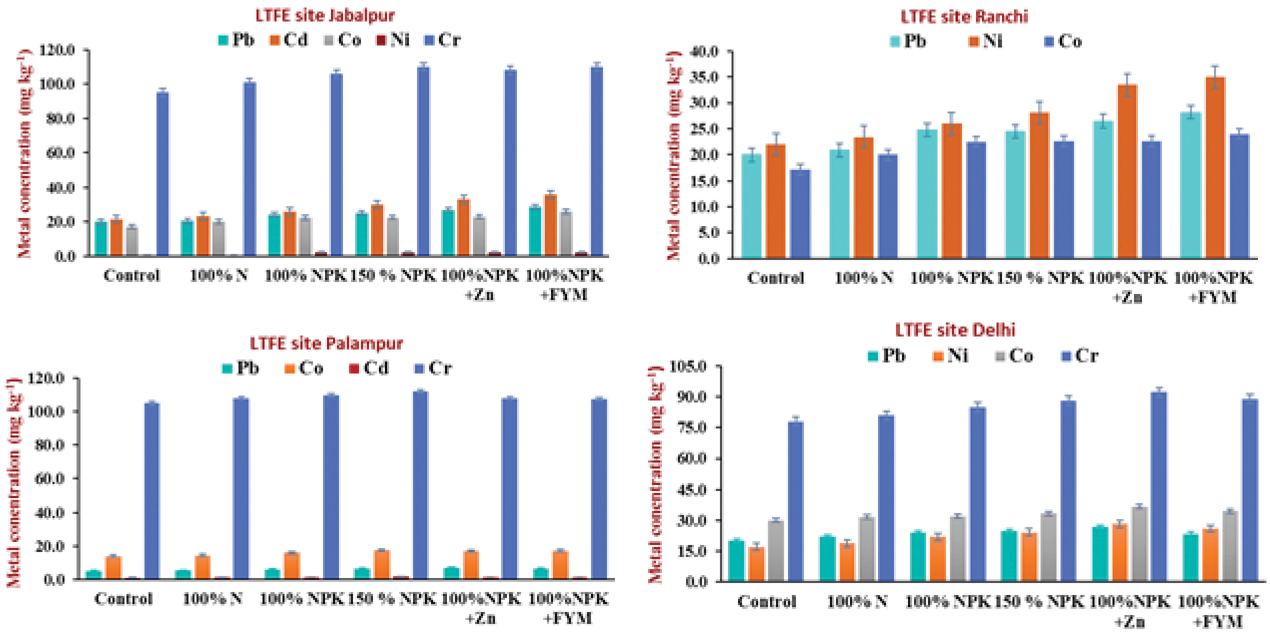

Figure 6. Total heavy metal concentration (mg kg^{-1}) in top soils (0-15 cm) after 35 years of long-term fertilizer experiment at Jabalpur, Ranchi, Palampur and Delhi sites (Source: Adhikari et al., 2019).

of fertilizer depending upon the raw material used for manufacturing. Organic fertilizers especially FYM contain heavy metals, found in complexes with the functional groups such as carboxylic and phenolic groups. When applied to the soils, heavy metals form complexes or chelates with different functional groups and get absorbed by the plants.

Long-term fertilizer experiments (LTFE) of India, which received regularly fertilizers for many decades serve as the ideal sites for monitoring buildup of the heavy metals added through them. Soil and plant samples were monitored for the accumulation of these metals. Results presented in **Figure 6** did not show any specific pattern/trends of heavy metal accumulation/status in the soils after 35 years of continuous application of fertilizers under different treatment combinations. In general, accumulation of chromium (Cr) and cadmium (Cd) was much higher than lead (Pb), nickel (Ni) and cobalt (Co) (**Figure 6**). Use of phosphatic fertilizers like, DAP and SSP and organic manures have been identified as the major products responsible for increase in the heavy metal contents in the soil. Phosphate rock used as raw material in manufacture of phosphatic fertilizers contain lot of impurities in the form of heavy metals. At Ludhiana, Cr was recorded in the FYM-amended plot. Since FYM is an output of animal dung which is fed on fodder probably grown on soil contaminated with Cr, this could be the route of its entry into the soil. Currently, the contents of heavy metals at all the LTFE centers are far below the safe limits reported in literature. However, continuous application of the metal-rich fertilizer sources may become deleterious for crop growth in future. Higher accumulation of heavy metals was recorded in rice, wheat and soybean at the LTFE sites at Barrackpore and Jabalpur. Straw recorded higher metal accumulation than the grains (**Figure 7**). At Barrackpore, the increase in Cr and Ni content was more in rice grain and Cd was higher in rice straw. Increase in the heavy metals content was more in treatment receiving 150% recommended dose of fertilizer than 100% NPK + FYM. Soybean grown at Jabalpur showed higher accumulation of Pb and Ni as compared to other metals (Adhikari et al., 2019). Long-term studies have shown that the continuous application of fertilizers and manures in excessive amounts may cause buildup of heavy metals in the soils and plants (Singh et al., 2019). Presence of the heavy metals in excessive amounts is deleterious and matter of concern because of their ability to accumulate in soils and bioaccumulate in plants and animals (Brigden et al., 2002).

Nitrate Pollution

Rise in nitrate-linked groundwater pollution is being reported in India. Excessive use of urea has been cited as one of the major factors for the increase in nitrate (NO_3^-) levels in drinking waters and river systems. The water quality assessment studies carried out in 17 Indian States by NEERI showed that out of 4,696 water samples analyzed, the NO_3^- levels in 1,290 samples (27%) exceeded the WHO drinking water

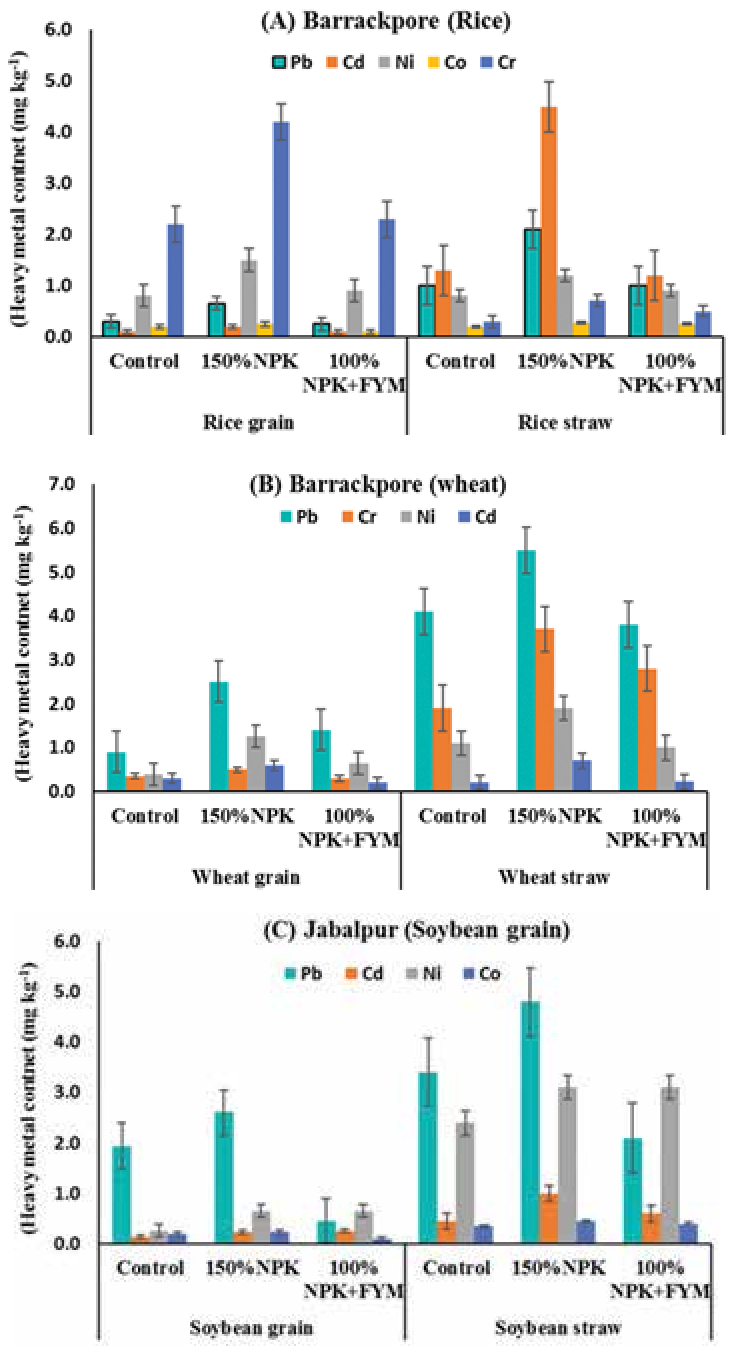

Figure 7. Heavy metal concentrations in rice (A), wheat (B) and soybean (C) grain after 35 years of experiments at Barrackpore and Jabalpur sites under LTFE (Source: Adhikari et al, 2019).

standards. Analysis of ground water in agricultural districts of Srikakulam in Andhra Pradesh located in Vamsadhara river basin revealed that the nitrate concentrations in the samples ranged from traces to 450 mg NO_3^- L^{-1}. Increase in the nitrate concentrations was observed following the fertilizer applications (Rao, 2006). Present consequences of nitrate pollution of freshwaters in India are a sad reflection on the legacies of excessive applications of fertilizers and manures of the past and continuing unabated currently. Nitrate-N (NO_3^-N) content in the groundwater in Punjab exhibited a consistently rising trend from 1975 (when the samples were analyzed for the first time) onwards (Bijay-Singh et al, 1995). Using data generated by reconnaissance of nitrate content in shallow ground waters, the Central Ground Water Board of India categorized Punjab region as the high-risk zone with respect to nitrate pollution of groundwater. Using a remote sensing and GIS approach based on data pertaining to fertilizer use,

Table 3. Nitrate and phosphate content in Sutlej River at three different sites in Punjab

Location	Season	NO_3 (mg L^{-1})	PO_4 (mg L^{-1})
Ropar head works	Winter	0.32 – 0.43	0.10 – 0.20
	Summer	0.40 – 0.62	0.22 – 0.27
	Post-monsoon	0.53 – 0.82	0.20 – 0.32
Budha Nullah at Phillaur	Winter	0.38 – 0.62	0.21 – 0.31
	Summer	0.80 – 1.05	0.33 – 0.50
	Post-monsoon	0.82 – 1.26	0.33 – 0.57
Budha Nullah at Wallipur	Winter	0.80 – 1.30	0.52 – 0.70
	Summer	1.10 – 1.35	0.67 – 0.98
	Post-monsoon	1-16 – 1.62	0.76 – 1.10

soil properties and rainfall at 1 km^2 grid size, and N loss coefficients, derived from published N dynamics studies, Chhabra et al. (2010) reported that about 29% of the fertilizer N applied to rice is lost as nitrate in the coarse textured soils of Punjab. The weighted average nitrate-N loss via leaching in Punjab was estimated to be more than 50 kg ha^{-1} $year^{-1}$.

Pollution in Water Bodies

Phosphate content in the drinking water and rivers may rise as a result of the transport of applied phosphatic fertilizers with the surface water flow. Accumulation of NO_3^--N in the soil leads to higher NO_3^- uptake by the plants whose accumulation in leafy vegetables like lettuce and spinach leads to the formation of carcinogenic substances such as nitrosamines. Future researches need to concentrate on improving water and fertilizer management in agroecosystems, which can reduce the contribution of fertilizers to nitrate pollution of water bodies (Sattar et al, 2014). Of course, a host of other factors also determine the magnitude of fertilizer-related pollution. Study conducted on nutrient loads exported by rivers to coastal waters in Bay of Bengal Large Marine Ecosystem (BOB LME) in 2000 revealed that rivers exported 7.1 Tg N and 1.5 Tg P to the BOB LME. Three rivers (Ganges, Godavari, Irrawaddy) accounted for 75–80% of the total river export of N and P. It was simulated that the river export of N may increase to 8.6 Tg by 2050 (Pedde et al., 2017). The increased load in BOB LME led to the changes in nutrient stoichiometry (Tripathy et al., 2005) and, as a consequence, there occurred the harmful non-siliceous algal blooms (Garnier et al., 2010). Rise in the dissolved N and P loads is connected mainly with the increased N and P losses from agriculture and sewage systems. Reduction in the export of particulate N and P is associated with damming of rivers and increased human water consumption. Large differences, however, exist in nutrient exports across the rivers. Rivers draining into the western BOB LME generally export more N and P than do the eastern BOB LME rivers (Pedde et al., 2017).

Concentrations of nitrates and phosphates in some inland waters of ponds, lakes, and rivers in the country exhibit significant variations (Vass et al., 2015). Higher concentrations of N and P in lake and groundwater and channel waters (1.87 to 6.79 mg L^{-1}) were reported in western Uttar Pradesh, and Mysuru district, Karnataka due to the application of high levels of N and P fertilizers. Nitrate concentrations were high enough to damage the fish in Karnataka. Camargo et al. (2005) reported that the 50 mg NO_3^- L^{-1} (WHO safe limit fixed for drinking water by humans) can adversely affect the freshwater invertebrates upon their long-term exposures.

Phosphate concentration in waters of north-western rivers [Ravi (0.17 – 0.20 mg L^{-1}), Sutlej (0.12 – 0.15 mg L^{-1}), Beas (0.18 – 0.29 mg L^{-1})] is much higher as compared to the waters of rivers of eastern [Brahmaputra (Tr - 0.02 mg L^{-1}), Damodar (Tr - 0.35 mg L^{-1}), Brahmani (Tr - 0.03 mg L^{-1}), and Mahanadi (Tr - 0.001 mg L^{-1})], western [Narmada (Tr - 0.10 mg L^{-1})], or southern India [Godavari (0.06 – 0.18 mg L^{-1}), Krishna (0.04 – 0.30 mg L^{-1}) and Cauvery (0.02 – 0.94 mg L^{-1})]. Jindal and Sharma (2011) reported that the higher concentrations of nitrates and phosphates in water at three points of Sutlej River in Punjab were due to inflow of Buddha Nullah at Wallipur which contained industrial effluents rich in nitrates and phosphates, a point near the industrial area of Ludhiana (**Table 3**).

Phosphate concentrations increased over a period of 36 years (1960–1996), indicating the increased P pollution of the river water. Variations in phosphate concentration in river Ganges at Haridwar, Kanpur, Prayagraj, Varanasi and Patna clearly demonstrated the role of industrial effluents, which was the highest at Kanpur (0.07 – 0.21, 0.01 – 2.10 and Tr – 2.50 mg L^{-1} during 1960, 1980 and 1996, respectively), the most industrialized town on river Ganges while it was nil at Haridwar which does not have any major industry (Vass et al., 2015). In another study, Tiwari et al. (2016) revealed that both the nitrate and phosphate levels

Table 4. Nitrate and phosphate concentration in Ganges River water at three locations

Location	Quality parameter	Summer	Monsoon season	Winter
Kanpur	Nitrate (mg L^{-1})	1.70	0.45	0.94
	Phosphate (mg L^{-1})	1.58	0.66	0.82
Allahabad	Nitrate (mg L^{-1})	1.50	1.40	0.23
	Phosphate (mg L^{-1})	1.50	0.63	0.78
Varanasi	Nitrate (mg L^{-1})	2.60	2.40	2.10
	Phosphate (mg L^{-1})	1.42	1.11	1.37

were highest at Varanasi (**Table 4**). As per limit prescribed by MPCA (2007), total phosphorus levels above 100 ppb (0.1 mg P L^{-1}) may cause eutrophication. Thus, as per available data on P concentration, the inland waters in India may be highly eutrophic. Moreover, N: P ratio in most Indian inland waters being less than 10, may influence the possibility of developing phytoplankton 'Bloomers', leading to fish mortality.

Greenhouse Gases (GHGs)

While on one hand, accelerated use of agrochemicals in modern intensive agriculture made the country food secure, it created several negative impacts on environmental quality and human and animal health (Abrol and Adhya, 2017). Current consumption of fertilizer N in India is about 18 Mt (14% of the global total N). Agroecosystem is the largest consumer of fertilizer-N. Cereals consume the highest proportion of fertilizer-N. But because of poor crop N use efficiency (<35%) in cereals, >65% of applied N is being lost to the environment (**Figure 8**). Contribution of N loss from horticultural crops is less than the agricultural crops; however, the modern high intensity horticultural production systems also cause outflow of substantial volume of reactive N (Nr) into the environment. Rising trends in nitrate concentrations in surface and groundwaters have been observed in the intensively cultivated states of Haryana, Punjab, Uttar Pradesh, Maharashtra, Karnataka and Andhra Pradesh due to enhanced mobilization of N through cultivation, animal husbandry, and industrial and domestic discharges of wastewaters. Overexploitation of groundwater has exacerbated the deterioration of the groundwater quality, thus impacting the ecosystem services including animal and human health. Nitrous oxide (N_2O) - an important greenhouse gas (GHG) which is 300 times more lethal than CO_2 - has several negative impacts on human health and ecosystem services. Oxides of nitrogen (NOx) and ammonia (NH_3) are important sources which influence the radiation

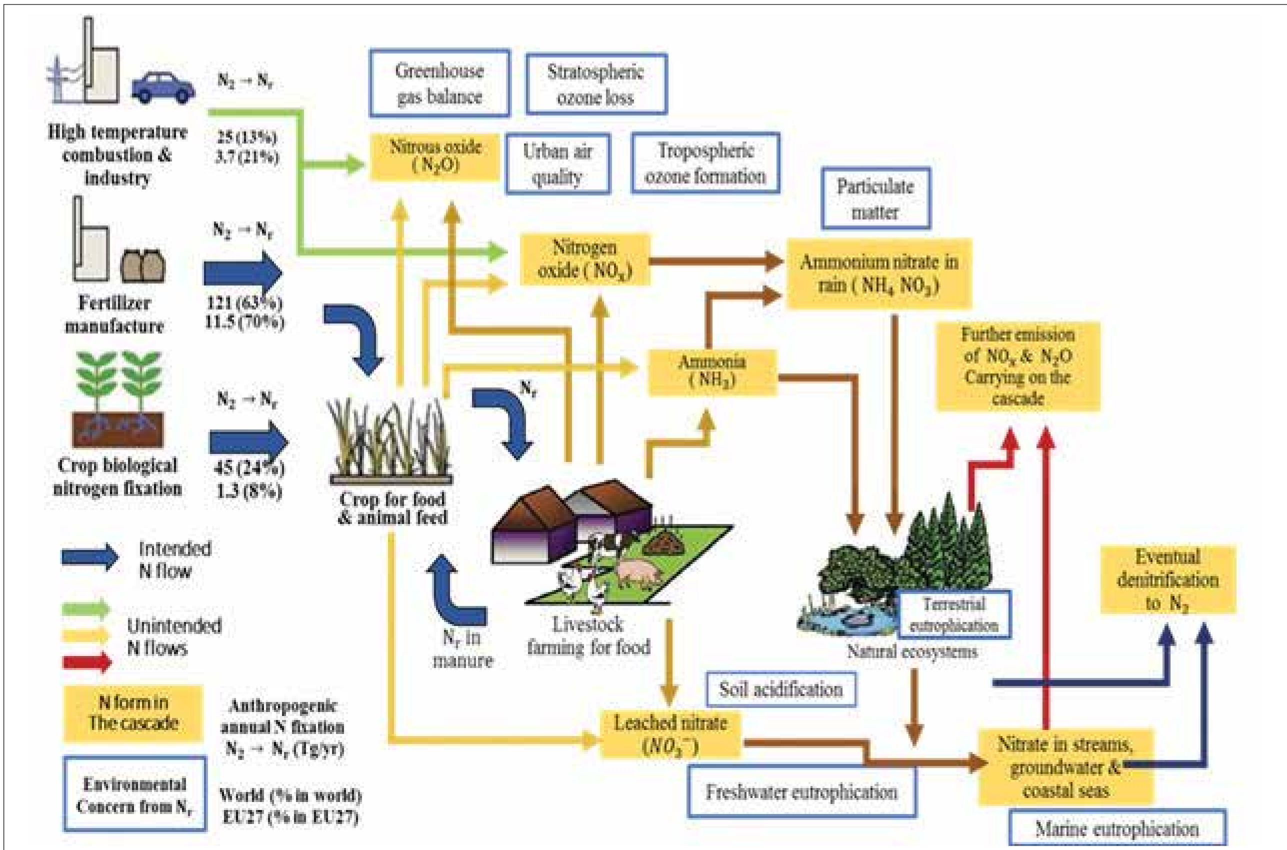

Figure 8. Global N cycle depicting N losses, fixation of N_2 to Nr and the dissipation of energy as Nr is eventually denitrified back to N_2 (Adopted from Sutton et al., 2017).

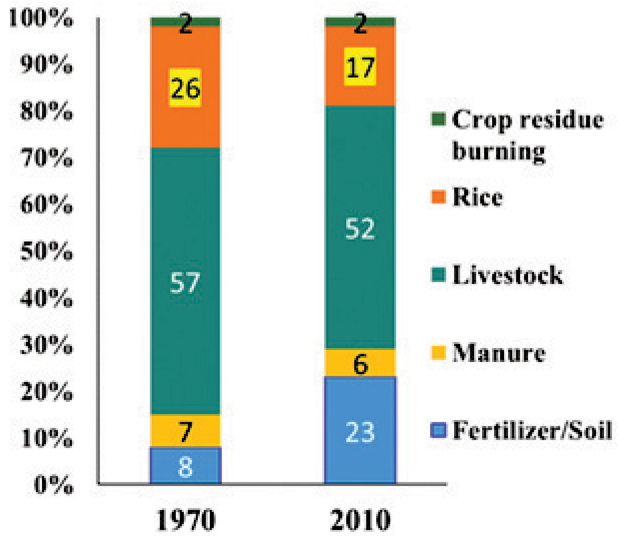

Figure 9. Relative contribution (%) of different sources of greenhouse gases in Indian agriculture in 1970 and 2010 (Source: Pathak et al., 2014)

budget of the atmosphere through O_3 formation and oxidation capacity of the atmosphere through release of hydroxyls (-OH) and nitrates. Nitrogen losses in rice field through NH_3 volatilization are higher under the surface broadcasting of N fertilizers, thus causing reduction in the NUE (Ladha et al., 2005). Emissions of nitrogen oxides (NOx) from combustion sources are increasing rapidly at 6.5% year^{-1} currently. By comparison, population growth rate is lower (2% year^{-1}), while ammonia (NH_3) emission increase is even less (1%) due to smaller changes in livestock numbers. At current rate, Indian NOx emissions will exceed NH_3 emissions by 2055. In addition to fertilizer N, the livestock sector, particularly cattle (56.1%) and buffaloes, contributes the largest amount of Nr in the form of ammonia. Scenario is becoming quite alarming with the growth of poultry industry, which has current annual growth rate of 6% and is expected to contribute 1.089 Mt of reactive N by 2030. India is currently losing Nr worth US$ 10 billion year^{-1} in terms of fertilizer value, while costs of Nr to health, ecosystems, and climate are estimated at US$ 75 (38-151) billion year^{-1}. Relative contribution of fertilizer N application to total GHG emission increased from 8% in 1970 to 23% in 2010 (**Figure 9**). The GHG contribution from rice field decreased from 26% to 17% during same period due to promotion of direct seeded rice in contrast to puddled rice (Pathak et al., 2014).

The Nr leakage tends to be higher in the major river basins of the country having extensive economic and agricultural activities and bearing the burden of high population pressure. The vast portion of coastal areas along Indian coastline is experiencing ecological damage due to inflow of extensive inputs of Nr from river system as well as other enhanced anthropogenic activities near the seashore. Nitrogen assessment (NO_2 and NO_3 form) of surface waters carried out in the Indian exclusive economic zones and the adjoining areas of seashore during the years 1998-2007 revealed that the annual concentrations of NO_2 in the Andaman Sea, Bay of Bengal and Arabian Sea ranged from 0 to 0.7 mM, 0 to 0.6 mM, and 0 to 0.4 mM, respectively. Accordingly, the NO_3 concentrations varied from 0 to 3.5 mM, 0 to 3.0 mM, and 0-2.5 mM.

Even though BNF is environmentally-benign source of N, this also leads to the production of Nr, albeit to a lesser extent. Besides the economic development, societal demands for increased energy, transport has caused massive transformations in structure and functions of nitrogen cycling during the last five decades. This huge anthropological development has made N cycling the most perturbed biogeochemical cycle. Substantial increase in Nr and its loss to aero-geo-biological system has overcast disastrous consequences both to the environment and ecological balance, like eutrophication, atmospheric N deposition, biodiversity loss, and other ecosystem services. The major challenge for India is to harness Nr efficiently as a source of fertilizer-N, because its current inefficient use is putting huge burden to the country's exchequer in the form of subsidy as well as environmental degradation associated adverse climate and animal/human health consequences.

Soil Acidity

Abundant amount of ammonia present in the atmosphere regulates the atmospheric acidity. It forms part of atmospheric aerosols, which get deposited to soil through rains and its oxidation releases acidic compounds and creates the soil acidity. Soil pH is an intrinsic property determined by the exchangeable cations on clay surface and takes long time to change. In addition to these atmospheric depositions, the excessive use of inorganic fertilizer leads to the generation of Nr, major source for the environmental damage. Major negative impact of Nr depositions on soil quality is soil acidification. Long-term fertilizer experiment conducted at Punjab Agricultural University (PAU), Ludhiana, India revealed that soil acidity increased significantly under 100% NPK (pH 7.39) and 150% NPK (pH 7.25) treated plots as compared to non-treated control (7.90) after 36 years of manuring and fertilization of maize-wheat cropping system (Brar et al., 2015). Further, excessive application of N fertilizers has a potential of impairing the soil health via soil carbon degradation and affecting adversely the structure and function of soil biological communities.

Long-term application of N-fertilizer alone over the years caused significant reduction in soil pH at different experimental sites of India (**Figure 10**). Changes were more drastic in Alfisols of Bengaluru, Palampur, and Ranchi. However, the effects of fertilizer at Bhubaneshwar and Pattambi sites were

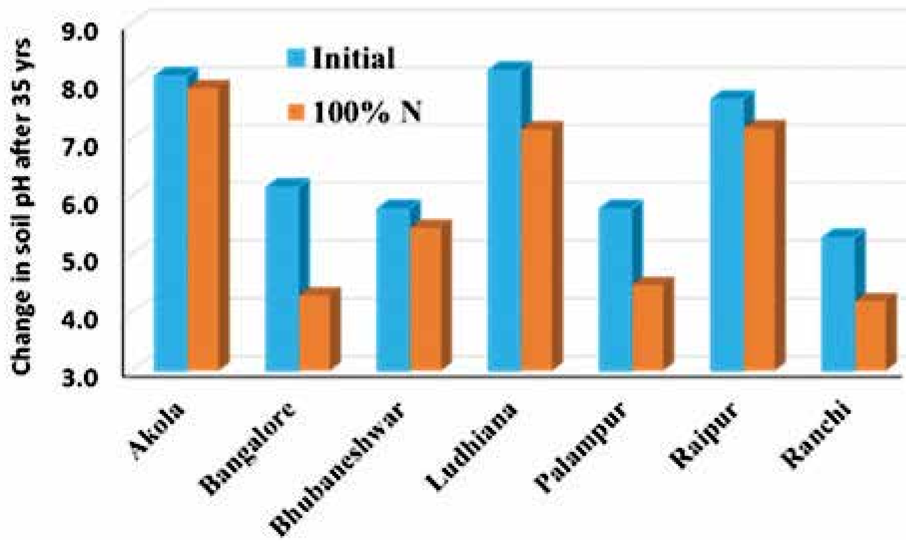

Figure 10. Decrease in soil pH due to continuous application of fertilizer N for 35 years (Source: Brar et al., 2015)

of relatively lower magnitude, because at both the places rice-rice is grown under submerged conditions and soil pH normally stabilizes near neutrality under prolonged submergence. The effect of fertilizer application on pH of soils other than Alfisols is not much visible because of probably strong buffering by exchangeable cations.

Damage to Animals and Humans

Another important aspect of excessive use of nutrients, especially nitrate and phosphate, on environment is a massive overgrowth of algae, known as an algae bloom, which harms the water quality and damages the aquatic life. Algal blooms reduce the ability of aquatic life to find food due to cloudiness of water and clog the gills of fish. Some algal blooms produce toxins that can cause illnesses or death of animals like turtles, seabirds, dolphins, fish and shellfish. People experience a wide range of health effects like stomach aches, rashes and more serious problems when they come in contact with or are exposed to the algal toxins. Excessive use of agrochemicals also contributes to the pollution of surrounding air. Long-term health effects from air pollution include heart diseases, lung cancer, and respiratory diseases such as emphysema. Air pollution can also cause long-term damage to people's nerves, brain, kidneys, liver, and other organs.

Micronutrient vis-à-vis *Nutrition and Human Health*

Micronutrients play a key role in the growth and development of plants, animals and humans. Use of micronutrients, which has increased during last decade, has significantly contributed in increasing food grain production of the country (Shukla and Behera, 2012). Food and fodder produced on micronutrient-deficient soils are characterized by poor trace element concentrations, whose consumption is responsible for micronutrient malnutrition in the animals and humans. Even though the levels of trace elements like Cu, Zn, Mn, Fe, Mo, Se and Co in crops are sometimes sufficient for producing optimum yields but these are not adequate to meet the needs of livestock, leading to widespread deficiency. Widespread nutritional deficiencies of vitamin A, Fe, Zn, and iodine (I) have affected human health disproportionately, especially women and young children. Soil-related deficiencies of trace elements such as selenium (Se), Cu, Fe and Zn are also implicated as the causal factors for anemia. Toxic concentrations of some trace elements in soils also adversely affect the animal and human health.

Survey conducted in Vadodara district of Gujarat showed that the dry fodders tested low in Fe (61%), Zn (72%), and Cu (87%) and green fodders were low in Fe (17%), Zn (5%) and Cu (23%) in spite of the fact that most of the soils were adequate in available Fe, Mn and Cu to support crop yields and needed only Zn fertilization to get good yields. In humans, Zn deficiency was recognized as a health concern for the first time in 1961 (Prasad et al, 1961, 1963). First cases of human Zn deficiency syndromes included growth stunting, delayed sexual development, and hypogonadism in young adults from Iran and Egypt. Besides, Zn deficiency has been reported to lead to diarrhoea, respiratory malfunctions, weak immune system, impaired cognitive function, neuronal atrophy, behavioural problems, memory impairment, spatial learning, lesions on dermal tissue/keratin, and parakeratosis. It is estimated that one-third of the world population which lives in developing countries suffers from high prevalence of zinc deficiency. The vulnerable populations include infants, young children, and pregnant and lactating women because of their higher zinc requirements, as they are at the critical stages of growth and physiological needs. In

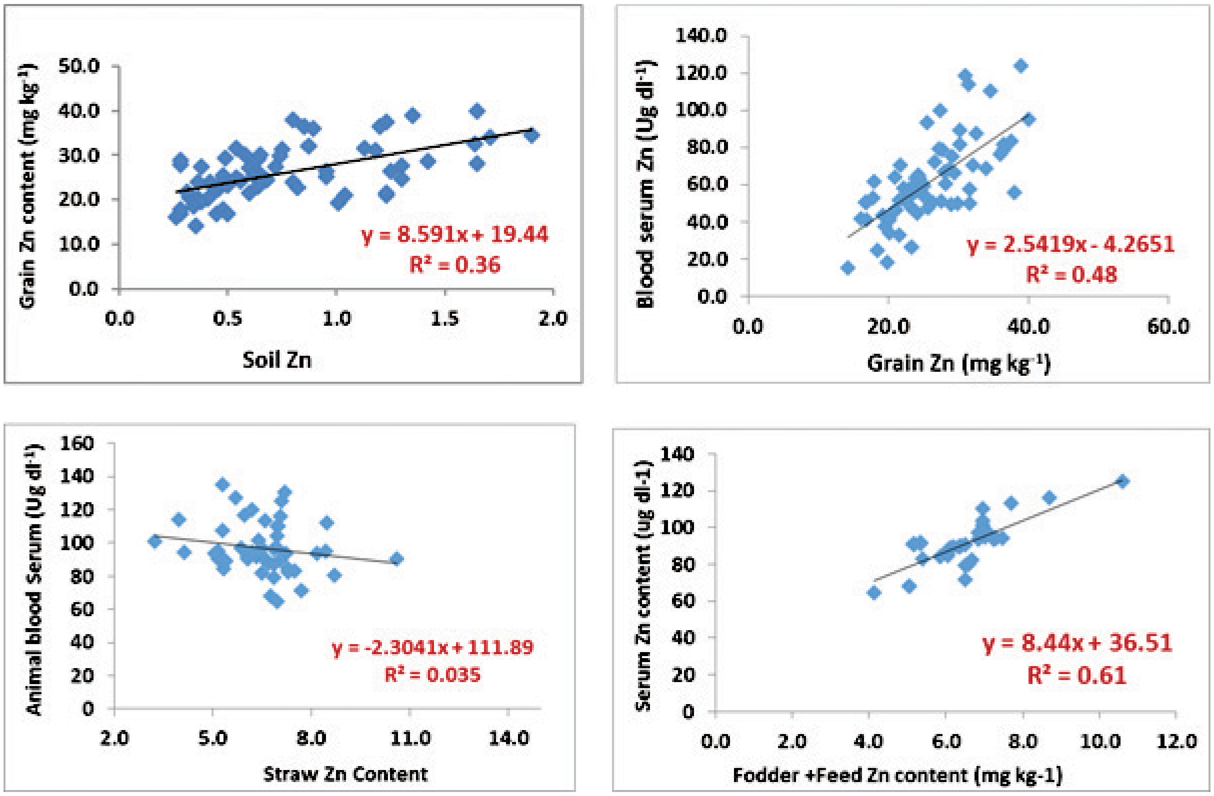

Figure 11. Relationship between soil, plant, animal and human Zn

general, a strong correlation has been reported between soil Zn status and human Zn deficiency levels (Shukla et al., 2016). By and large, dietary Zn intake in the poor people of this country is far below the normal levels and is imbalanced consisting mainly of rice and wheat, which are low in Zn and high in phytate causing low Zn-bioavailability. In the States of Assam, Bihar, Odisha, Tripura, and West Bengal, the average consumption of Zn among various age groups is much lower than the recommended dietary allowance (RDA). Therefore, populations relying primarily on a plant-based diet, exclusively on cereals are susceptible to Zn deficiency. A large section (84%) of the families have deficient Zn intakes and more than 50% having moderate to severe deficiency level of Zn in their dietary intake. About 82% of pregnant women worldwide also have an inadequate zinc intake to meet the normative needs of pregnancy. In India, about 25% of the total population suffers from Zn deficiency. The prevalence of nutritional stunting due to Zn deficiency is about 47.9% in children of below 5-year age while it is 33% in the world's population. High incidence of Zn deficiency (43.8%) was confirmed among children belonging to low socio-economic groups in five major Indian states **(Table 5)**.

Table 5. Distribution of children below 5 years of age in India according to their serum Zn levels (Source: Kapil and Jain, 2011)

State (n = No of samples)	Serum zinc levels	
	< 55 µg dL^{-1}	< 60 µg dL^{-1}
Odisha (n = 345)	34.5	43.2
Uttar Pradesh (n = 316)	29.4	40.2
Gujarat (n = 353)	25.8	34.0
Karnataka (n = 356)	19.1	26.4
Madhya Pradesh (n = 285)	14.7	22.8
Total (n = 1655)	**25.0**	**33.5**

Highest Zn deficiency was in Odisha (51.3%), followed by Uttar Pradesh (48.1%), Gujarat (44.2%), Madhya Pradesh (38.9%), and Karnataka (36.2%). Another cross-sectional study (n = 630) also confirmed low plasma Zn concentration and poor cognitive performance in 45% of the adolescent girls (10-16 years) from two secondary schools of Pune. Supplementation of Zn-rich recipes improved plasma Zn status, cognitive performance and taste acuity signifying the need to adopt dietary Zn intake for normal health (Kawade, 2012).

Case study conducted in Mandala district of Madhya Pradesh revealed that analysis of Zn content in soil, grain, straw feed, animal and human blood serum were strongly correlated with one another, thus showing the interdependence among soil-plant-animal-human continuum (**Figure 11**). The coefficients of determination (R^2) between soil Zn

Table 6. Changes in SOC under long-term cropping and manuring (Source: Jha et al., 2021)

Locations (Initial SOC stock - Mg ha^{-1})	Treatments	Steady state SOC stock (Mg ha^{-1})	No. of years required to reach steady state
Jabalpur(33.8)	No fertilizer	29.0	55
	NPK	41.0	48
	NPK + FYM	60.0	108
Palampur(40.5)	No fertilizer	40.6	1
	NPK	49.0	40
	NPK + FYM	57.0	62
Ludhiana(14.7)	No fertilizer	15.9	44
	NPK	26.3	95
	NPK + FYM	37.6	116

content and grain Zn concentration were 0.36 and that between Zn concentration in human blood serum and grain Zn concentration were 0.48. However, no relationship was recorded between straw Zn content and animal blood serum Zn concentration. When contribution of Zn through feed and Zn content in grazing grass was included with fodder Zn content, it exhibited a highly significant relationship with animal blood serum Zn (R^2 = 0.61).

Impact of Long-Term Fertilizer Application on Soil Nutrient Status

Long-term fertilizer experiments (LTFEs) on arable lands in India established in 1972 in different agro-climatic regions of North and Central India under sub-humid climatic conditions showed variable crop responses and changes in soil C status. Long-term Fertilizer Experiments (LTFEs) conducted at Jabalpur with soybean-wheat system and at Palampur and Ludhiana with maize-wheat cropping sequences revealed that the grain yield was markedly improved with application of NPK and NPK+FYM. Long-term application of balanced fertilization and integrated plant nutrient supply (IPNS) improved the crop yields as well as underground root biomass, and thereby soil C pools in different agro-ecosystems. Integrated plant nutrient supply (IPNS) and balanced fertilization lead to carbon stabilization at higher levels (**Table 6**). Application of optimum NPK dose increased the SOC stock by 20%, 12%, and 61% over the initial SOC stocks at the Jabalpur, Palampur and Ludhiana sites, respectively, whereas the treatment receiving NPK+FYM increased the SOC stocks by 46%, 30%, and 107% over the initial value, respectively (Jha et al., 2021).

LTFEs conducted across the length and breadth of the country showed that continuous application of fertilizer P in balanced amounts led to the buildup of

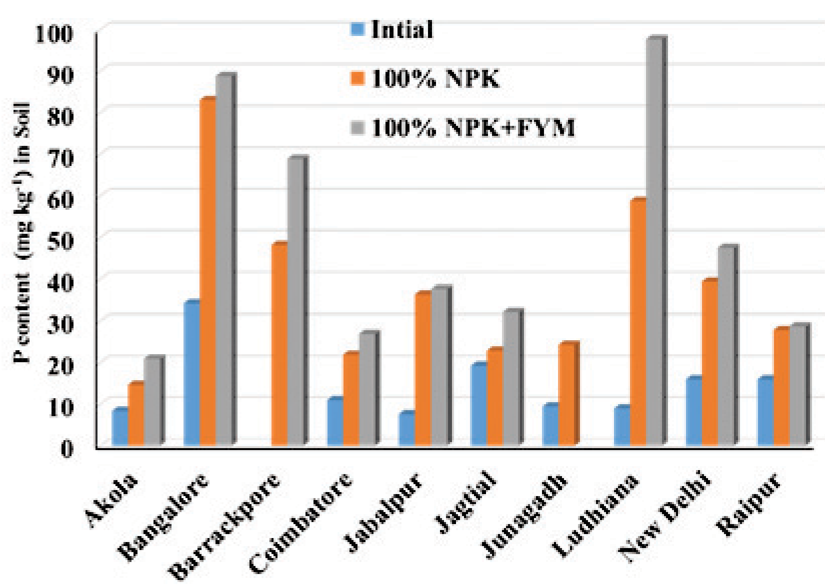

Figure 12. Phosphorus build-up in soils under 35 years of manuring and fertilization on various cropping systems (Source: Singh et al., 2019)

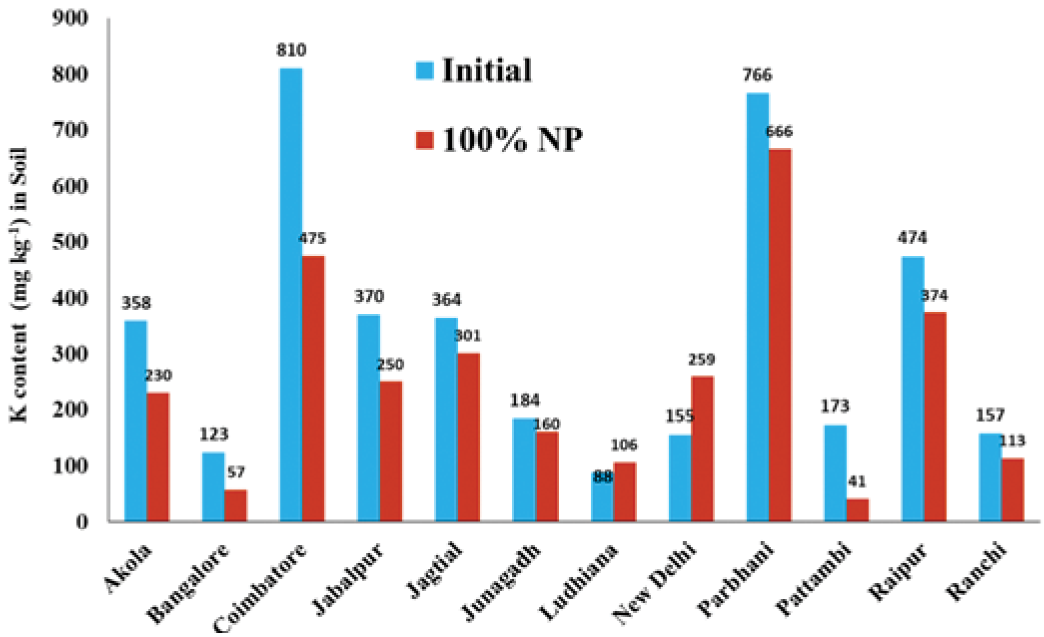

Figure 13. Potassium mining from soils under 35 years of manuring and fertilization in different cropping systems (Source: Singh et al., 2019)

available P in the soil (**Figure 12**). This accumulated P could be reutilized by readjusting the P doses in succeeding crops. Farmers have been paying little attention to the use of K in agriculture due to the myth that 'Indian soils are rich in K'. Continuous absence of K in fertilization schedule or its application in inadequate quantities has led to the net negative balance of K in Indian soils (**Figure 13**). Vertisols respond to K application due to slower release of K from non-exchangeable pool and reduction in the available K content. Application of K fertilizers for maintaining K fertility status of soil is very expensive as the potassic fertilizers are imported entirely from abroad.

Technologies and Strategies to Monitor and Control the Impacts of Fertilizers on Human Health and Environment

Based on the data from large number of on-station and on-farm studies, best nutrient management strategies identified for reducing the adverse impact

Table 7. Environmental problem associated with fertilizers and mitigation strategies

Environmental problems	Causative mechanisms	Mitigation strategies
Groundwater contamination	Nitrate leaching	Judicious use of fertilizers through LCC, increasing efficiency through novel fertilizers, use of nitrification inhibitors and *neem* coated fertilizers
Eutrophication	Loss of nutrients (nitrate and phosphate) through erosion and surface runoff	Reduce runoff through water harvesting and controlled irrigation
Methemo-globinemia	Consumption of high nitrates through drinking water and food	Reduce N leaching by adopting crop rotation with crops of different rooting zone. use balanced fertilization and *neem* coated urea (NOCU)
Acid rain and ammonia redeposition	Nitric acid originating from reaction of N oxides with moisture in atmosphere, ammonia volatilization	Reduce ammonia volatilization losses through use of novel fertilizer formulations and nitrification inhibitors
Stratospheric ozone depletion	Nitrous oxide emission from depletion and global warming	Use nitrification and urease inhibitors and increase the N use efficiency. Synchronize N use with crop demand.

of fertilizers in various crops and cropping systems are summarized in the **Table 7**.

Promotion of Neem Oil Coated Urea

Use of nitrification inhibitors and modified urea materials in reducing the N losses has been well documented (Prasad, 2013). Promotion of *neem* cake/ oil coated urea has the dual benefit, both as fertilizer and pesticide. The key active ingredient in neem is azadirachtin - which exhibits and confers nitrification retardation and insecticidal as well as immunomodulatory and anti-cancer properties. It acts as an antifeedant, repellent, and repugnant agent and induces sterility in insects by preventing oviposition and interrupting sperm production in males. Extensive research done across the country has demonstrated that the application of *neem* coated urea, (NCU) @ 200 kg *neem* cake t^{-1} urea or *neem* oil coated urea (NOCU) @ 0.5 kg neem oil t^{-1} urea exhibits nitrification inhibition properties and could cause significant enhancements in crop yields and N use efficiency as compared to prilled urea. Metanalysis studies indicated that about 30% comparisons did not exhibit increase in crop yields and/or NUE. Yield increase using NOCU reported at farmers' fields is generally lower than the researcher's plots due to poor crop management and plant protection measures. Farmers applying high and above optimal levels of urea-N in different crops may not observe significant improvement in yield levels due to NOCU application. In India, more than 50% of the urea is consumed in rice and wheat crops. Replacement of urea with NCU or NOCU could enhance the grain yield by 5% to 6% in plots managed by researchers. The effect of nitrification inhibitors depends on concentration of triterpenoids in *neem* cake/oil, soil texture, pH and also on redox status of the soils determined by irrigated or rainfed conditions. Nitrification inhibitors work better in acidic soils than in the neutral or alkaline soils, in coarse textured soils than in fine textured soils, and in irrigated crops than in rainfed crops.

Neem is used as a natural alternative to synthetic pesticides; however, little attempt has been made to study pesticidal properties associated with NCU or NOCU. Baboo (2014) has cited few studies associated with *neem* coated urea. Yash Roy and Gupta (2000) reported that *neem* oil is used as an eco-friendly and economical agent to avert termites' attack in the field. At one of the locations in the State of Uttar Pradesh, application of *neem* coated urea in rice fields by the farmers reduced the menace of blue bull (*Boselaphus tragocamelus*). At Panipat in Haryana, farmers observed no incidence of leaf folder and stem borer in the rice crop, and at Sangrur and Gurdaspur in the State of Punjab, farmers observed reduced incidences of white grub with the use of *neem* coated urea in the wheat crop. Site-specific NOCU application using LCC led to higher or similar levels of crop production *vis-a-vis* untreated urea but with lower fertilizer application rates (Shukla et al., 2004). With farmers increasingly adopting NOCU urea coupled with SNM principles for fertilizer management, demand for NOCU may exhibit a decline over the current demand for urea.

Nutrient Efficient Genotypes

Identification of nutrient-efficient genotypes could be an important strategy in crop production. Nutrient-efficient cultivars or genotypes are capable of extracting or absorbing relatively large amounts of nutrients from soil even under low indigenous nutrient levels (Behera et al., 2021). These cultivars produce high grain yield per unit of the nutrients absorbed, and store relatively small amounts of nutrients in the stover/straw portions.

Preventive Strategies

In recent years, traditional techniques are being reassessed as the technology options to modern intensive agriculture that could help in decreasing or avoiding the need for undesirable chemical inputs and creating environment-friendly sustainable systems. Numerous models exist and have been advocated in this regard. These include integrated pest management (IPM), low external input sustainable agriculture (LEISA) and organic agriculture (Tomer et al., 2014).

Organic Farming

Organic farming system in India is not new, having been followed since the ancient time. It is primarily aimed at cultivating the land and raising crops in such a way, that keeps the soil alive and in good health by use of organic wastes (crop, animal and farm wastes, aquatic wastes) and other biological materials along with beneficial microbes (biofertilizers), and releases nutrients to crops for increased sustainable production in an eco-friendly pollution-free environment. India ranks 8th in World in terms of area under organic agriculture and 1st in terms of total number of producers (Willer et al., 2020). As on 31st March 2020, total area under organic certification process, registered under National Programme for Organic Production was 3.67 Mha (2019-20). Country produced around 2.75 Mt of certified organic products in 2019-20 which included all varieties of food products namely, oilseeds, sugarcane, cereals & millets, cotton, pulses, aromatic & medicinal plants, tea, coffee, fruits, spices, dry fruits, vegetables, processed foods, etc.

Farmer's Perception on the Use of Fertilizers and their Impact on Natural Resources and Food Production System

The N and P consumption has exponentially increased as the farmers believe that the fertilizer N and P use enhance the crop productivity at a faster pace by boosting the crop growth. They overlook the merits of balanced application of fertilizers because of simple economic considerations like availability of urea at cheaper rate under the policy. Maintenance of favourable $N:P_2O_5:K_2O$ consumption ratio at 4:2:1 becomes the first casualty. This ratio is very wide in high productivity areas such as Punjab, Haryana, and Uttar Pradesh.

Diagnostic surveys conducted in intensively cropped areas of Indo-Gangetic plains indicated that farmers' fertilizer practice was skewed toward N because of N being comparatively cheaper than P and K, with optimal to suboptimal use of P, and utter neglect of K, S, and micronutrients (Singh et al., 2013). In intensively cultivated areas, the situation has become more alarming due to imbalanced application of nutrients by the farmers. Farmers apply only Zn to rice crop and that too at a suboptimal rate. The indiscriminate use of N not only widens the fertilizer consumption ratio but also intensifies the nonsustainability by way of promoting nutrient imbalances in soil-plant system, decreasing NUE, enhancing groundwater pollution through NO_3 leaching, and incurring more expenditure on the production inputs.

Mohanty et al. (2013) made significant observations on the knowledge of farmers about the practices related to pesticide use. As per their study, about 70% of farmers perceived that the pesticide spraying affects a person's health. Only 40% were aware that it affects the environment. Two-thirds of the farmers (62%) were aware that pesticide enters the body through nose and affects lungs and awareness on other modes of entry was less. Majority (76%) of them were aware of training programmes conducted by government agriculture department on pest management. Between 40% and 70% of farmers did not use any protective equipments during pesticide spraying. Around 68% of farmers indiscriminately disposed off the empty containers. Around 48% farmers buried the leftover pesticides.

Elaborate Research – Extension- Farmer Linkages in Fertilizer Use in Agriculture and Dissemination of Best Management Practices

Government of India has developed an effective network of scientists-extensionists-farmers interface though Krishi Vigyan Kendras (KVKs) operated by Indian Council of Agricultural Research and National Agricutural Research and Extension System (NARES). The basic aims of KVKs are to assess the location-specific technology modules in agriculture and allied enterprises, through technology assessment, refinement and demons-trations. More than 700 KVKs have been functioning as knowledge and resource centres of agricultural technology supporting initiatives of public, private and voluntary sectors for improving the agricultural economy of the district and are linking the NARES with extension system and farmers. Each KVK has a provision of providing advisories on the use of agrochemicals (fertiliser nutrient mangment and plant protection measures) through soil scientists/ agronomists, and plant protection scientists across the country.

The Government of India started the Soil Health Card Scheme in 2015. It is endorsed by the Department of Agriculture & Co-operation under the Ministry of Agriculture and Farmers Welfare with a view to enhance awareness about the balanced fertilizer application as per soil test requirement. A soil health card is used to assess the current status of soil health and, when used over time, to determine changes in soil health that are affected by land management. Soil health card displays soil health indicators and associated descriptive terms. It provides every farmer data on the soil nutrient status of his land and advises him accordingly on the dosage of fertilizers and essential soil amendments that should be maintained for good soil health. The soil health card scheme properly examines the farmers' soils and accordingly give them a formatted report so that they can decide upon which types of crops to be cultivated for more income with balanced use of fertilizers and manures as per soil test report and crop demand.

Research and Development Needs/Capacity Development of Stakeholders to Reduce Adverse Impacts and Increase Fertilizer Use Efficiency/ Optimum Use

- In order to optimize the fertilizer application, greater emphasis should be made on the use of organics (enriched composts, crop diversification with legumes, crop residue and waste recycling, industrial by-products) in addition to FYM. This will help in development/refinement of nutrient management practices/customs for CA, rejuvenating agriculture (RA) and integrated farming systems (IFS) with effective nutrient fluxes and flows.
- Promoting the availability of quality manure and formulating cropping system-specific fertilizer prescriptions involving locally available organic sources through establishment of highly mechanized composting units in rural areas.
- Identification of nutrient smart farmers (farmers adopting best fertilizer management practices or nutrient smart villages and introduction of incentivization schemes for smart farmers/ villages). This would help in capacity building of stakeholders and encouraging soil health rejuvenation campaigns involving field

demonstrations on agricultural chemical management technologies and informal education/ skill development to enhance farmers' awareness on nutrient recycling and safe use of pesticides.

- To ensure reduction in adverse impacts of agrochemicals use and promote the optimum use of pestcides and nutrients, the best management practices for rejuvenating agriculture should be linked with the GOI initiatives *e.g.*, National Mission on Sustainable Agriculture (NMSA), Doubling of Farmers, Income (DFI), National Food Security Mission (NFSM), Pradhanmatri Krishi Vikas Yojna (PKVY), Soil Health Card Scheme (SHC), Mission for Integrated Development of Horticulture (MIDH), etc.
- Identification and disposal of basket of technologies, which encompasses the principles and practices that restore/improve soil health, protect crop from insect pest and diseases, and ensure sustained high productivity while minimizing environmental footprint.
- It is more realistic to promote practices for increasing SOC stock and improving soil quality. The benefits accrued by small increases in SOC may not necessarily translate into the increased crop yield but improve the soil health and ensure the environment safety.
- Existing LTFEs (AICRP-LTFE, DA, IFS) serve as the repository of information. These need to be modified to retain their relevance, and converge with present-day farming issues, like organic inputs, tillage, residue recycling and crop diversification.

Challenges of Fertilizer Use in Agricultural Systems

- To meet the additional foodgrains required by 2050, it will be necessary to increase the use of fertilizer nutrients if the NUE remains unchanged under the current business as usual. Bringing urea under nutrient-based subsidy would initially lead to its cost escalation unless accompanied by adoption of BMPS leading to improvement in NUE. Long-term benefits accruing from bringing in urea under NBS will be the increased adoption of balanaced fertiliation and IPNS.
- There is a need to intensify research on using alternative management practices beneficial to both the group of indicators *i.e.*, use of organic fertilizers for biological soil quality as well as increase in crop yields.
- Notwithstanding established benefits of IPNS, its adoption at large scale could not become possible due to availability of subsidized fertilizers urea, time and labour needed for preparation of farmyard manure and composts, and higher handling cost of organic manures.
- Use of fertilizer or organic manure alone leads to decline in SOC and yield. In view of this and emphasis on soil health scheme of the Government of India, there is a need for revival of interest in IPNS and its effective execution in mission mode for improving indigenous nutrient supplying capacity of soil, optimize nutrient input, enhance fertilizer use efficiency, and rejuvenating soil health.
- Crop rotations play an important role in rejuvenating soil fertility by utilizing the native nutrients at a variable rate with different depth. However, farmers are reluctant to change the cropping system due to lower yield of legumes and insecurity of MSPs for new crops.
- Crop response to K, S and micronutrients has increased over time under intensive cropping, but their use is still inadeqaute to meet the crop demand and sustain the soil health. In general, mining of K from soil and its low use in crops has left the annual K balances highly negative across all the cropping systems. Continued neglect of K input has led to a gradual change in the mineralogical make-up of soil, indicating deterioration in K supplying capacity of soils.

Way Forward

- India has a huge opportunity to seize the N challenge by collective effort of enhancing public and institutional awareness among the stakeholders of threat perceptions of increased Nr in the environment. India can achieve 20-30% reduction in the fertilizer use, particularly N and P by adopting best crop and fertilizer management practices in synchrony with effective policy implementation.
- BMPs for different soil-crop contexts need to be devised for improving NUE by including the strategies such as balanced fertilization, IPNS, inclusion of legumes, precision N management, and CA technologies.
- There is a need for providing impetus to research on development of new fertilizer products, and evaluation of their efficacies under diverse soil-crop scenarios.
- Policies should be streamlined/dovetailed to enhance awareness about the use of secondary and micronutrients to address the issue of nutritional security/malnutrition and improving utilization of macronutrients and crop quality.

- Multidisciplinary research needs to be encouraged for developing strategies for higher NUE, improved crop productivity and reduced environmental degradation.
- National action plan may be developed and implemented for better fertilizer quality control, strengthening global policies on safe and sustainable use of fertilizer materials, scaling up training to the relevant stakeholders, and ensuring accessibility of suitable and affordable fertilizers to the farmers.

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