Strategy Paper

taas
Progress Through Science

Rationalizing Fertilizer Use for Managing Ecological Sustainability and Subsidy

JC Katyal

taas

Progress Through Science

Trust for Advancement of Agricultural Sciences (TAAS)

GOAL

Harnessing the potential of agricultural sciences for the welfare of the people.

MISSION

Promoting growth and advancement of agriculture through scientific partnerships, policy advocacy and public awareness.

OBJECTIVES

- To act as a 'Think Tank' to deliberate on key issues relating to agricultural research and innovation for development (ARI4D) and influence policy decisions
- To organize workshops, conferences, brainstorming sessions, policy dialogues seminars and special lectures on emerging issues and new developments in agricultural sciences
- To disseminate knowledge among stakeholders through publication of proceedings, strategy papers and policy papers
- To confer awards to the scientists of Indian and foreign origin for their outstanding contributions having impact on Indian agriculture
- To facilitate scientific interactions and partnership building of non-resident Indian agricultural scientists with Indian scientists

Rationalizing Fertilizer Use for Managing Ecological Sustainability and Subsidy

JC Katyal

taas
Progress Through Science

Trust for Advancement of Agricultural Sciences (TAAS)
Avenue-II, Indian Agricultural Research Institute, Pusa Campus
New Delhi - 110 012, India
Phone: +91-11-25843243; 8130111237
Email : taasiari@gmail.com; Website: www.taas.in

Citation : TAAS. 2023. *Rationalizing Fertilizer Use for Managing Ecological Sustainability and Subsidy - Strategy Paper*. Trust for Advancement of Agricultural Sciences (TAAS), Avenue II, Pusa Campus, New Delhi. x+62 p.

Edited by : Raj Paroda, Bhag Mal and Umesh Srivastava

ISBN : 978-93-6076-762-4

Published by : Secretary
Trust for Advancement of Agricultural Sciences (TAAS)
New Delhi

For copies and further information, please write to :

Secretary
Trust for Advancement of Agricultural Sciences (TAAS)
Avenue II, Pusa Campus, New Delhi - 110012
Ph.: +91-11-25843243; +91-8130111237
E-mail: taasiari@gmail.com; Website: www.taas.in

Printed : December 2023

Contents

Acknowledgements

I express my heartfelt indebtedness to the TAAS and its Chairman Dr RS Paroda for his approval to publish this 'Strategy Paper' under the aegis of TAAS, New Delhi. I further express my deep sense of gratitude to Dr Paroda for his professional guidance in preparing and finalizing the manuscript.

I am also grateful to both Dr Bhag Mal, Secretary and Dr Umesh Srivastava, Consultant, TAAS for reviewing and editing the manuscript critically and comprehensively and for giving related technical support to bring out the original draft of the Strategy Paper to the printable version.

Unstinted logistic assistance provided by Ms Simmi Dogra in facilitating the smooth organization of the meetings with the Chairman, TAAS and other functionaries and professionally handling the communications is appreciably recognized and gratefully acknowledged.

JC Katyal

Acronyms and Abbreviations

AE	Agronomic Efficiency
AI	Artificial Intelligence
AICRP	All India Coordinated Research Project
AICRPDA	All India Coordinated Research Project on Dryland Agriculture
ASF	Alternative Systems of Farming
BCKV	Bidhan Chandra Krishi Vishwavidyalaya
BEAM	Biologically Enhanced Agriculture Management
BHU	Banaras Hindu University
BMPs	Best Management Practices
BPKV	*Bhartiya Prakritik Krishi Paddhati*
CA	Conservation Agriculture
CAG	Comptroller and Auditor General
CAGR	Compound Annual Growth Rate
CFR	Cost and Freight Rate
CSE	Center for Science and Environment
DAP	Diammonium Phosphate
DFM	Derived from Molasses
DSS	Decision Support System
EI	Ecological Intensification
FAI	Fertilizer Association of India
FK	Fertilizer Potassium
FKRE	Fertilizer Potassium Recovery Efficiency
FN	Nitrogenous Fertilizer

FNRE	Fertilizer Nitrogen Recovery Efficiency
FNUE	Fertilizer Nitrogen Use Efficiency
FP	Phosphatic Fertilizer
FPRE	Fertilizer Phosphorus Recovery Efficiency
FUE	Fertilizer Use Efficiency
FYM	Farmyard Manure
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GoI	Government of India
HNM	Holistic Nitrogen Management
HYVs	High Yielding Varieties
IFA	Integrated Farm Assurance
INSAM	Integrated Nutrient Supply and Management
IoT	Internet of things
IT&C	Information Technology and Communication
LCC	Leaf Colour Chart
LISA	Low Input Sustainable Agriculture
LTFE	Long Term Fertilizer Experiment
MOP	Muriate of Potash
MRP	Maximum Retail Price
NAAS	National Academy of Agricultural Sciences
NBS	Nutrient Based Subsidy
NF	Natural Farming
NO_2	Nitrous Oxide
NPK	Nitrogen Phosphorus and Potassium
NR	Natural Resources
NTP	Non-Thermal Plasma
NUE	Nitrogen Use Efficiency

PFP	Partial Factor Productivity
PIB	Press Information Bureau
R&D	Research and Development
RA	Regenerative Agriculture
RDF	Recommended Dose of Fertilizer
RDF-N	Recommended Dose of Fertilizers Nitrogen
SCU	Sulphur Coated Urea
SHC	Soil Health Card
SNMI	Soil Nutrient Mining Index
SOC	Soil Organic Carbon
SSNM	Site-specific Nutrient Management
TAAS	Trust for Advancement of Agricultural Sciences
TIFAC	Technology, Information, Forecasting and Assessment Council
TSP	Trisodium phosphate
USA	United States of America
WHO	World Health Organization
ZBNF	Zero Budget Natural Farming

Rationalizing Fertilizer Use for Managing Ecological Sustainability and Subsidy

Background

India made great strides in foodgrain production, which increased more than six times since independence – from 51 mt in 1950-51 to 316 mt in 2021-22 (Fig. 1); and now 330.5 mt (2022-23). This impressive accomplishment on the food front paralleled consumption of fertilizers (jointly with high yielding varieties (HYVs), assured irrigation, etc.) i.e., nitrogenous (N), phosphatic (P), and potassic (K) or NPK fertilizers. Since independence, NPK use increased from merely 0.07 mt (~0.5 kg NPK/ha of gross sown area) in 1950-51 to 29.8 mt (147 kg NPK/ha of gross sown area) by 2021-22 - a rise of 426 folds (FAI, 2021-22). Incidentally, foodgrain crops share two thirds of the NPK fertilizers consumed in India. Of the fertilizers applied to all food gain crops, a big chunk (78%) is appropriated by rice (52%) and wheat (26%). No wonder, these two crops together make up 75 per cent (rice 40%;

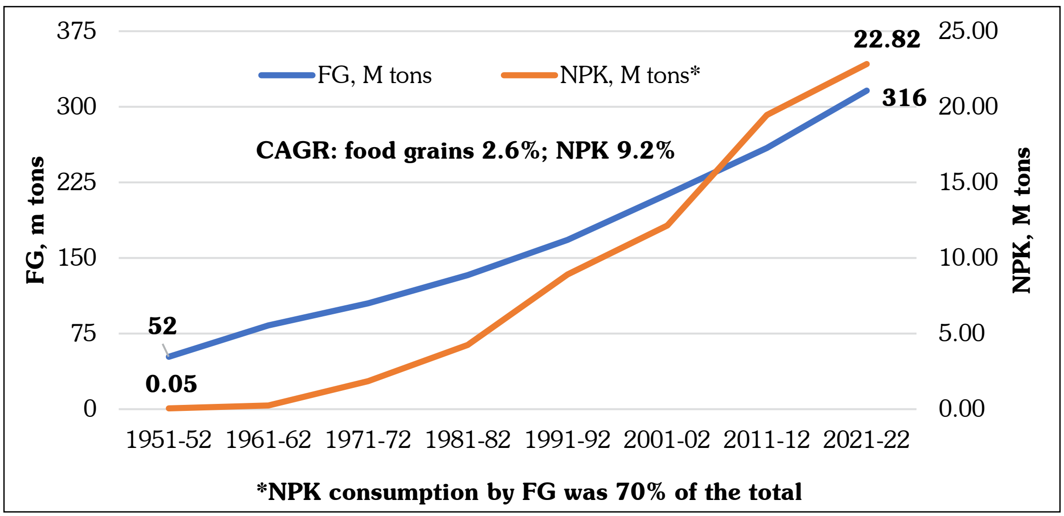


Fig. 1. *Growth in NPK consumption and foodgrain (FG) production*

(Data source: FAI, 2021-22)

wheat 35%) of the total foodgrains produced in the country. Buildup of rice and wheat production formed the backbone of India's food self-sufficiency and fertilizers contributed 40-50 per cent to this great achievement (Isherwood, 2000). The relatively low share of fertilizers allocated to rainfed crops, ~40 per cent of irrigated crops, is an important cause of their poor productivity. Uncertain and insufficient supply of water for plant growth drives low fertilizer use and consequently the low yield of rainfed crops.

On all counts, it appears that increasing fertilizers use (along with HYVs, irrigation, etc.) played a major role in foodgrains production and taking India from a deficit situation of 1960s and 1970s to that of self-sufficiency by 1990s. Since early 2000, India has been exporting foodgrains to several needy nations around the world.

It is reiterated that fertilizers played a key role in enhancing food security. To promote fertilizer use, the Government of India (GoI) played a unique role. Successive Governments in India supported this program by making NPK available to farmers at affordable prices. On the back of this advocacy was the induction of a policy operating since mid-1950s, called 'Fertilizer Subsidy Scheme', which assured supply of N, P, and K products to farmers at prices less than the prevalent market rates. The GoI in 2022-23, spent Rs 2.25 lakh crore (Rs 2,250 billion) on fertilizer subsidy. However, this support tilted more towards urea N, which attracted >60 per cent of the total financial investment. This unequal treatment made the application of P and K fertilizers 3 to 5 times more expensive. As a result, farmers paid greater attention to N treatment and neglected the use of the other two major nutrients. This continuing imperfection in the fertilizer subsidy scheme triggered over-use of N, relegating the application of P and K fertilizer, in particular. Additionally, availability of relatively cheaper urea fueled its mismanagement. Disproportionate use of N, P, and K along with mishandling, typically of urea treatment, produced negative effects on the health of soil, quality of water, natural composition of air, and biodiversity. These developments contributed to the fall in productivity and profitability with a rise in higher investment in fertilizers which tantamounts to the collapse of use efficiency, specifically of FN (from >50% in 1970s to <35% in 2022-23), declining output per unit of fertilizer application. The consequences are seen as: i) a significant rise in fertilizer consumption without commensurate increase in productivity, ii) progressive upsurge in subsidy budget, and, iii) damage to soil health and sustenance of environmental quality. Gurumurthy and Goedeccle (2015) showed that just 1 per cent reduction in urea-N subsidy would decrease soil health degradation by 3 per cent. This is an added reason to contain fertilizer subsidy investment. Apparently, the need is to rationalize fertilizer use without compromising growth in production and health of natural resources.

Reduction in fertilizer consumption is possible by increasing efficiency of use due to a negative relationship between the two as confirmed by Bumb *et al.* (2022). Also, complementary addition of native sources, both organic and inorganic, exhibit significant potential to surrogate chemical fertilizers. These two approaches (use efficiency and native materials) are projected to diminish dependence on synthetic fertilizers to about one half of the current and futuristic consumption and affect thereby containment of subsidy budget. The credentials of these two plans - use efficiency and native material supplements, of being pro-productivity and pro-nature are well-documented. This report reviews the available evidence to outline doable ways and means to quantify the possible savings in fertilizers by improving use efficiency and induction of native sources without any cost to ecological sustainability (a combine of necessary productivity growth and no harm to health of soil and environment) but with economy in subsidy budget.

NPK Fertilizer Sources, Consumption, and Indigenous Manufacturing

Sources of fertilizers

In general terms, fertilizers are materials either organic or inorganic, natural, or synthetic, which supply one or more of the 17 essential elements required for plant growth. In this Strategy Paper, fertilizers refer to synthetic chemical compounds except muriate of potash (MOP) which is extracted from the mineral langbeinite supplying three major nutrients N, P, and K. Naturally occurring fertilizers are mentioned as organic manures.

Fertilizer consumption

Regarding fertilizer sources, Indian farmers depend on 20 diverse fertilizer carriers – 7 straight (single nutrient) and 13 multi-nutrient products (compound fertilizers) (FAI, 2021-22). Of these, only 3 straight carriers (urea, MOP, and single superphosphate) and one compound fertilizer (diammonium phosphate- DAP) dominate the scene. In 2020 (FAI, 2021-22), urea, DAP and MOP, respectively supplied 79, 61 and 65 per cent of the total NPK sources that were used in the country. With a consumption of 32.4 mt NPK in 2020-21, India ranked second in consumption (Fig. 2). On individual nutrient use basis, India's position was second in the consumption of N and P and fourth in the consumption of K. However, with

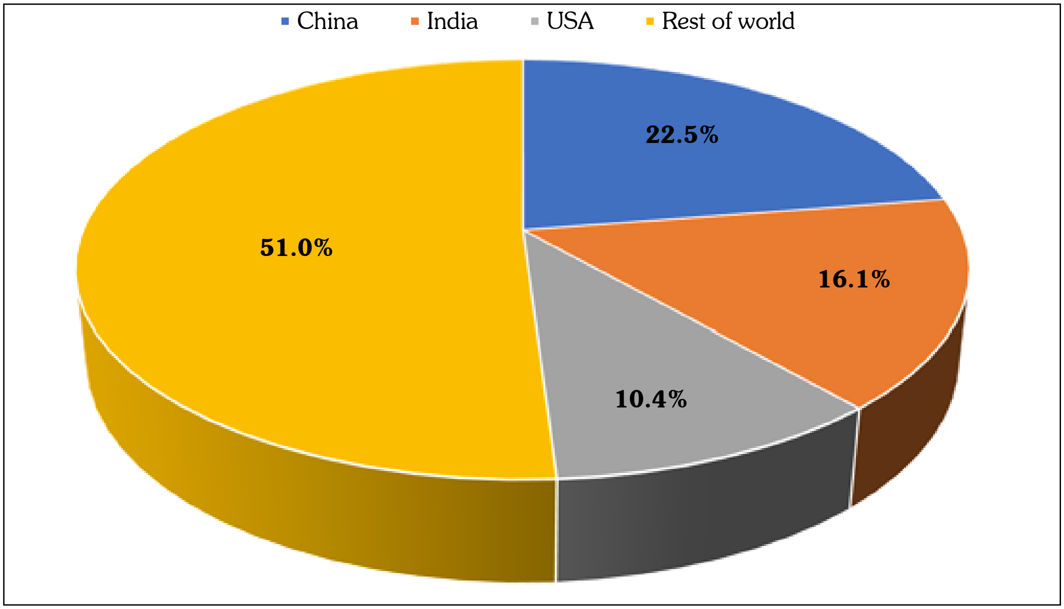


Fig. 2. *Share in global NPK consumption of China, India and USA*

(Data source: FAI, 2021-22)

per hectare NPK use (e.g., intensity of fertilizer application or kg NPK/ha gross sown area in 2021-22 of 160 kg), India is far behind many developed and developing countries. Even the farmers in Bangladesh apply nearly 50 per cent higher dose of NPK than their Indian counterparts.

Fertilizer manufacturing

Since independence, India invested heavily for the development of fertilizer industry. Accordingly, GoI's policies aimed achieving self-reliance in indigenous fertilizer manufacturing. Currently, India ranks second in nitrogenous fertilizer (FN) production and third in phosphatic fertilizer (FP) manufacture (FAI, 2021-22). With sparse utilization of known K reserves (details in a later section), India meets its fertilizer potassium (FK) demands through imports. Recently, GoI, however, notified use of K derived from molasses (DFM) having K content of 14.5 per cent. To encourage DFM use, subsidy as freight has been made admissible (PIB, 2023; https://pib.gov.in/PressReleaseIframe Page.aspx?PRID=1886054)

Despite public support to industry, indigenous fertilizer manufacturing in India is still sustained by imports to meet growing demand. During 2021-22 of the total 63 mt of NPK fertilizer products consumed in India, 27 per cent urea, 59 per cent

DAP, 100 per cent MOP, and 14 per cent NPK complexes were imported (PIB, 2023). Besides spending foreign exchange for import of finished products, India must invest heavily for bringing in raw materials like natural gas for manufacture of urea and phosphoric acid and ammonia for the production of DAP.

There is a dark side of fertilizer manufacturing (and consumption; details in the following section), typically urea. It pertains to concomitant generation of carbon (C) footprint – a known source of carbon dioxide (CO_2) emission. Hence, urea synthesis acts as a trigger to global warming/climate change. On an average, in India each ton of urea manufacture generates 0.7 ton of CO_2. Corresponding data for China, EU, and Russia on CO_2 generation are higher. However, Indian values are inferior to the best FN manufacturing units in the world e.g. Babrala (Yara) (https://cdn.cseindia.org/attachments/0.88942600_1564389532...). More disturbing is the fact that one third of the plants in India leave far higher C footprint (>1 ton CO_2/ton urea). However, the silver lining is that the Government's policy to shift urea manufacturing through natural gas-based plants, CO_2 emissions *aka* C footprint is seen to fall. Currently, 36 gas-based urea manufacturing units produce 28.4 mt/annum (98% of the total) (https://www.fert.nic.in/urea-policypricing-and-administration...). Additionally, urea manufacturing generates nitrous oxide (NO_2) – a GHG that exhibits nearly 300 times higher global warming potential. Estimates showed that N_2O footprint constitutes 35.2 per cent of the total synthetic N fertilizer-associated emissions (1.25 GtonsCO_2e in 2018; current figure 1.5 GtonsCO_2e) (Menegat *et al*., 2022) (https://ntptechnologies.com/our-impact/). It is unfortunate that the fertilizer market, between 2021 and 2026 is likely to grow at a CAGR of 11.9 per cent (https://www.tpci.in/indiabusinesstrade/blogs/india-eyes-new-fertilizer-policy-to-reduce-import-dependence/), the ominous signs are generation of larger CO_2/N_2O footprints and resultant bigger greenhouse gas (GHG) effect, accelerating climate change.

A recent development is about the launch of 'non-thermal plasma (NTP)' technology, which from air generates water soluble nitrate that is then bubbled into water producing nitrogen enriched water or NEW fertilizer. It is claimed that NTP technology frees dependence of FN manufacture on fossil fuels (https://ntptechnologies.com/our-technology/) and this pro-nature manufacturing of FN is reliable and reproducible. However, because of prevailing scientific disagreements, more R&D is necessary before the claims of NTP technologies are accepted and expanded.

Apart from negatively influencing the quality of air, in vogue fertilizer N (FN) manufacturing affects the quality of soil and water in 3 different ways. Firstly, FN manufacturing is a water-use intensive process. The outcome of excessive groundwater extraction is the rise of possible soil and water salinity. Secondly, pollution of ground- and surface-water is another concern related to fertilizer manufacturing. According to a report by the Center for Science and Environment (CSE) analysis (http://cdn.cseindia.org/attachments/0.88942600_1564389532...), 15 out of the 18 plant sites surveyed did not comply with the BIS standard prescribed for ammonia concentration in drinking water. Thirdly, several plants generate effluents that are harmful for the quality of agricultural produce and health of humans and animals. Since the hard data on these adversaries is sparse, there is a need to explore these issues from all aspects concerning safety of natural resources (NRs), food, and human/ animal health.

Fertilizer Subsidy Scheme – A Policy Inspiring NPK Consumption

Certainly, fertilizers played and will continue to play a key role in sustaining India's food security as well as to some extent nutrition security. As per Katyal and Choudhary (2021), so important was the increased fertilizer consumption that in its absence, the country would have needed 63 mha more cereal area to harvest the equivalent production of that obtained with the use of fertilizers. Saving this big chunk of acreage for foodgrain production proved a boon for the country like India, who nearly exhausted all the cultivated area with practically no possibility of expansion. In other words, India's food production would have faced a setback of at least 40 per cent, had the fertilizer use been ignored. Globally, it was projected that 52 per cent of the population might have starved without raising the consumption of fertilizers (Richie, 2017; (https://ourworldindata.org/how-many-people-does-synthetic-fertilizer-feed), and India would have been no exception to that.

Successive governments in India maintained a firm policy of nurturing self-sufficiency in food staples for containing price rise. Accordingly, Katyal (2022) reported that notwithstanding the fluctuations in market prices, fertilizer use was made affordable (affordability index <1) and attractive (BC ratio >1). In pursuance of that goal, GoI, from time to time, came up with subsidy schemes (revised from time to time) to insulate farmers from the shock of ups in market rates of fertilizers. It is reemphasized that these prices are patterned on the prevailing international prices of finished products, raw materials, and the cost of manufacturing in India. Russia-Ukraine conflict caused recent exponential spike in the value of imported products and raw materials from February 2022. The government has been and continues to compensate the fertilizer producers and importers for the difference between their costs and the prices fixed by it. Called subsidized rates, represent the difference between the cost of production/import of a fertilizer (equivalent of market price) and the actual amount that farmers pay or retail price of a fertilizer.

This difference between the market and the retail prices forms the basis for fertilizer subsidy budgeting.

A 12-year mean subsidy amount (Rs/ton) provisioned in respect of urea, DAP and MOP is shown in Figure 3. A deep delve into the value figures points out that the government extended the maximum support to urea (64%) followed by DAP (26%) and MOP (10%). On an average (12-year mean) the retail price of DAP and MOP has been four and three times higher, respectively than urea (Fig. 4). This differential

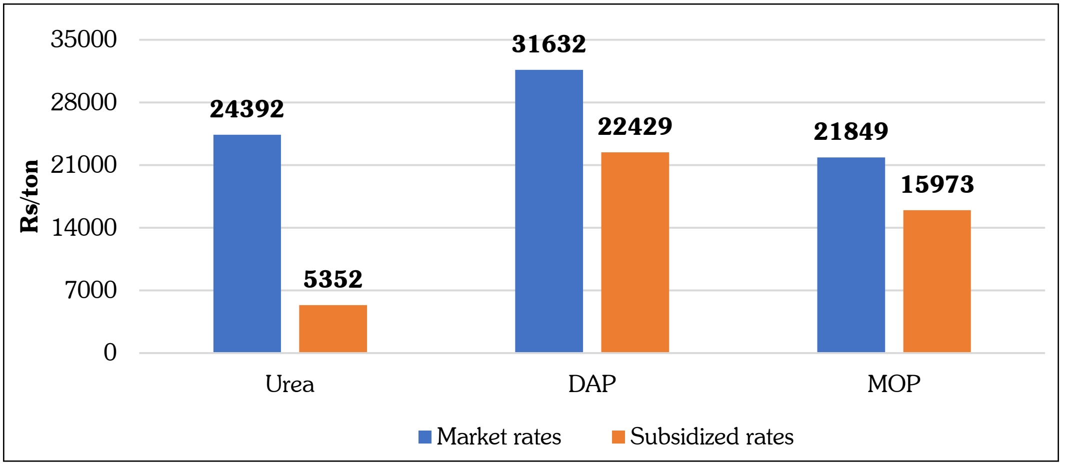


Fig. 3. *Comparison of market and subsidized rates*
(Rs/ton; data represent mean values of period covering 2010-22)

(Data source: FAI, 2021-22)

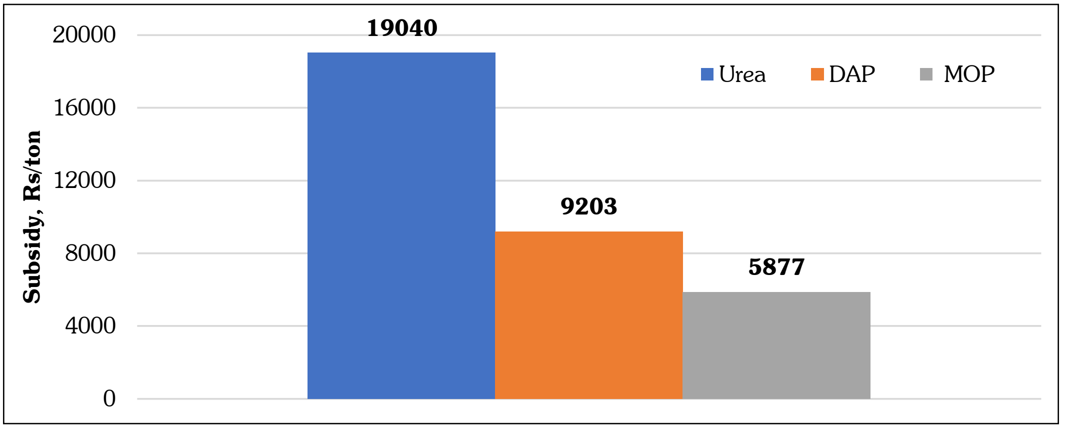


Fig. 4. *Average (2010-2022) subsidy (Rs/ton) extended to urea, DAP, and MOP*

(Data source: FAI; Author's calculation) treatment is borne out of the intentional and random step-motherly grant of subsidy to DAP and MOP. The details on this aspect will follow:

History of fertilizer subsidy scheme

The first fertilizer subsidy scheme came into existence in 1957 in the form of fixing MRP for urea *via* the Fertilizer Control Order (Fertilizer Performance Audit, CAG Audit Report 2011, https://cag.gov.in/en/audit-report/details/2521). Since then, Fertilizer Subsidy Scheme has been revised 11 times. The last revision came in April 2010 in the form of Nutrient Based Subsidy Scheme (NBS), which specifically covered subsidy to P (DAP), K (MOP) and S (compound fertilizers) and following that NBS provisions were modified; and the major revision came in April 2021 (PIB, 2023).

Subsidy to urea

Urea is kept out of the NBS and is treated individually. Its retail price is governed by a statutorily notified uniform MRP. As per the latest guidelines, a 45 kg bag of urea (all neem coated) is being marketed at MRP of Rs 242.10 (indigenous) and Rs 266.50 (imported) (PIB, 2023). Based on the 12-year mean (2010-2022), farmers pay only 22 per cent of the market rates for urea. The corresponding price burden is 71 per cent more for DAP and 73 per cent for MOP, which works out ~3.5 times higher than urea. Negative aspects of this differential treatment apart (explained in a subsequent section), maintaining affordable price of urea is essential because: i) N is normally deficient in Indian soils, hence must be given greater attention when it comes to assuring continuous supply and management for sustainable productivity growth, ii) crops, typically cereals (rice and wheat), require it in large amounts (~25 kg/ton of produce) necessitating higher application rates to be repeated every season, iii) it is farmers' favorite nutrient as they see quick and visible response (lush green crop) on application, and iv) being part of the living biosphere, N is intimately related with the cycle of life as humans need N-rich foods (proteins and essential amino acids) to support good physique and mental health.

Nutrient based subsidy (NBS)

Under the provisions of NBS, subsidy is granted on the nutrient content of DAP (P_2O_5 46% +N 18%), MOP (K_2O 60%), and compound fertilizers (S). The focus of NBS is, however, primarily on DAP and MOP. Subsidy guidelines governing NBS are revised from time to time. As per the most recent information (PIB, 2023), NBS rates granted to DAP and MOP have been raised substantially both for indigenous and imported fertilizers (Fig. 5). As is evident from the data, within one-year NBS rates were raised about 5, 5, and 2.5 times in respect of N, P, and K. As a result, subsidy per kg for urea or DAP is nearly the same (Table 1). Significant enhancement in NBS on N, P, and K has made their prices attractive which is likely to boost application rates of DAP and MOP. This is seen as a genuine step promoting balanced nutrition, which was at odds earlier (details in a subsequent section).

Fertilizer subsidy budget has grown exponentially – CAGR 9.55 per cent since 1990-91 (Fig. 6). Subsidy on fertilizer amounting to Rs 2.25 crores constituted 0.83 per cent of India's GDP (Rs 272.41 lakh crores) in 2023. Several factors contribute to the rise in fertilizer subsidy provisioning. Accordingly, a multifaceted approach is necessary to contain it (Mankunnummal, 2022). However, based on the

Table 1: Prevailing rates of NBS (Rs) granted to imported DAP and MOP and notified subsidized rates of urea

Fertilizer (Imported)	Price/bag	MRP/bag	MRP/kg	Subsidy/bag	Subsidy/kg
Urea	2450	266.5	5.33	2183.5	48.52
DAP	4073	1350.0	27.0	1918.0	50.02
MOP	22654	1700.0	34.0	759.0	

(Source: https://govtschemes.in/fertilizer-subsidy-scheme-2022)

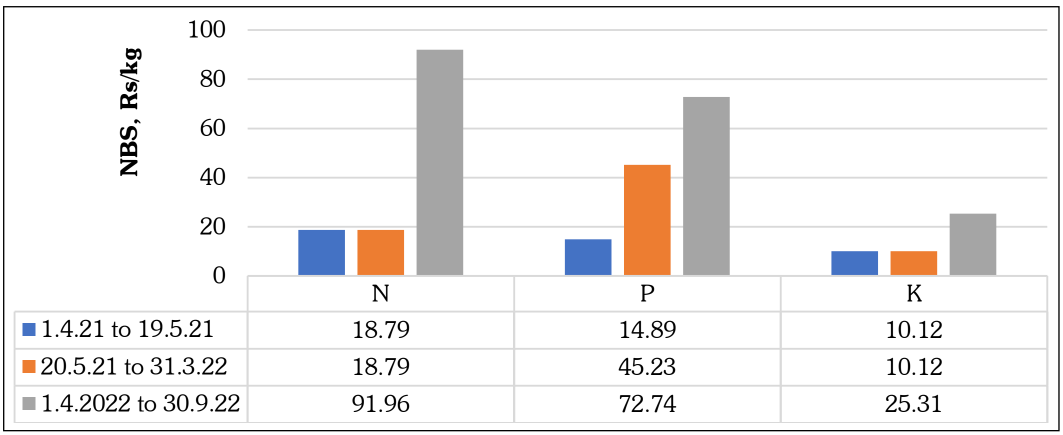


Fig. 5. *Changes in nutrient based subsidy (NBS) (N and P of DAP, and K of MOP) from 2021 to 2022*

(Data source: PIB, December 2022)

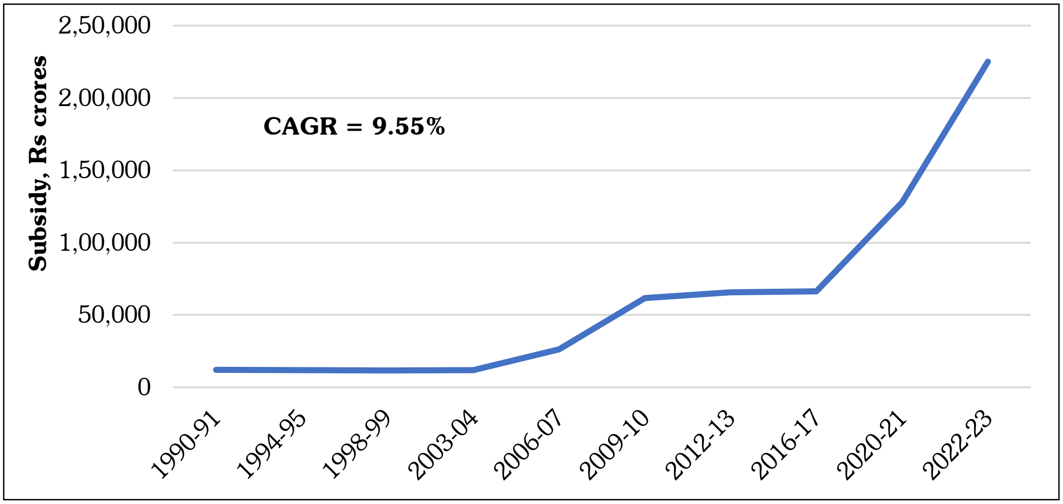


Fig. 6. *Growth in fertilizer subsidy (Rs, crore) since 1990-91*

(Data source: FAI, CAG Reports, Dept. of Fertilizers Budget documents).

scope of this report, total NPK consumption and imported price of raw materials/ finished products are the main factors. Their role is detailed in the following section.

Role of NPK consumption on subsidy budget

GoI has a genuine commitment to sustain foodgrain productivity growth to remain self-sufficient. It is echoed yet again, fertilizers had in the past and would also have in future an inescapable role in nurturing that goal. This is necessary to keep pace with the rising demand of foodgrains (~5m tons/annum) created by an unrelenting burgeoning population. For that, it is estimated that fertilizer use must continue to increase at least @ 5.3 per cent as was observed since the inception of Green Revolution. It means subsidy expenditure will further mount since NPK consumption is strongly influenced (correlation coefficient 0.81) by NPK consumption (Fig. 7).

Role of fertilizer prices on subsidy budget

As explained earlier, difference between the cost incurred by the fertilizer manufactures and importers and the retail price notified by the government forms the basis of subsidy payment. Over the years, slowly and steadily the cost of fertilizers increased (Fig. 8). Beginning 2022, it, however, jumped violently. As narrated earlier in this paper, Ukraine-Russia conflict triggered the spike both in the

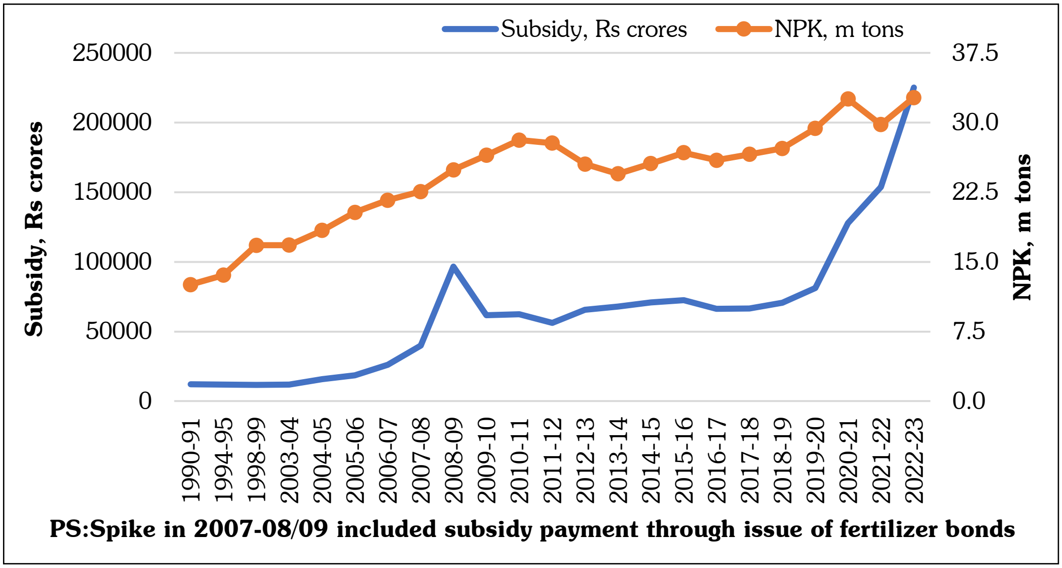


Fig. 7. *Relationship between fertilizer consumption (NPK mt) and subsidy budget (Rs crore).*

(Data source: FAI and Department of Fertilizers)

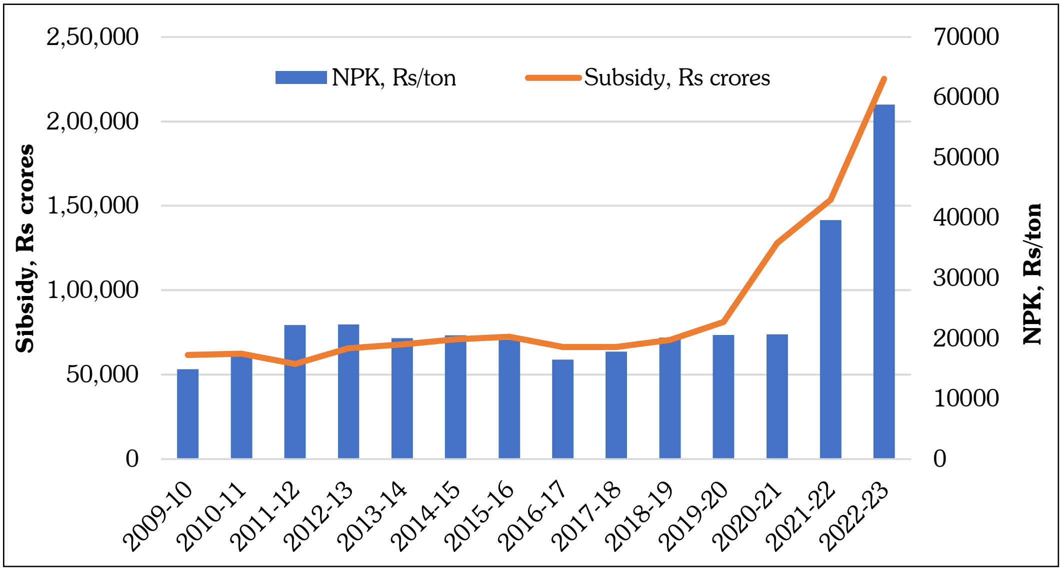


Fig. 8. *Relationship between price of NPK fertilizers (mean Rs/ton) and budgetary provisions for subsidy (Rs, crore).*

(Data source: FAI Statistics and Budgets of Department of Fertilizers) prices of finished products and raw materials. Since then, compared to NPK prices in 2020, in 2022 these jumped more than three- and one-half times in respect of urea and DAP and little over two-times for MOP (compiled from FAI Statistics 2010-21). The corresponding increase in retail prices, except MOP, of urea and DAP was insignificant. The widening difference had strong bearing (correlation coefficient 0.93) (Table 2) on fertilizer subsidy; nearly 100,000 crore more in 2022-23 than that in 2020-21. No doubt, international fertilizer, and raw material prices since 2022 have eased but remain at historically elevated levels. Without subsidy, fertilizer use remains unaffordable (https://blogs.worldbank.org/opendata/fertilizer-prices-ease-affordability-and-availability-issues-linger) and Katyal (2022).

Approaches to manage fertilizer subsidy bill

Several factors influence subsidy budget and so do the elements to contain it (Mankunnummal, 2022). However, based on the synthesis of the information presented above, both NPK consumption and market price are the key factors influencing subsidy financial plan. Therefore, to maximally contain subsidy financing both NPK consumption and market price must fall. While NPK consumption is possible to manage (details in a subsequent section), limited means are available to control international prices of fertilizers and fertilizer raw materials. Besides these two influencers, there are some administrative approaches to manage subsidy costs, which relate to making changes in fertilizer subsidy policy. The possible options are described below:

A. ***Equalized NBS*:** First suggestion is to grant equal NBS support to all fertilizer nutrients including urea-N,as this move is likely to support balanced NPK application by correcting distortions in NPK pricing. If that happens, it would be conducive to minimize the widely prevalent unacceptable NPK use ratio. For example, a widening NPK use ratio has strong bearing on soil health, agricultural productivity, climate change, and viability of domestic fertilizer manufacturers. An adverse outcome of shift to equalized NBS would be a possible rise in urea retail prices. Allowing only partial decontrol of urea may keep the price within an acceptable range depending on the market situation. The Government seems to have considered this move but was not accepted several practical hiccups. While urea subsidy regime remains unchanged, NBS extended to DAP and MOP has been raised substantially since April 2022 (Table 1). To a large extent that is likely to inspire a more balanced NPK use ratio.

B. ***Limit subsidy support to small and marginal farmers*:** Second alternative is that government exercises only necessary control and command on fertilizer production, distribution, marketing, and pricing. The market self-serves the interest of fertilizer producers and farmers; typically, big farmers who produce for markets. Correspondingly, the dominating group of small and marginal farmers have limited participation in the market. Accordingly, the interests of this vulnerable group need to be taken care of. In pursuance, it is recommended to build their otherwise *limited purchasing power* to buy a critical input like fertilizer (and seeds). Such farmers could be granted '*purchasing power support*' either in the form of cash or well-designated vouchers to receive an assigned amount of fertilizers. The kind of fertilizer-buying assistance could be linked to general soil test values given in the soil health-card. Since the main objective of the financial backing is to sustain fertilizer consumption by small and marginal cultivators, this plan complements their limited financial resources to invest in an otherwise costly input like fertilizer. In-kind support through vouchers is considered superior to cash handouts. Many African countries have successfully implemented voucher programs to support poor farmers (Druilhe and Hurlé, 2012). However, the proposed move to exclude big farmers from the beneficiary list is bound to create serious problems and unrest among them. Hence, the GoI is less likely to accept this approach too. Bumb *et al.* (2022) gave details on the above two alternatives to contain the subsidy budget.

C. ***Decelerating fertilizer consumption rise*:** Finding lack of unanimous support to alternatives to ongoing subsidy scheme, the most viable option to contain its financing seems to rationalize NPK consumption. While doing that it would be essential to ensure *ecological sustainability*, which means reducing use of fertilizers without affecting the target productivity growth and no cost to health of soil, water, and air. The overall goal of the proposed approach is 'to enhance fertilizer subsidy financing efficiency'. By priori it means containing growth in subsidy budget by condensing fertilizer consumption without affecting sustainability of farm productivity and farming profitability. It also tantamounts to substituting partially the requisite fertilizer dose by another source. It also means induction of better management practices that help increase use efficiency and reduce dependence on synthetic fertilizers. Either way productivity will be sustained, and soil, water, and air quality conserved. In brief, with subsidy budget containment as the epicenter, this paper focusses on suggesting practical ways and means for minimizing consumption of synthetic fertilizers for sustaining food security, nurturing soil health and mitigating climate change. In pursuance of these targets, maximizing fertilizer use efficiency (FUE), more specifically of FN, will be the master strategy on decelerating consumption.

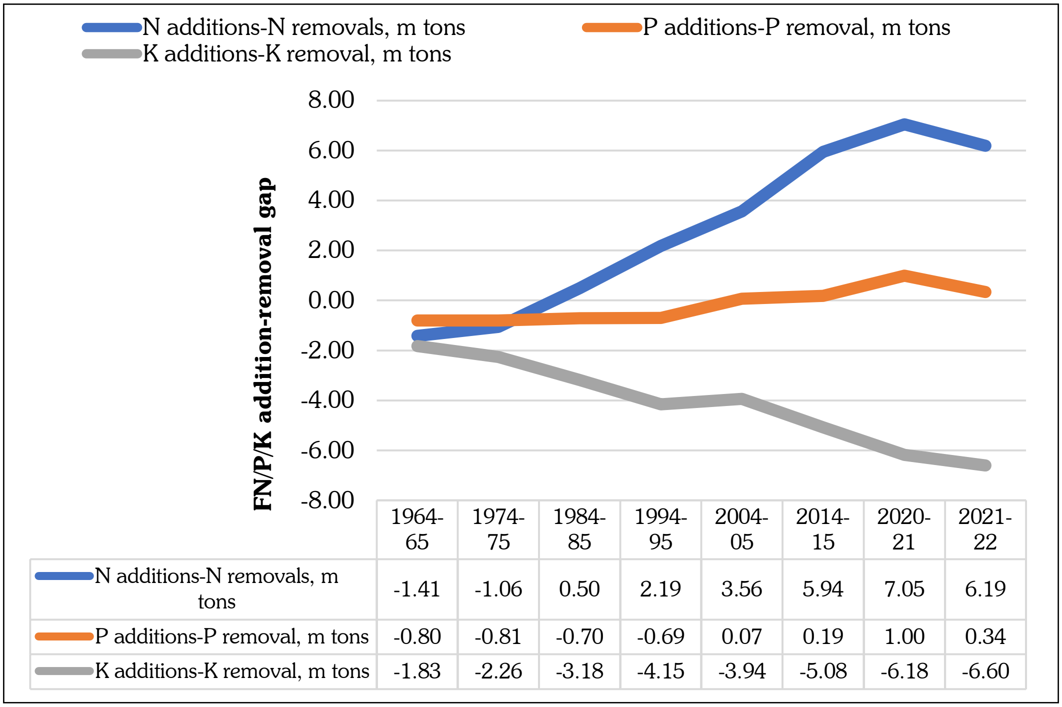
Fertilizer Use Efficiency

Rationale

Before delving into the subject of fertilizer use efficiency (FUE), the role of fertilizers in influencing foodgrain production (a necessary element of sustaining food security), soil health, and climate change (sustainable development in all its aspects) is explained first. The data on growth in foodgrain production and fertilizer use are considered since 1970-71 – the period from which the change due to introduction of HYVs and budget due to fertilizer subsidy scheme started becoming striking. Increasing fertilizer use (CAGR 5.3% since 1970-71) has been a plank for significant foodgrain production (CAGR 2.1% since 1970-71). This approach centering exclusively on raising fertilizer consumption by preferential subsidy support to FN elevating production, progressively dented health of soil (a harmonious blend of natural fertility, physical integrity, and biology), quality of water, normal composition of air, and life of biodiversity (Bumb *et al*., 2022). These developments opposed conservation of environmental sustainability consequences of which are detailed below.

Fertilizer use related concerns and ecological sustainability

Rationalizing fertilizer use, besides containing subsidy budget and saving foreign exchange spent on imports, seems imperative to minimize above stated adverse environmental consequences. The reasons are explored here briefly. With the rise of hitherto unknown negative ecological developments, the productivity of soil and water gradually dipped, affecting foodgrain production growth. It also led to deterioration in standard quality of air accelerating global warming/climate change. For instance, imperfections in subsidy policy promoted excessive fertilizer-N use, which had two clear side effects. Firstly, N balance tended to shift towards FN credits. The data on addition – removal gap is witness to that. The information presented in Figure 9 demonstrated that with time, the difference, FN additions minus crop N removals, tilted towards additions. It indicated that application rates exceeded crop needs. This pushed accumulation of soil-N. Buildup of soil-N catalyzed soil organic carbon (SOC) loss (Khan *et al*., 2007, Katyal and Chaudhary, 2021) – the seat of adverse ecological developments. Coincidentally, soil health deteriorated, and greenhouse gas (GHG) emissions increased, thereby fueling global warming/ climate change. Setback to soil health exhibited itself in the form of weakening of soil fertility, (particularly that of soil-K), loss of soil integrity, water holding capacity and death of useful soil biology - all known to negatively affect crop productivity. Falling productivity growth rates of foodgrains, while other conditions remained favorable, validated that conclusion (Fig. 10).



	1964-65	1974-75	1984-85	1994-95	2004-05	2014-15	2020-21	2021-22
N additions-N removals, m tons	-1.41	-1.06	0.50	2.19	3.56	5.94	7.05	6.19
P additions-P removal, m tons	-0.80	-0.81	-0.70	-0.69	0.07	0.19	1.00	0.34
K additions-K removal, m tons	-1.83	-2.26	-3.18	-4.15	-3.94	-5.08	-6.18	-6.60

Fig. 9. *Progressive shift in FN, FP, and FK addition-removal gap (mt)*

(Data source: FAI, Author's calculations)

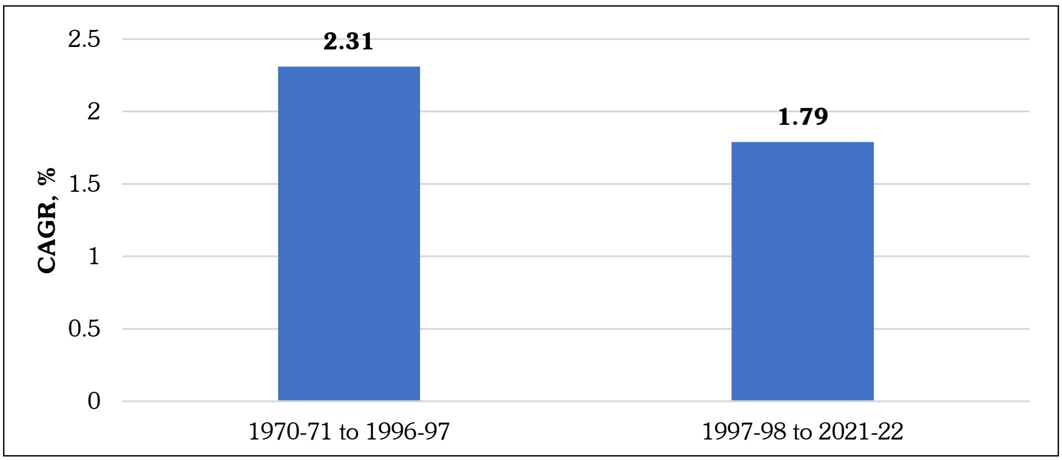


Fig. 10. *Comparison of CAGR (%) of foodgrain production between fist 26 years (1970-71 to 1996-97) and the next 25 years (1997-98 to 2021-22) of Green Revolution.*

(Data source: FAI 2021-22; Author's calculations)

(https://www.sciencedaily.com/releases/2019/09/190917115439.htm#:~:text=N2O%20is%20a, times%20greater%20than%20carbon%20dioxide). During the last 30 years, N_2O concentration increased.

Soil accumulated N-driven breakdown of SOC promoted continuous production of carbon dioxide (CO_2). In addition, microbial transformations of accrued soil-N heightened nitrous oxide (N_2O) emissions. Both these events are deeply concerned with climate change/global warming. Focus is, typically, on N_2O of whose flux moves up with fertilizer-N consumption (Park *et al*., 2012; Katyal and Chaudhari, 2021) (Fig. 11). No doubt, current air concentration of N_2O (~330 ppb) is only ~1000th of CO_2 concentration, however, comparatively it exhibits ~300 times higher global warming potential and stays far longer in the atmosphere (half-life 114 years). It is also the main cause of depleting protective ozone shield. During the past 30 years, N_2O concentration increased 36 per cent and the key contributing factor was the rising consumption of fertilizer-N (Park *et al*., 2012; Katyal and Chaudhari, 2021).

It is re-emphasized that subsidy policy gave preferential push to urea-N – the major N carrier (~80% of total FN consumed). It was done by making it available at cheaper rates compared to DAP and MOP. For instance, currently urea is ~70% less priced. However, DAP, despite being expensive, is farmers' favorite. This preference is linked to superior response it produces and the ease of placing it as basal dressing, Farmers, in general, follow recommended dose of DAP treatment. As a result, P balance has stayed near neutral (Fig. 9). Corresponding to urea and DAP, because of cost and not so visible response, use of MOP remains largely ignored. This neglect has hurt the balanced application of NPK fertilizers – a fundamental

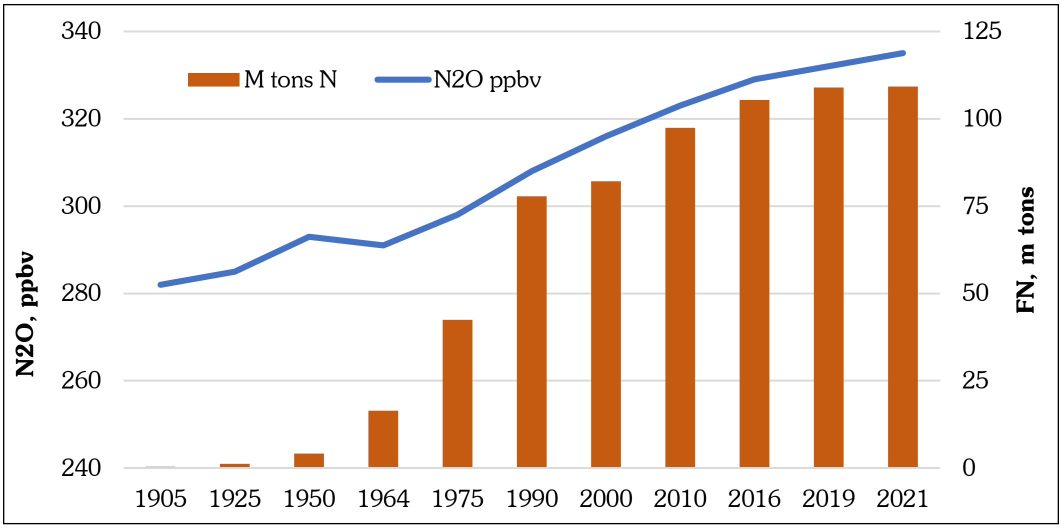


Fig. 11. *Effect of fertilizer N consumption (FN, m tons) and aerial concentration of N_2O.*

(Data source: FAO, FAI; https://www.n2olevels.org) necessity to sustain soil fertility and productivity. Thousands of fertilizer experiments in the farmers' fields and long-term studies conducted at research farms across length and breadth of the country (Katyal and Chaudhari, 2021) proved beyond doubt the need for balanced use of NPK to sustain productivity and profitability of farming. Currently, NPK use ratio of 7.7:3.3:1 (FAI, 2021-22) paints a distorted picture of a needed equalized NPK treatment. In fact, unbalanced NPK application seems to have been the norm since the introduction of fertilizer subsidy policy in mid-1950s. A 65 year mean value of 7.0:2.3:1 is a proof to suboptimal application of FK. Typically, a wide N to K use ratio points to an under-emphasized use of FK, meaning thereby a relentless dependence of crop growth and yield on depleted soil K. Incessant mining of soil-K over the last 60 years established a negative K balance.

It is suggested to employ a 'Soil Nutrient Mining Index (SNMI)' to estimate progressive plunder of soil-K. The proposed SNMI is calculated by the nutrient balance or budgeting method of the IFA (Reetz, Jr., 2016). It is obtained by dividing total crop uptake/removal (grain and straw) of a nutrient (called NR or nutrient removal) by input of that nutrient from all sources (synthetic and natural). It is referred as nutrient input or NI. A value of SNMI >1 indicates soil mining. The greater the SNMI value, the higher is the depletion intensity. On the contrary, values of SNMI <1 points to soil buildup of that nutrient. SNMI values were assessed for Indian foodgrain crops for the period from 1964-65 to 2021-22. Estimates presented in Figure 12 showed that K SNMI was consistently greater than 1.5; meaning that K removals exceeded K inputs by a factor of at least 150 per cent. On the same lines, SNMI values for P were a shade <1 after 2000. It signaled that food-grain crops being grown on Indian soils were not being mined as removals were neutralized by additions. Remarkably, SNMI for N fell significantly below 1.0 since 1990, confirming overuse, typically of FN. Two revelations reverberate from SNMI analysis: i) intensity of FN use is possible to reduce at least by 25 per cent to minimize negative developments like soil health decline and global warming rise (refer to above), and ii) K mining of soils is rampant and calls for urgent action to reverse its adverse effect on foodgrains production growth (Fig. 10). These deductions on SNMI are in sync with the conclusions drawn from nutrient gap analysis (Fig. 9). Both these point towards a possible negative effect on food security and global warming/climate change.

Making fertilizers available at subsidized (low cost) prices did not necessarily inspire prudence in use (judicious management for efficient use). Findings of long-term fertilizer experiments unambiguously confirmed (Katyal and Chaudhari, 2021)

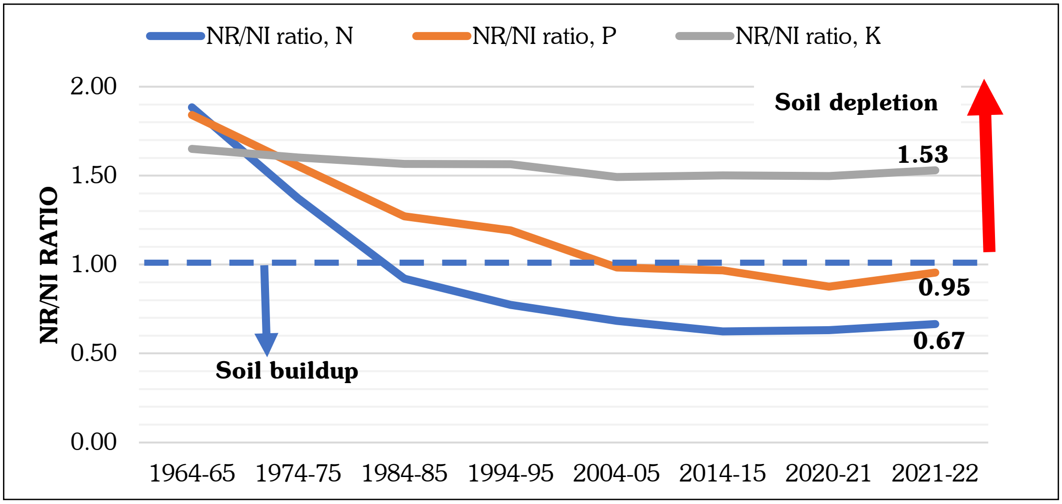


Fig. 12. *Dynamics of SNMI values pertaining to N, P, and K (removal/addition ratio or NR/NI) for foodgrain (FG) crops*

(Data source: FAI; Author's calculations)
PS assumptions: total FG production = grains + straw (FG*1.6); of the total NPK consumption 70% (formed of FN, 50%; FP 40%, and FK 30%) was diverted to FG crops; NI was calculated by adding, respectively FN + 50 of N removal (total crop uptake), FP + 50% of P removal and FK + 60% of K removal.

that fertilizers *per se* were not averse to sustaining productivity growth, soil health, and containing climate change it was mainly the over- and under-use, respectively of FN and FK that were important contributors to these negative developments. Besides, poor management of fertilizers and non-adoption of standard agronomic practices punished the soil health maximum. This finding was a reflection on the weakening of the technology transfer system. For instance, extension agents informed farmers about the role of increasing fertilizer applications for lifting productivity but the consequences of doing that remained largely underemphasized raising fertilizer treatment to some extent compensated the productivity loss, but the health of natural resources took a dive (refer to later section for experimental evidence). As a result, input cost increased without commensurate advantage in terms of output value – an indication of dipping fertilizer use efficiency (FUE, i.e., more output/unit input) and a consequent upsurge in fertilizer subsidy budget. Besides bad economics, increasing fertilizer use multiplied processes leading to ecological degradation, i.e., fall of soil health, pollution of groundwater, rise of global warming/climate change, etc. all impinging on human well-being (Bumb *et al.*, 2022). As lessening fertilizer consumption is necessary for containing subsidy budget (refer to above synthesis), improving fertilizer use efficiency offers the best possible solution. It is because this low-cost strategy is both pro-economic (more output/unit input) and pro-nature (ecologically sustainable).

Apart from the adverse influence of rising NPK consumption on soil health and climate change, FN manufacturing also promotes degradation of soil, water, and air quality. Since the role of fertilizer production is direct in sustenance of normal composition of atmosphere leading to climate change, this subject is being brought upfront. As explained in a previous section, chemical fertilizer synthesis – typically FN (urea) is accompanied by the emission of global warming CO_2 and N_2O gases. Their amount enriching the atmosphere is in addition to that produced and released following field application of FN. The two sources - factory and field, together are, thus, contributors to ongoing climate change. Called 'the life cycle GHG emissions footprint' related to synthetic FN constitutes 21.5 per cent of the total emissions generated by the agricultural activities. Menegat *et al*. (2021) estimated the share of FN production and consumption on GHG emissions. As per their projections, the former (factory) constitutes 35.2 per cent, the latter (field) 62.4 per cent and the remainder 2.4 is released during transport. Apparently, the role of FN application to field in mitigating climate change dominates. Also, if field use falls so will be the need to manufacture, which will lessen factory related GHG emissions. No doubt, minimizing GHG emissions during manufacturing remains significantly important. Rationalizing FN consumption by improving FUE seems to be an additional win-win strategy to contain climate change and subsidy budget.

Description of FUE and rationale of centering on it to minimize NPK consumption

In general parlance, as described in an earlier section, FUE refers to nurturing output (say foodgrain production) with less input (say fertilizers). Pursuance of widening output-input ratio must also prop up soil health and air quality. In simple terms, FUE gives an expanded view of ecological sustainability, which amplifies: i) promoting the target pace of growth in foodgrain productivity/production with minimum dependence on synthetic fertilizers to feed the burgeoning population, and ii) zero damage to natural resources-led provisioning of environmental services, such as maintaining flow of productivity growth, sustaining SOC, and containing climate change (Fig. 13).

From the description given above and summed up in Figure 13, it seems that FUE scores more as a 'concept' than being an empirical 'term'. It is justified for FUE conveys a broad perspective emerging from real life experience like minimizing

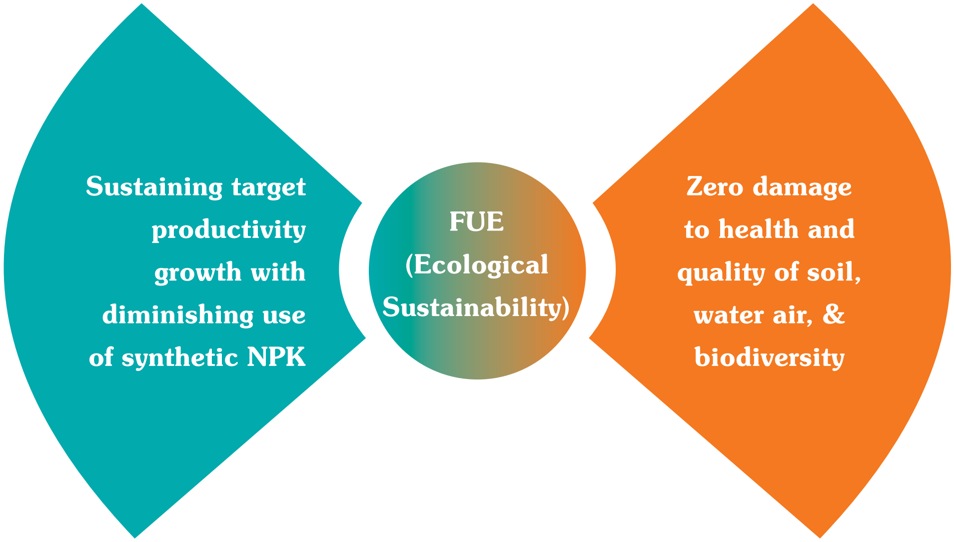


Fig. 13. *Conceptual model of FUE/ecological sustainability*

fertilizer use by supplements or substitutes for sustainable productivity growth and degradation-neutral flow of environmental services. With this conceptual framework, FUE calls for involvement of several intersecting practices as follows:

- Raising fertilizer productivity or nutrient use efficiency for which the focus is on good management practices that are site-specific but holistic (i.e., application of an entire set of standard agronomic practices including best management of soil, crop, water, and input in unison); introduction of fertilizer saving diversified cropping systems/varieties, and development of innovative products that are more efficient, economically favorable, and environmentally benign.
- Integration of complementary sources that replace a part of synthetic fertilizers and synergize the positive output (yield), outcome (better soil and air health), and impact (quality of human health).
- Insertion of indigenous substitutes (minerals and ores) that cuts down dependence on synthetic carriers, and/or imported products and raw materials. Alternative farming methods that champion greater reliance on-farm resources by harmonizing application of tradition and technology (natural farming, conservation agriculture, regenerative agriculture, etc.).

Strategy on the value of each one of these approaches in strengthening concept of FUE is discussed in detail in a subsequent section. However, a few additional details on comparative relevance of FUE concerning N, P, and K are given here. Of these three major plant nutrients, primary focus is on FN because FP use efficiency though no more than 25 per cent for the immediate crop receiving application, is considered 100 per cent (Bumb *et al*., 2022) justified by explaining that the residual FP after the first crop stays in the soil and sooner or later becomes available to the following crops. Same logic they extended while assigning 100 per cent use efficiency to FK too. In striking contrast to FP and FK use efficiency by crops of FN is generally less than 35 per cent. This assessment stands vindicated because the unutilized FN left in the soil after the crop receiving application is of little benefit (no more than 15%) to the crops in rotation (Katyal, 2019). Almost 50 to 60 per cent of the applied FN is considered lost because it exits the soil-plant system and is beyond the reach of crop roots. Remarkably, the loss processes begin after application and ebb on completion of the life cycle of the treated crop. This element, in fact, is the main contributor to the notoriously low use efficiency of FN. Not only does the FN disappearance bring down the economics of investment on fertilizers but this plunder is also a source of rising environmental concerns. It is no exaggeration to state that the FN use efficiency (NUE) echoes largely FUE. Loss of FN happens through a series of processes. It goes out as: i) ammonia (NH_3) vapors by the process called NH_3 volatilization, ii) N_2O gas through a course of microbial transformations known as nitrification followed by denitrification, iii) movement down into the soil profile with infiltrating water as nitrate (NO_3) following the route termed leaching, and iv) a small portion is immobilized by the soil also.

NH_3 volatilization – a surface phenomenon, happens in the oxic flood waters of poorly drained flooded rice soils (also occurs from the wet surface of upland soils). However, under anoxic conditions, occurring across a wide variety of crop growing conditions, denitrification – a multistep microbial action, dominates. According to the research findings summed-up by Katyal (2019), contribution of FN loss as N_2O from the submerged soils is not of great consequence. Leaching, on the other hand, is the process that takes place in well-drained light-textured soils (sandy to sandy loams). Infiltration following irrigation or heavy downpour accelerates the progression of leaching. Katyal (2019), from the synthesis of available information concluded that NH_3 volatilization, in general, is a major concern of pervading low NUE as it causes relatively higher losses of FN than either denitrification or leaching. Flooded rice, estimated to consume 35 to 40 per cent of the total FN, offers the maximum opportunity to save fertilizer by improving consistently low FN use efficiency (currently ~30). Additionally, NH_3 volatilization also remains a serious phenomenon of irrigated upland soils where FN broadcast on the wet surface, a common practice of fertilizer management, provokes its incidence (Katyal *et al*., 1987). Denitrification incidence gains momentum when nitrified FN formed under aerobic upland conditions confronts anaerobic environment created temporarily after irrigation or rain events. Leaching is largely limited to heavily percolating sandy loam soils (entisols/ inceptisols) as are commonly found in Punjab or elsewhere. Singh and Craswell (2021), based on the synthesis of global data, highlighted that only a small portion of FN is likely to leach down and reach ground and surface water bodies.

Ammonia volatilization does not lead to any significant environmental or human health concerns, except that NH_3 enriched air may cause impaired visibility, irritation in the eyes or may corrode the implements. Denitrification driven generation of N_2O is a serious source of climate change (refer to details in an earlier section). Since N_2O kills protective ozone shield, it may expose terrestrial life to harmful consequences of UV rays. Uninterrupted FN driven NO_3 leaching into groundwater may raise its concentration to dangerous levels (> 50 ppm NO_3 as per WHO), nitrate levels above the safe limit when ingested may cause blue baby syndrome or anoxia and a few other health problems (Bumb *et al.*, 2022).

Expression and measures of FUE and NUE

Both FUE (refer to NPK fertilizers) and NUE (refer to FN) are expressed by applying different yardsticks. By and large over the years, irrespective of the measure employed, values of FUE and NUE have moved downwards. An account of both is presented below with evidence – estimated and experimental.

Partial factor productivity (PFP or fertilizer productivity)

PFP presents ratio of foodgrain production and consumption of fertilizers. It is expressed as foodgrain production per unit of NPK use (tons foodgrains/ton of NPK). Since 70 per cent of the total NPK consumption is allocated to foodgrain crops, this factor is incorporated into yearly fertilizer use statistics before computing PFP values. On this basis, the PFP values demonstrated that PFP values collapsed from 81.0 tons foodgrains/ton NPK in 1970-71 to 14.0 tons foodgrains/ton NPK in 2021-22. This striking descent followed an equally sharp ascent in NPK consumption. A correlation coefficient (r) value of -0.77 confirmed the negative association between the two. Since the PFP is an indicator of long-term trends, describing role of fertilizers in sustaining production, a plunge of 67 per cent points is a matter of grave concern - both from economic and environmental angles. Nevertheless, conventional PFP measurements are known to overestimate as these ignore the contribution of initial soil fertility to growth and yield of foodgrains (Olk *et al.*, 1999; Ladha *et al.*, 2016). To overcome this oversight, Katyal and Chaudhary (2021) reckoned only 40 per cent share of fertilizers in increasing foodgrain production in their estimates of PFP. With that adjustment, no doubt the PFP plummeted but somewhat gently (Fig. 14). For example, the PFP value of 32.4 during 1970-71 tumbled to 5.6 tons foodgrains/ton NPK in 2021-22. These estimates seem reasonably acceptable. Despite this improvement, there exists deficiencies in PFP estimates. Bumb *et al*. (2022) suggested to use other measures of expressing FUE, like agronomic efficiency, for NPK and nitrogen use efficiency for FN (see details below).

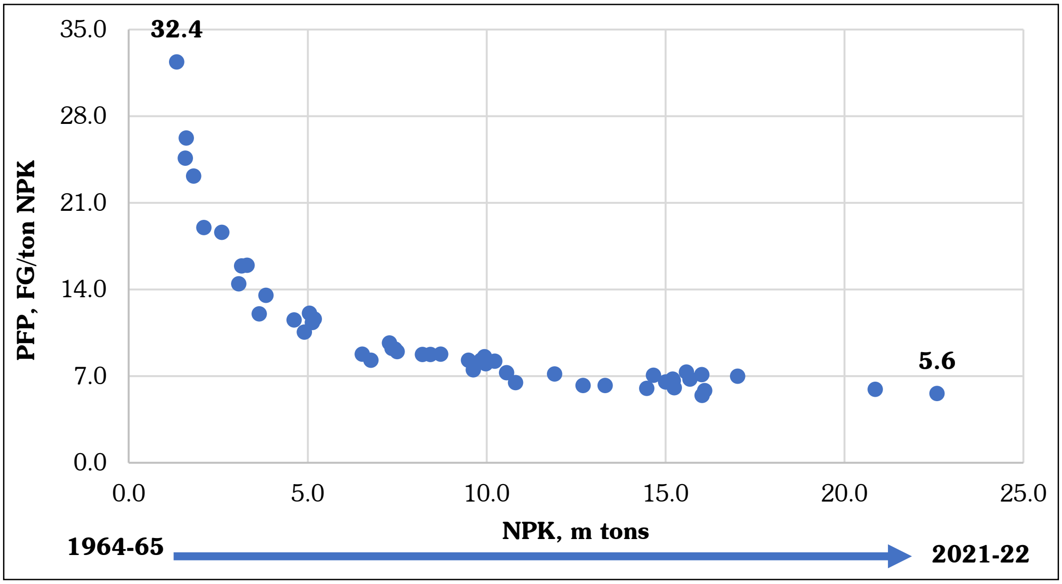


Fig. 14. *Dynamics of PFP (tons FG/ton NPK) since 1964-65. Assumptions for computation: NPK consumption for foodgrains (FG) was 70% of the total, and 40% of total FG increase was attributed to NPK.*

(Data source: FAI; Authors calculations)

Agronomic efficiency (AE) is used to measure productivity gain due to fertilizer treatment. It is calculated by subtracting kg grain yield of unfertilized plot from kg grain yield of fertilized plot and dividing the difference by kg of applied NPK. AE expressed as kg grain yield per kg of NPK is also called response ratio. AE estimates suit assessment at micro-level where data from fertilized and unfertilized plots are available for calculations. At the macro-level - regional, national, or global, based on the review of earlier literature, Katyal (2019) reported that during 1970s, each kg of NPK fertilizer produced 10-12 kg foodgrains, which stumbled to less than one half 40 years later. Utilizing the Indian fertilizer consumption and foodgrain production statistics, he devised an innovative method (Bumb *et al.*, 2022) to calculate AE at the country level. He estimated AE by subtracting decadal mean of foodgrain production and NPK consumption from the decadal means of next decade. For example, considering 2002-11 mean values (say first decade): total foodgrain production was 209.7 mt at the expense of 17.7 mt of NPK consumption. Accordingly for 2012-21 being the next decade, the corresponding mean value were: total foodgrain production 267.2 mt, total NPK consumption 23 mt (FAI, 2021-22). Katyal and Chaudhari (2021) reported that 40 per cent increase in foodgrain production was due to fertilizers. Also, they informed that 70 per cent of the NPK consumption was allocated to foodgrain. Incorporating these corrections, the respective values would be 107 and 84 mt (foodgrains) and 23 and 16 mt (NPK). The agronomic efficiency works out 6.2 kg FG/kg NPK (i.e., 107-84/23-16). Compared to that, applying the same yardstick, respective AE value for the decade 1970-79 was 10.7 kg FG/kg NPK. Data presented in Figure 15 exhibit the dynamics of AE values beginning with the decade 1960-69 and up to 2010-19 including triennium 2020-22. Falling AE with time indicates that a relatively higher dose of NPK has become necessary to sustain productivity growth equal to the yester years. It is both economically less profitable and environmentally more harmful. To a greater extent, in the recent times when the international prices of fertilizers and raw materials rose viciously, affordability to use fertilizers has become less sustainable (Katyal, 2022). To neutralize the additional burden on farmers of

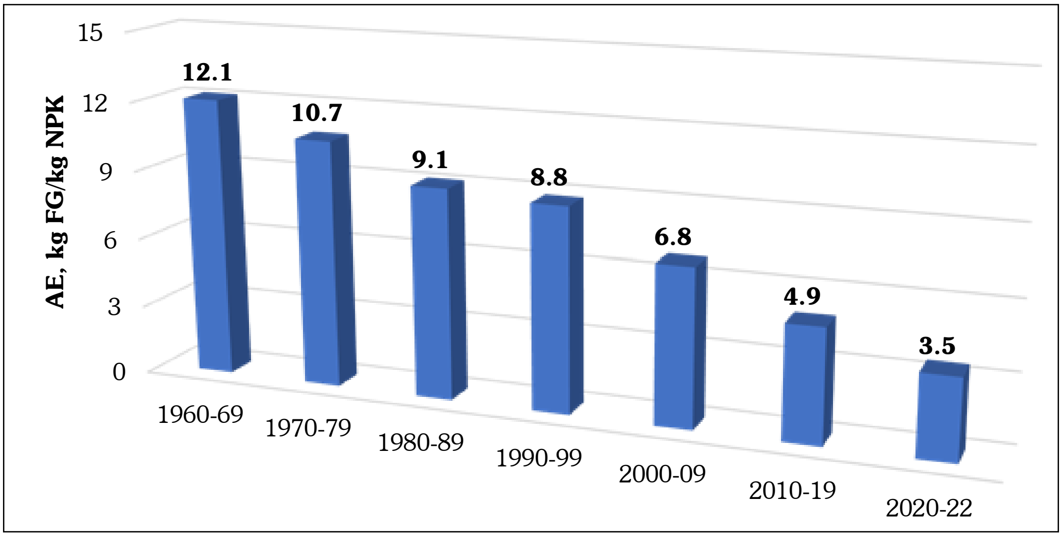


Fig. 15. *Decadal mean (except triennium 2020-22) agronomic efficiency (AE, kg FG/kg NPK) since 1960.*

(Data source: FAI 2021-22; Author's calculation) price rise, the government continues to offer NPK at the previously fixed market rates. Resultantly, there has been an abrupt rise in the subsidy budget (details in an earlier section).

Fertilizer Nitrogen Recovery Efficiency (FNRE) refers to the difference between FN absorbed by the above ground parts of the fertilized crop from that by the unfertilized crop and dividing the result by the amount of FN applied. Like FNRE, FPRE and FKRE can also be calculated. In this report, as explained above, focus of nutrient use efficiency in respect of P and K is assumed to be 100 per cent. In pursuance of that, focus is on FN use efficiency or FNRE alone

FNRE estimates utilizing the above procedure give higher values. This happens because the assessments exclude the boost that FN absorption gets from soil-N pool. This is called 'priming effect'. On this count, FNRE appraisal by the susbtration method is not real and is, therefore, referred to as apparent FNRE. This problem is overcome by using ^{15}N labeled fertilizers that can distinguish the exact part of N uptake from the FN and soil-N. NUE estimates involving ^{15}N labelled fertilizers across some representative crops and growing environments (Table 2) showed that the lowest (~30%) FNRE values were obtained with lowland rice. There was no difference in FNRE values between urea and ammonium sulphate fertilizers; indicating that lowland rice is prone to poor use efficiency. Nevertheless, sulphur coated urea (SCU), a slow-release N carrier, was more efficient than either urea or ammonium sulphate. These data additionally showed that upto 55 per cent FN was not absorbed by the crop and hence was lost. Also, irrigated wheat exhibited superior FNRE values compared to lowland rice. A less common potassium nitrate fertilizer demonstrated the maximum use efficiency with wheat. Also, relatively higher FNRE figures (>50%) corresponding to rainfed crops are remarkable, typically, for deep Alfisols and Vertisols. However, with shallow soils the FNRE did not exceed 40 per cent (Hong *et al*., 1992). Because of uncertain moisture availability and lingering chances of crop failures, farmers cautiously fertilize rainfed crops. Contrary to this perception, rainfed crops require fertilizer treatments for sustaining good growth and yield. Long term experiments, conducted across diverse soils and environments proved beyond doubt the profitability of fertilizer treatment.

FNRE estimates involving ^{15}N labelled carriers, no doubt, give valuable insights into crop N absorption patterns and loss pathways. A comprehensive review of this material is helpful in innovating fertilizer saving practices by devising loss minimizing management methods. However, to develop N budgets that influence context and construct of regional/country level practices, and policies utilizing the power of

Table 2. Findings of FN recovery efficiency (% ^{15}N) – Indian experience.

Source	Soil	^{15}N recovery	^{15}N loss	Reference
		Lowland Rice		
Ammonium sulfate	Inceptisol	28	46	Katyal *et al*. (1985)
Urea	Inceptisol	20	55	Khind and Datta (1975)
Urea	Inceptisol	23	48	Katyal *et al*. (1985)
Urea	Inceptisol	31	39	Goswami *et al*. (1988)
Sulphur coated urea	Inceptisol	42	28	Singh and Katyal (1985)
		Irrigated Wheat		
Urea	Vertisol	24	60	Shinde *et al*. (1985)
Urea	Inceptisol	35	30	Katyal *et al*. (1987)
Potassium nitrate	Inceptisol	65	5	Katyal *et al*. (1987)
		Rainfed Sorghum		
Urea	Vertisol	55	6	Moraghan *et al*. (1984a)
Urea	Alfisol (deep)	64	8	Moraghan *et al*. (1984b)
Urea	Vertisol	56	7	Hong *et al*. (1992)

(Source: Katyal 2016)

labelled sources is neither practically feasible nor economically viable. Absence of such information also impedes establishing crucial role of FN in sustaining food security, maintaining good soil health, containing climate change, and nurturing well-being of life on Earth.

Over the last decade or so, focus shifted from experimental plots to estimating FNUE at landscape, regional, country, or global levels. A simple technique, called nitrogen use efficiency (NUE) was widely used. The procedure involves calculating the ratio of total N output in the harvested produce (N removed by grain + straw) to that of N input (FN + natural N pool). Apparently, various elements of requisite data to determine NUE by this method are available from the primary statistical tables or can be calculated effortlessly. Except the N contributed by the natural sources (organic manures, SOC, N_2 fixation) must be aggregated from the published literature. In this paper, a value equal to 50 per cent of the total N uptake by the harvested produce was assumed to be sourced from natural means. This assessment matches that made by Ladha *et al*. (2016), who assigned ~50 per cent credit to natural N pool in the total N uptake. In other words, the N input was the sum of FN consumption and 50 per cent value of crop N removal.

Lassaletta *et al.* (2014) an alternative NUE assessment method to compute 50-year trend (1961-2009) analysis of NUE of agriculture across 124 countries and the world. Findings of their evaluation pertaining to India, China, and the USA are presented in Figure 16. Results showed that in respect of China and India, NUE decreased with time and rising level of N input had a negative effect on the speed of dive. NUE of the Indian agriculture (decadal mean) fell from 54 per cent in 1961-70 to 34 per cent in 2001-09. The fall in NUE paralleled nearly that of China. Strikingly, compared to these 2 countries, NUE of the USA agriculture remained nearly constant (61% in 1961-70 vs 64 per cent in 2001-09) over the 50-year period of the study. Not only that, even the state of world NUE seemed superior to India and China (~30% vs 40%) (Zhang *et al.*, 2010; Lassaletta *et al*., 2014; Omara *et al*., 2019). NUE findings on Indian agriculture are a matter of great concern from economic and environmental angles. These disturbing statistics call for launching serious efforts to improve NUE for ensuring huge savings in FN consumption (Zhang *et al*., 2010; Lassaletta *et al*., 2014; Omara *et al*., 2019). Nevertheless, information about the target crops and cropping systems and their share in total N consumption *vis a vis* NUE was missing from these statistics. Data of this genre is essential for rationalizing consumption and to develop strategic plans to improve NUE. For instance, foodgrain crops, rice, and wheat usurp,

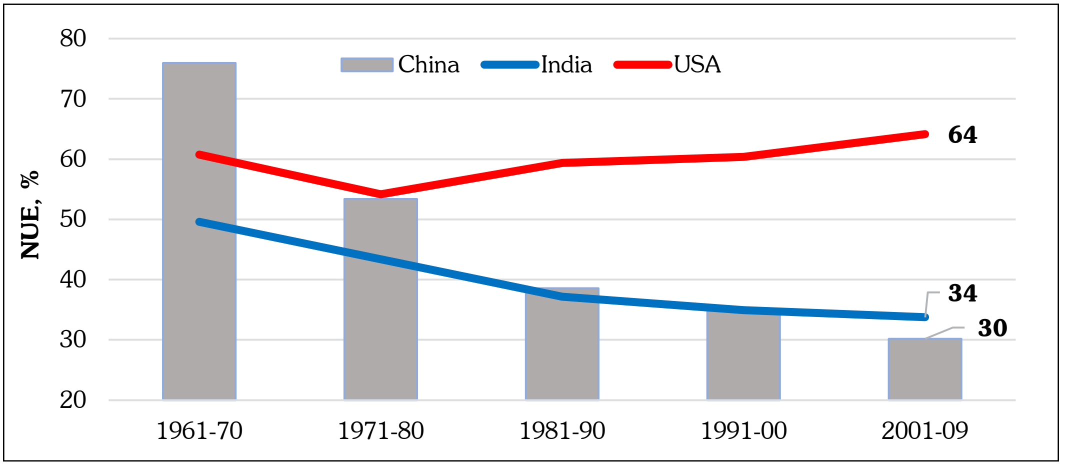


Fig. 16. *Dynamics of decadal NUE values (mean) of China, India, and USA agriculture, since 1961.*

(Data source: Lassaletta *et al*., 2014) respectively about 70, 29, and 23 per cent of the total FN consumed in India. Utilizing this information on FN consumption and grain production pertaining to these crops, 45-year NUE trends were computed (Figs. 16, 17).

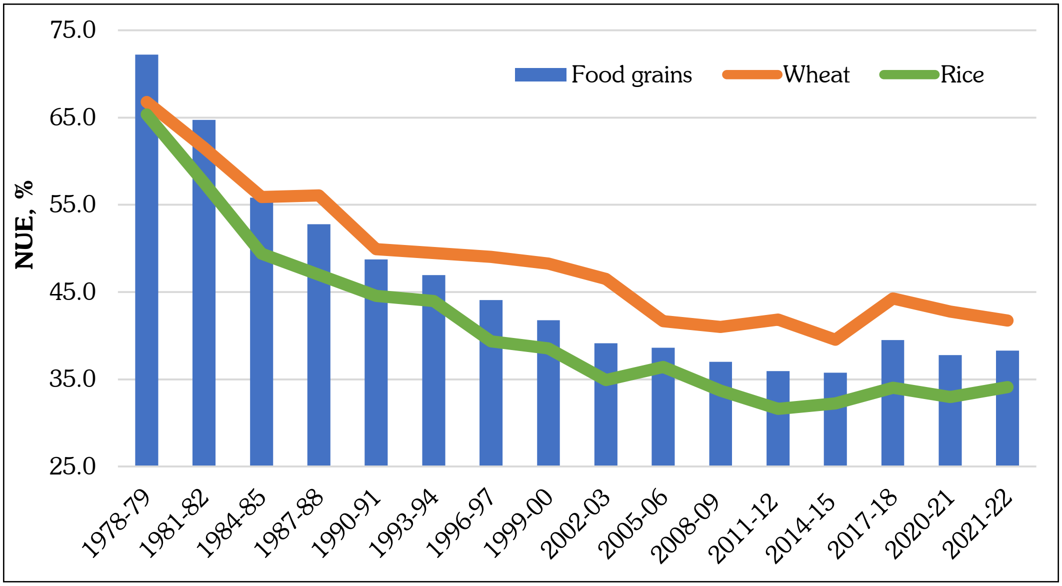


Fig. 17. *Forty-five year trends in NUE (%) of foodgrains, wheat, and rice - India.*

(Data: Diverse sources; Author's calculation)

Like trends presented in Figure 16 on agriculture (Lassaletta *et al.,* 2014), information on NUE on foodgrains rice and wheat crops exhibited a sharp depression with time. Irrespective of the time-period, rice demonstrated lowest NUE values compared to foodgrains or wheat. This behavior confirmed the research findings obtained by employing ^{15}N labelled FN (mainly urea) (Table 2). By priori, it means that while improving NUE across diverse crop growing environments is necessary to minimize FN consumption, relatively greater savings are possible by focusing more on vulnerable rice. Since rice among all other crops takes away the largest share of the total FN, interventions on reducing consumption offer greater possibilities. A strong negative correlation coefficient ('r' -0.91) between FN consumption and NUE establishes the potential role of NUE in cutting down dependence on FN (Fig. 18).

Potential value of NUE in cutting down FN consumption

Findings of ^{15}N balance studies and NUE calculations suggest only ~35 per cent of FN is effective for crop production. Assuming ~15% of FN stays in the soil, the

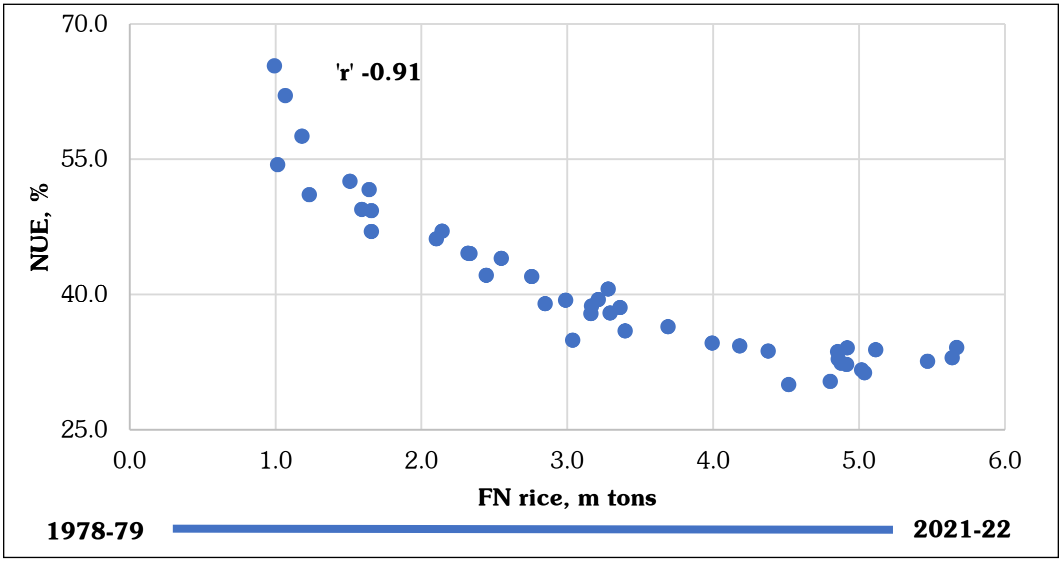


Fig. 18. *Relationship between FN consumption (rice, mt) and NUE (%).*

(Data: Several sources; Author's calculations)

remainder ~50 per cent exits the soil-plant system and is, thus, lost. It represents 'FN surplus', which if prevented is equivalent to FN saved. In 2021-22, FN consumption by foodgrain was 13.7 mt (70% of 19.4 mt of total N consumption) and contribution of N from natural sources to foodgrain production amounted to 3.2 mt. It means total N input for foodgrain production summed up to 16.8 mt. Hence, N loss was 8.4 mt, which represents 'N surplus' (Table 3). In other words, it is equal to FN loss. It also means that the higher is the 'N surplus' the lesser is the NUE.

Table 3: Effect of current (2021-22) NUE (35%) and projected NUE for the year 2029-30 (50% Scenario 1, and 60% Scenario 2) on surplus N

Current (2021-22)				Projected (2029-30)			
Harvested N (FG)*, m tons	**Input N, m tons**	**NUE (%)**	**Surplus N, m tons**	**Harvested N (FG), m tons**	**Input N, m tons**	**NUE (%)**	**Surplus N, m tons**
6.5 (316)	16.9	35	8.4	6.9 (340)	19.34	50	6.8 (Scenario 1)
6.5 (316)	16.9	35	8.4	6.9 (340)	19.34	60	4.8 (Scenario 2)

**Figures in parenthesis represent foodgrain production, current (2021-22) and projected (2029-30)*

Utilizing the above computation method, with projected NUE at 50 per cent (Scenario 1) and 60 per cent (Scenario 2) possible 'N surpluses' was calculated for the year 2029-30. Foodgrain production was reckoned at additional 3 mt/year (total 340 mt) and FN consumption was elevated at 2 per cent/year (the rate at which FN consumption grew during the previous 8 years). Information presented in Table 3 demonstrates that by raising the NUE from the current 35 to 50 per cent, 1.6 mt (8.4-6.8) FN may be saved without any cost to requisite growth in foodgrain production. Lesser use of FN will also be pro-environment (details in an earlier section). Further reduction in FN use (i.e., 3.6 mt or 8.4-4.8) will become possible if NUE rises from the current 35 to 60 per cent in 2029-30. The question is whether these projections on NUE mediated FN savings are possible to achieve? A firm answer is yes, provided FN is managed not by the current casual approach, i.e., 'one size fits all' but in a more scientific way that follows contours of biophysical attributes of diverse soils and crop growing environments.

Strategies to Enhance NUE

Increasing NUE by employing innovative FN use efficient management practices is imperative to right-track food production growth, with a reduction in fertilizer consumption and without harming the environmental sustainability. However, to lessen dependence on synthetic fertilizers below 50 per cent of the projected requirements, increasing NUE may just not be adequate. In addition to improving NUE, the need would be to maximize the potential contribution of fertilizers for sustaining food security and containing climate change by:

- Management of FN to enhance use efficiency
- Integration of natural complements and supplements to fertilizers
- Partial substitution of conventional fertilizers with minimally processed ores and minerals
- Alternative methods of farming

Before details on these options are presented, it is emphasized to begin by focusing on what is called 'Holistic N Management' (HNM). In essence, HNM welds together precise agronomic methods or standard agronomic practices (e.g., right kind of variety, infusion of cover crops, optimum seed rate, timely planting, weeding, pest control, good irrigation practices, post-harvest management, etc.), and the best fertilizer management practices like doses as per soil test values and crop needs, site specific fertilizer choices, placement methods and time of fertilizer treatment. Application of all these elements of HNM is prerequisite for ensuring the maximum outcome on adoption of the NUE enhancing strategies, enlisted above. 'One out', 'all out' principle applies. For instance, if weeds or pests are not controlled in time, the ensuing damage to productivity is irreparable, Also, similar is the negative effect on health of soil, water, and air. Coincidentally, all interventions on enhancing fertilizer use efficiency and cutting chemical fertilizer consumption become infructuous.

Management of FN to enhance use efficiency

Overuse, misuse, and imbalanced use are the main reasons of the lowest NUE figures for India even among some key rice growing countries of Asia (Fig. 19). Besides wasted economics, environmentally it is more worrisome, when India annually consumes ~20 m tons of FN (80% as urea), forming 18 per cent of the global consumption; occupying global second rank (as per 2020 data; FAI Statistics, 2021-22).

Overuse happens due to low price of urea, misuse because of broadcast method of application, and imbalanced use is driven by *ad hoc* recommendations and comparatively higher retail price of other two major fertilizers – FP and FK than FN. Experimental evidence as to how over-application than the recommended dose of

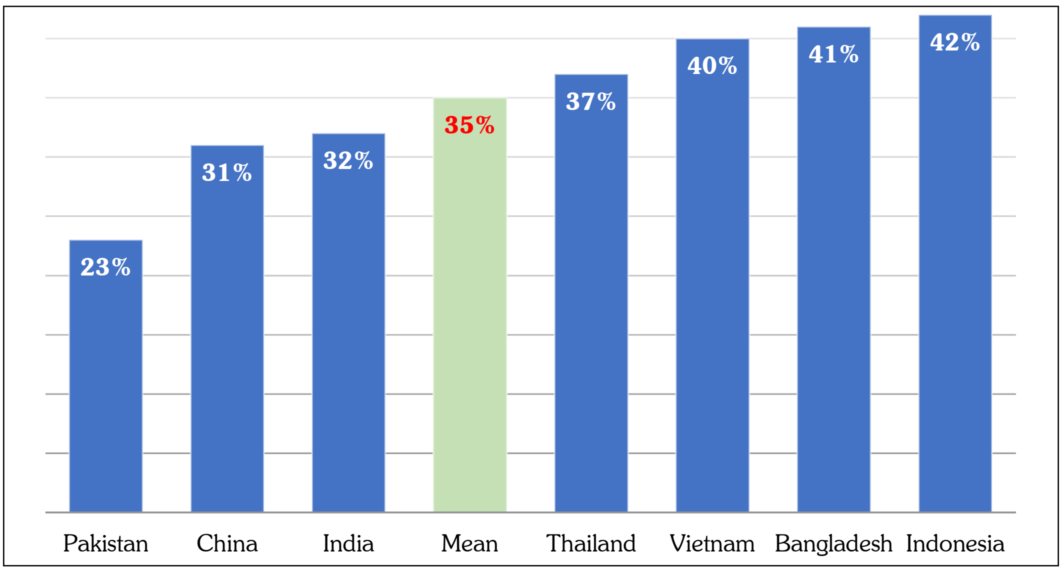
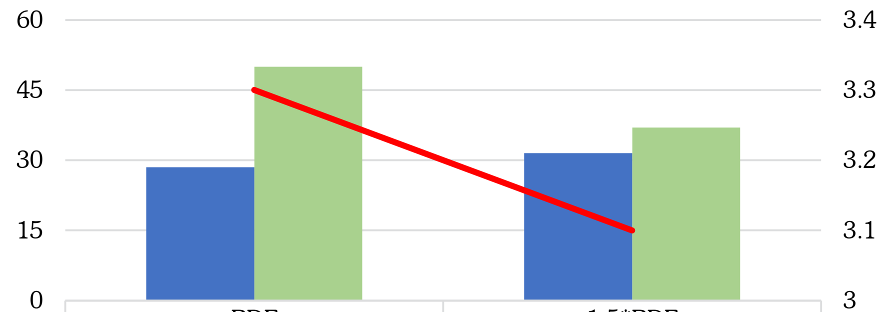


Fig. 19. *Comparison of NUE (decadal mean, 2000-09) of some rice growing countries of Asia.*

(Data source: Lassaletta *et al.*, 2014) fertilizer (RDF) affects yield, NUE and SOC build up (all figures represent 40 year-long mean values in maize) is presented in Figure 20. The findings confirmed that 50 per cent higher application increased yield to some extent but caused visible dip in NUE and SOC. Hence, over-application is less efficient and non-beneficial to soil health.



	RDF	1.5*RDF
Yield, q/ha	28.5	31.5
NUE, %	50	37
SOC, g/kg soil	3.3	3.1

Yield, q/ha   NUE, %   SOC, g/kg soil

Fig. 20. *Effect of RDF and 1.5*RDF (recommended dose of fertilizers) on yield, NUE and SOC (40 year mean values), crop maize.*

(Data: courtesy ICAR-AICRP LTFE)

Leaving the role of fertilizer policy apart, emphasis on the adoption of best fertilizer management practices may help contain ongoing overuse, disproportionate use, and mishandling of FN. Their essence has been captured in the concept called, '4R nutrient stewardship'. Popularized globally during the last 15 years. The '4R nutrient stewardship' to boost fertilizer use efficiency occurred at Brussels through an IFA convened conference on 'Fertilizer BMPs' (best management practices) in 2007 (Fixen, 2020). The 4Rs refer to the application of the right source, right rate, right time, and right place. In simple terms, the 4R FN management strategy combines BMPs to match N supply with crop requirements to minimize losses. The elements of '4R nutrient stewardship' concept to maximize FN use efficiency is captured pictorially and presented in Figure 21.

The 1st R focuses on source of fertilizer based on the nutrient requirements as per soil health card report. It means the product, besides FN, must combine dressing with deficient nutrients in adequate and requisite amounts. In general, among the N,

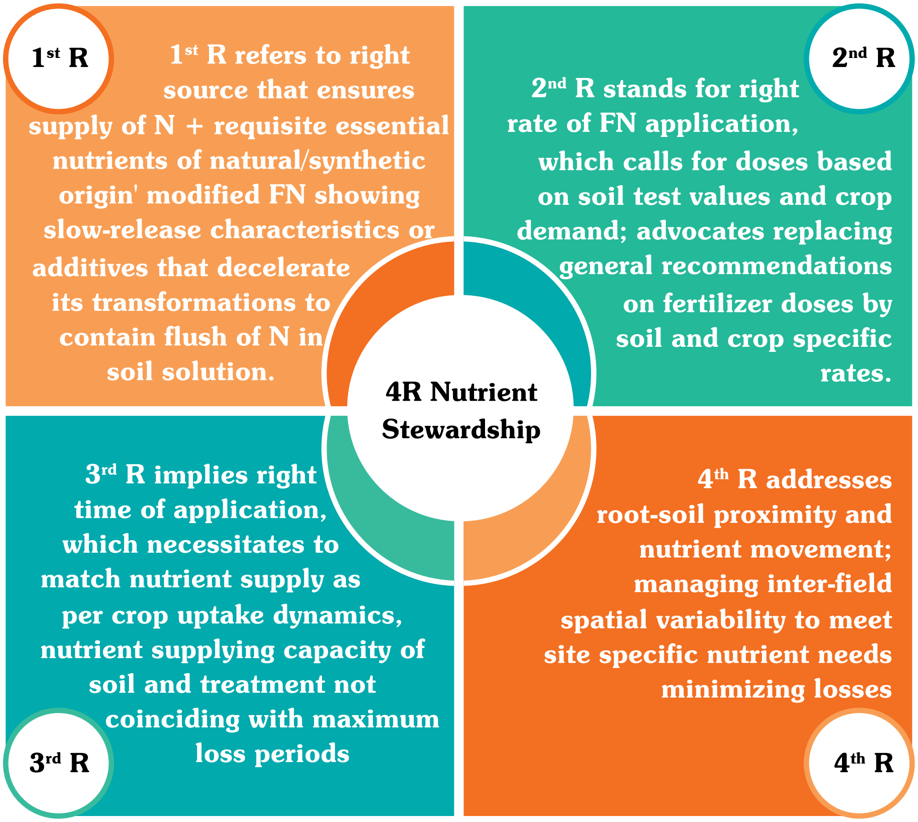


Fig. 21. *4R Nutrient Stewardship*

P, and K, the maximum focus is on FN and to a reasonable extent on FP. Omitting treatment or underuse of FK from fertilizer schedule is common (detailed account presented earlier in this report). Resultantly, potential yield (response) gets dented and NUE falls. Findings from country-wide farmers' management (representing largely imbalanced NPK use) of NPK and improved management across researchers' farm studies are witness to this fiasco (Katyal and Chaudhari, 2021). Information presented in Figure 22 validates this conclusion. Also, data exhibited in Figure 23 demonstrate that balanced application of NPK carriers together was necessary to maximize NUE of all crops forming maize-wheat or rice wheat rotations. Limiting full treatment of potassic or phosphatic fertilizers or both adversely affected NUE; loss was up to 60 per cent on country basis (Fig. 22) and up to 20 per cent on research farms (Fig. 23). These findings also confirmed that lower NUE of rice and wheat (Fig. 17) and those displayed for the country compared to USA (Fig. 16) were primarily because of neglect of K fertilizer treatment. A commonly observed wide N to K use ratio (7:1) corroborates that fact.

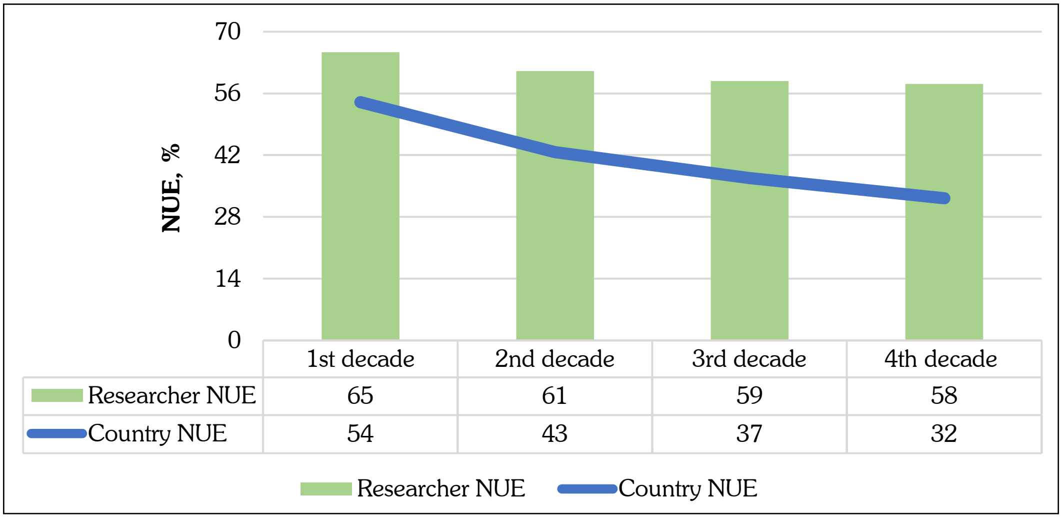


Fig. 22. *Comparison of NUE (%, decadal means, crop rice) values obtained on research farms and on all India basis after Green Revolution*

(Data source: FAI and ICAR-AICRP on LTFE; Author's calculation)

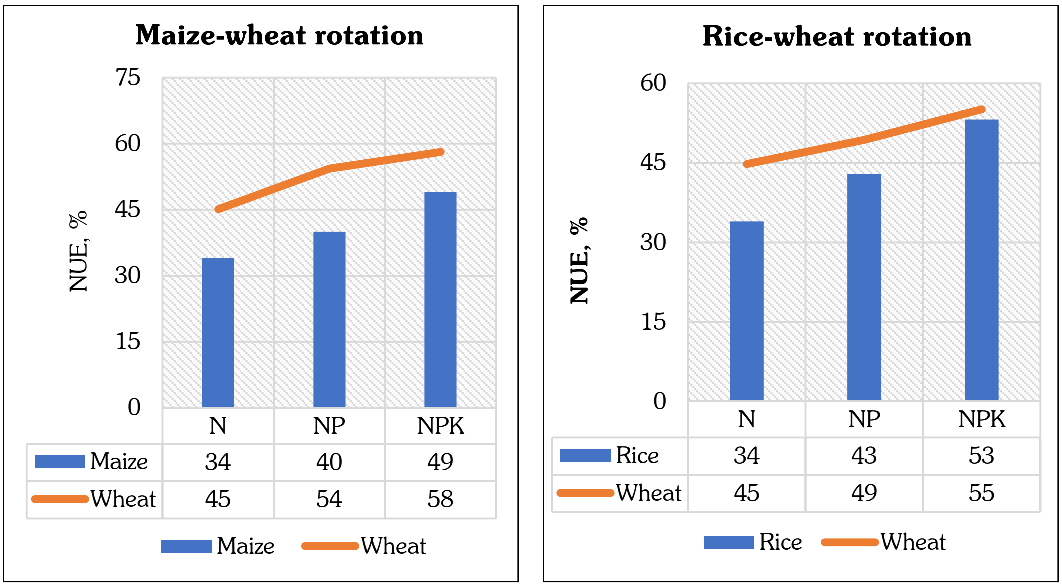


Fig. 23. *Forty-year mean NUE values in response to balanced and imbalanced application of NPK to maize-wheat and rice-wheat rotations*

(Data: courtesy ICAR-LTFE, Author's calculation)

Multi-nutrient complexes

To contain continuing imbalanced use of NPK (or other deficient nutrients), it is suggested to provide farmers with area-specific multi-nutrient complex/compound fertilizer products. No doubt, the use of multi-nutrient complexes is popular among farming communities (i.e., 12-32-16; NPK),but a common complex fertilizer does not necessarily supply the nutrients matching with the Soil Health Card based recommendations across all locations. Also, multi-nutrient carriers are applied at the time of sowing/basal, and urea is invariably a major part of the complex product. Existing approach makes N vulnerable to excessive loss (reasons explained in a subsequent section). Hence, muti-nutrient complex products need to limit N content and ensure requisite supply of other essential nutrients. It is possible to make crop need and soil fertility specific fertilizers, whose composition is likely to vary even across soil fertility grids (https://www.india.gov.in/spotlight/soil-health-card#:~:text=Soil%20 samples...). As a result of this micro-area variability, the need for complex fertilizers will be in small batches. It will, apparently, not be commercially viable for a big fertilizer manufacturer to undertake production of small lots of complexes having varying composition. For Instance, Tata Chemical's business on manufacturing of customized fertilizers launched in 2010 (https://www.tatachemicals.com/news-room/press-release/Tata-Chemicals-launches-Paras-Farmoola) went into near extinction by 2018 (https://www.dnaindia.com/business/report-tata-chemicals-softpedals-on-customised-fertilisers-1552001). To overcome this problem, Katyal (2019) recommended constructing customized multi-nutrient carriers by dry granulation instead of prevalent wet granulation. The proposed dry granulation, done by compaction, is feasible to adopt at the local level. The process is simpler and less energy intensive. In pursuance, synthesis must be decentralized and developed as a start-up/microenterprise/franchise of a big fertilizer manufacturing company to be in the heart of a major production system catchment (Katyal, 2022). Furthermore, cost of the customized product is nearly the same as it combines the requisite market available fertilizers (DAP, MOP, zinc sulphate, sulfur, boron granules, etc.). Details on the compaction process are available in a recent publication (Katyal, 2022). Fertilizer saving and environmental benefit on use of compacted products was explained by Purakayastha and Katyal (1998). Nevertheless, there is a need for more R&D to construct more efficient but economically acceptable products. More importantly, it will be necessary to study farmers' response to compacted multi-nutrient complexes.

Modified urea

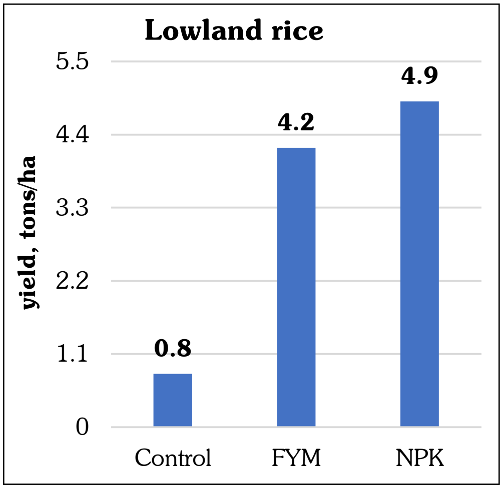
Pervading low use efficiency of FN is due to speed of urea transformations that generate highly reactive ammonium/ammonia (NH_3) and nitrate (NO_3) in the soil solution. Both these entities are susceptible to loss processes like NH_3 volatilization, denitrification, NO_3 leaching. To regulate solubility, urea granules are coated with sulphur and several other materials, ranging from polymers to oils and micronutrients. The product, sulphur coated urea (SCU) has been used widely and found effective in enhancing NUE (30 to 60%) and saving FN application rate by 10 to 30 per cent (Chen *et al*., 2020). Kundu *et al.* (2018) used nano zinc and nano rock phosphate to coat urea. Coatings improved NUE by 20-30 per cent in green house studies.

Besides coating to decelerate progress in water solubility, urea enriched with urease and nitrification inhibitors showed potential to reduce N loss and elevate NUE (Mustafa *et al*., 2022). Urease inhibitors regulate urea breakdown by reducing the speed of urease enzyme activity; thereby slowing down urea hydrolysis. Resulting reduction in NH_4^+ concentration in soil moisture contains NH_3 volatilization and enhancement in NUE (Malhi *et al*., 2003). However, longer retention of NH_4^+ ions in soil solution increases chances of NO_3 leaching, and nitrification-denitrification, fueling N_2O emissions. These losses are controlled by the addition of nitrification inhibitors. Apparently, a viable strategy to minimize N losses would be a combination of urease and nitrification inhibitors. This approach is, however, likely to make technology economically unfavorable.

Keeping in view the positive developments on coated urea and urease/ nitrification inhibitors, there is need to assess expected economic (productivity rise, and NUE enhancement mediated FN saving) and environmental benefits (containment of GHGs) under diverse crop growing conditions. R&D must, specifically, focus on evolving improved technologies and products for commercial manufacture of more efficient and less expensive slow/controlled release urea. In pursuance, a Center of Excellence on Development of Smart Fertilizers for lessening environmental problems by enhancing NUE is recommended to be established in public-private mode.

Natural sources

Like synthetic fertilizers, natural sources have also been used as nutrient sources to manage soil fertility. Organic manures and biofertilizers plus infusion of cover crops represent natural sources. Of the two, the former presents huge visible volume and exhibits equally big nutrient supplying potential. Estimates by Katyal and Chaudhari (2021) demonstrated that India annually generates 1.1 billion tons of organic resources (dry weight basis) of plant, animal, and human origin. Only 30 per cent (~350 m tons) is available for agriculture. Their assessment further reflected that of the total NPK value (~9 mt) only equivalent of ~3.5 mt is in the form of N available for agriculture. Even of this amount, plant usable organic N is released slowly and has limited immediate value for crop growth and productivity. This explains why organic manure (FYM), even if applied in amounts (in terms of N) matching the recommended dose of fertilizers (RDF) produced ~20 per cent lower yield (Fig. 24). Correspondingly, with rainfed *ragi* (*Eleusine coracana*), the yield deficit due to FYM treatment was strikingly lower (~45%). Compared to full complement of synthetic fertilizers, several past studies confirmed a yield loss of 30 per cent attributed to exclusive use of organic manures (Timsina, 2018).



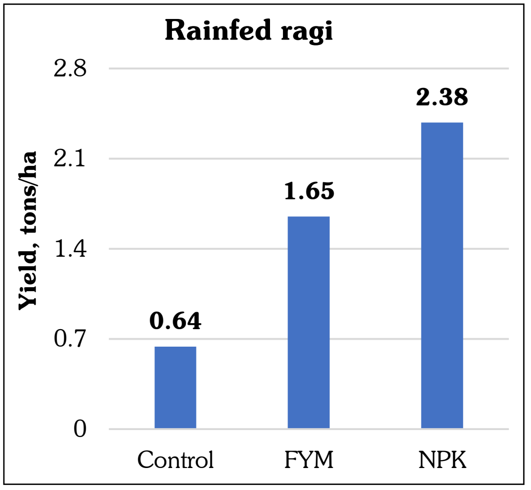


Fig. 24. *Relative grain yield (tons/ha) in response to NPK and FYM application to lowland rice (after 20 years) and rainfed ragi (after 40 years)*

(Data source: Singh *et al*., 2018; and ICAR AICRPDA)

Despite lower yield corresponding to synthetic fertilizers, regular treatment with organic manures re-established its known credentials in improving SOC (~10%) (Fig. 25). This positive development indicated improved soil health leading to diminished chances of CO_2 emissions. SOC upsurge is the center of these virtues. It is summerised that treatment with organic manures, whether administered to lowland rice or rainfed *ragi*, slowly and steadily promotes C sequestration than NPK treatment. Irrefutably, improvement in the health of soil and quality of air that follows is witness to the environmental positivity associated with organic manure use. On the other hand, application of synthetic fertilizers produces more yield but not necessarily good soil or quality air. It means, neither exclusive dependence on organic manures nor treatment with chemical fertilizers is adequate to backstop

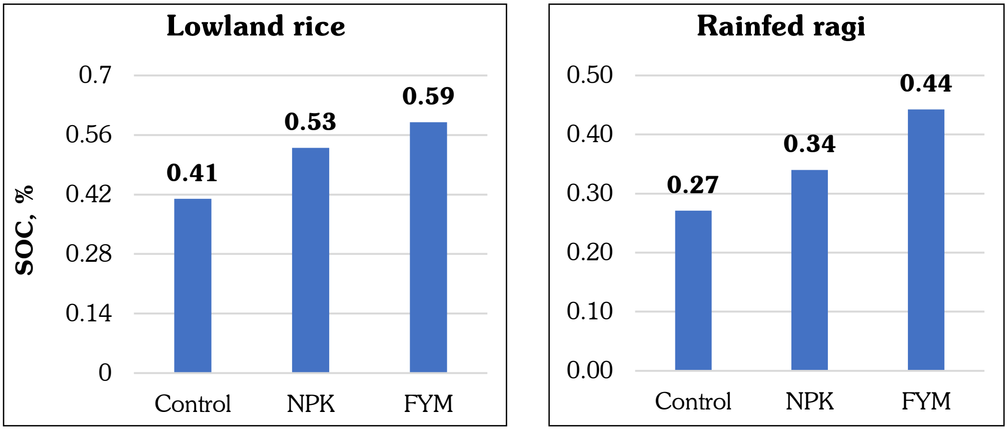


Fig. 25. *Relative buildup of SOC (%) in response to NPK, and FYM application to lowland rice (20-year mean) and rainfed ragi (40-year mean)*

(Data source: Singh et al., 2018 and ICAR-AICRPDA)

sustainable development of agriculture in all its aspects i.e., productivity growth, economic benefit, environmental security, and societal benefit (gains influencing all stakeholders). In simple terms, it means assuring sustainable productivity/ profitability buildup with uninterrupted flow of positive environmental services (C sequestration, containment of climate change, maintenance of water quality, security of biodiversity, etc.). Hence, fusion of fertilizers and organic sources becomes necessary to sustain productivity and profitability of agriculture and integrity of soil micro-ecology.

Integrated use of fertilizers and natural sources has, over time, been adequately investigated. The integrated nutrient supply and management (INSAM) advocates substituting a part of the recommended dose of fertilizers N (RDF-N) with organic manure N, while in others RDF was topped with an organic manure treatment. Data from a 20-year long-term experiment showed that 25 per cent substitution of the RDF-N by FYM-N not only increased yield but significantly improved NUE also (Fig. 26). More importantly, the rise in NUE (and yield) was associated with SOC buildup (Fig. 27).

Other set of long-term experiments evaluated RDF and RDF topped with FYM. Data showed uneven results, when NUE values between a low SOC (~0.3%) Inceptisol and a high SOC (~1.5%) Mollisol were compared. While in case of the former, there was a significant increase in NUE with FYM, same was not true with the latter (Fig. 28). Bumb *et al*. (2022) explained the reasons for this uneven response of initially low and high SOC soils. Despite this debacle, soil health (SOC rise) due to FYM treatment improved significantly. Typically, SOC and NUE seemed positively associated (Fig. 29) in case of low SOC Inceptisol but not necessarily with high SOC

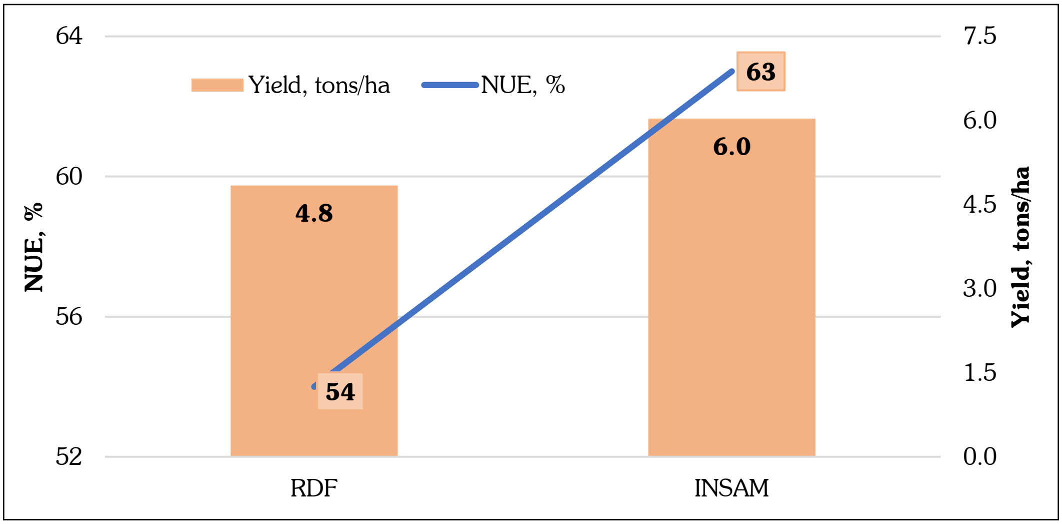


Fig. 26. *Comparison of rice grain yield and NUE after 20 years of RDF-N and INSAM (75% FN+25% through FYM).*

(Data source: Singh *et al.*, 2018)

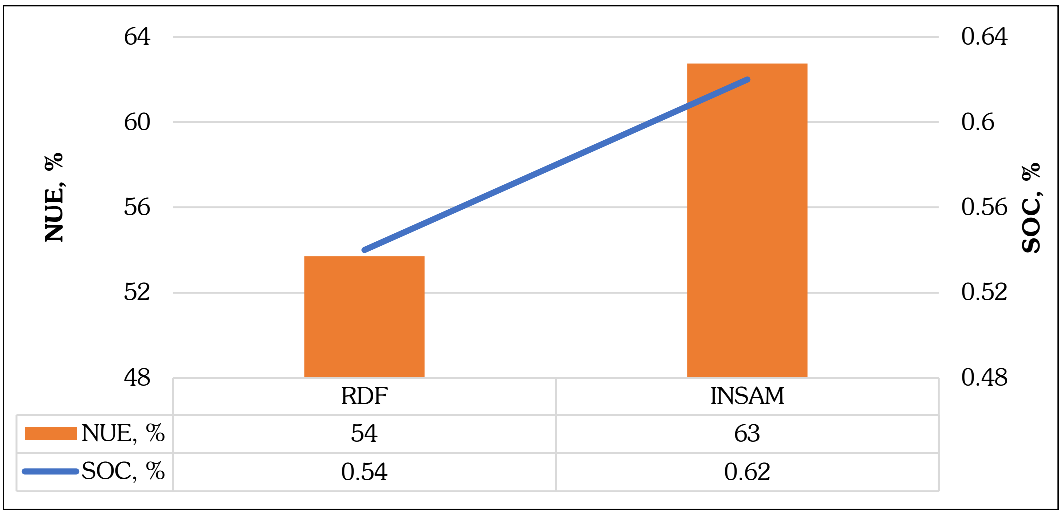


Fig. 27. *Movement of SOC and NUE after 20-year long treatment with RDF-N and 25% replacement of RDF-N with FYM-N (INSAM).*

(Data source: Singh *et al.*, 2018)

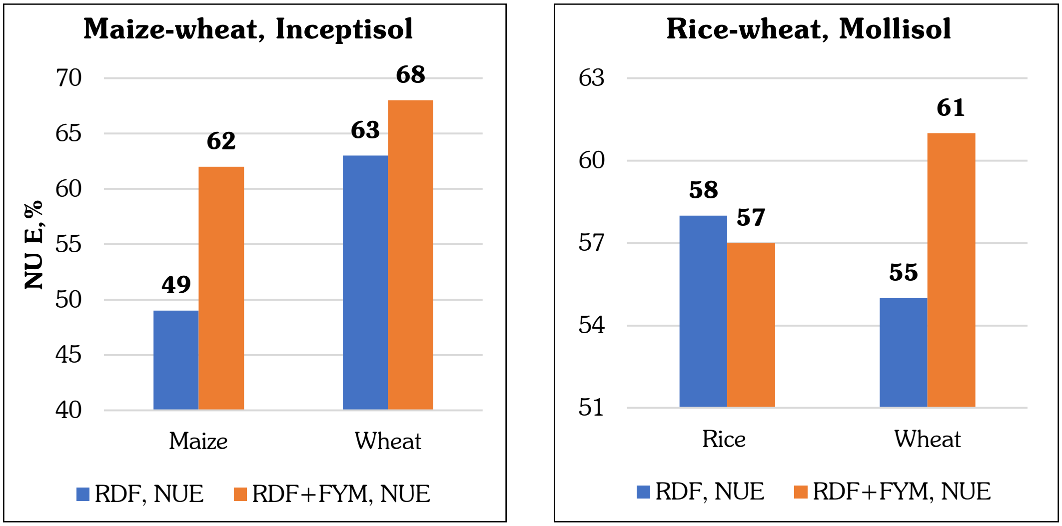
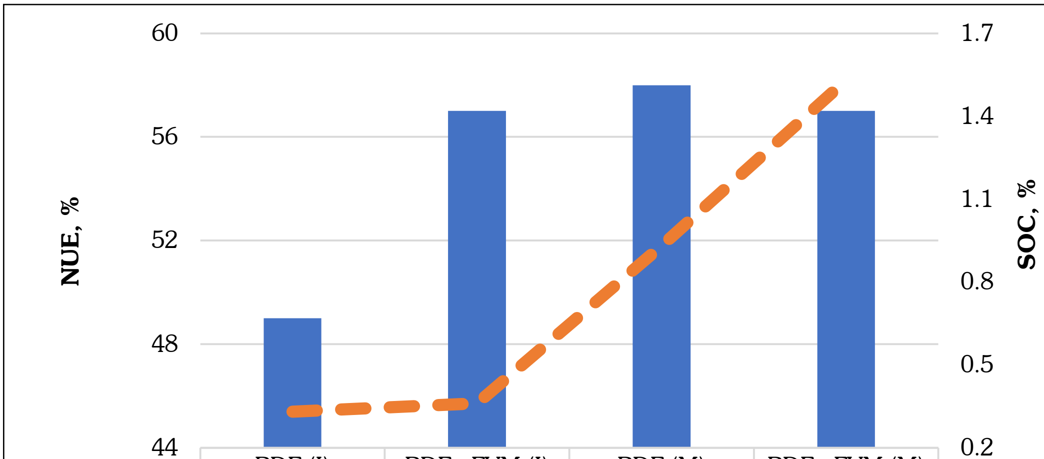


Fig. 28. *Comparison of NUE (40-year mean) of maize-wheat and rice wheat rotations in response to RDF and RDF + FYM*

(Data: courtsey ICAR-AICRP on LTFE)



	RDF (I)	RDF+FYM (I)	RDF (M)	RDF+FYM (M)
NUE, %	49	57	58	57
SOC, %	0.33	0.36	0.93	1.53

Fig. 29. *Movement of NUE and SOC in response to RDF and RDF + FYM (40 year mean values). M and I in parenthesis (given in x axis) stand for Mollisol, crop rice, and Inceptisol, crop maize*

(Data: courtsey ICAR-AICRP on LTFE)

Mollisol. What emerges is that the application of organic manures to natively high SOC soils can be withheld to save fertilizers, which is contrary to the abundantly occurring low SOC soils that require treatment with both to sustain productivity growth and soil health.

On an overall basis, it is concluded that 25 per cent FN is possible to save by complementing fertilizers with organic manures across diverse crop growing environments for sustainable growth of foodgrain production and accomplishing the goal of climate change mitigation. The GoI is likely to launch a policy on reducing dependency on chemical carriers, typically those being imported, to promote use of organic fertilizers (https://www.tpci.in/indiabusinesstrade/blogs/india-eyes-new-fertilizer-policy-to-reduce-import-dependence...) and with that development, popularity of organic manure use is likely to become a reality

The 2nd R of 4Rs suggests the right rate of application based on soil test values and crop demand. This strategy is necessary to avoid unnecessary use of fertilizer, which drives overuse and imbalanced use – the key elements contributing to dismally low NUE. Apparently, the need is to replace the commonly made *ad hoc* recommendations on fertilizer doses with scientifically validated soil test- and crop need-based recommendations. The advisories on right fertilizer application rates must be reflected in the Soil Health Card of each cultivator. Since field to field and even grid to grid soil test values vary so much, there is a need to generate a mass of data enabling extrapolation of recommendations to wider areas. To make real time recommendations, it would be necessary to transform vast pool of data points into area-action plans. Employment of modern IT&C tools like internet of things (IoT) comes to the fore. However, it will be an oxymoron if capability to utilize IoT with access to technology (range: lab analysis to reliable sensors techs), connectivity, cloud computing systems, machine learning tools and analytics and artificial intelligence (AI) is not in place. ICAR-AICRP on Soil Test Crop Response must develop capability to unify the soil health data (available in millions and millions of soil health cards) by subjecting its analysis to the untapped power of IoT devices so that potential power of digital world (AI) becomes affordable and viable and simultaneously making practical site-specific fertilizer recommendations a reality.

Sapkota *et al.* (2021) evaluated Nutrient Expert (NE) (http://software.ipni.net/) based site-specific nutrient management (SSNM) recommendations. NE advocates fertilizer treatment coinciding with plant nutrient demand and soil supplying capacity. Sapkota *et al*. (2021) focused evaluation of NE by establishing 1594 juxtaposed comparison trials and farmers practice of fertilizer management. This meta study involved rice and wheat cropping system followed widely across the Indo-Gangetic plains – the site of their study. Results showed that 80 per cent of the participating farmers by shifting to NE based fertilizer recommendations gained significantly in terms of crop yield and income. These advantages were attributed to rise in productivity with a coincident reduction in fertilizer use. Additionally, there was environmental benefit measured as lessening of global warming potential driven by savings in fertilizer use. In quantitative terms (Sapkota *et al*., 2021), by extension of NE based fertilizer recommendations to entire wheat and rice growing area, it was projected to conserve ~1.5 mt of FN, produce 14 mt of more rice and wheat, and generate ~ 5.4 mt less CO_2 as is currently happening in response to farmers' practice of fertilizer management.

Besides NE, there are other measures that have been used to feed the plant optimally – the soul of the SSNM concept, specifically FN. These include Green Seeker, Chlorophyll Meter, Leaf Colour Chart and Decision Support System (i.e., NE and Rice Crop Manager). Utilizing Leaf Colour Chart for FN management in farmers' fields, Singh *et al*. (2007) confirmed 45 per cent foodgain in agronomic response and 25 per cent rise in FN recovery efficiency (Table 4). It is concluded that use of digitally supported NE or physical measure like Leaf Color Chart supporting SSNM, offers opportunity to enhance NUE at least by 10 per cent, minimizing twin challenges faced by sustainable development i.e., food security and climate change.

Table 4. Leaf Colour Chart (LCC) guided SSNM: FN response of rice

Method of application	Response (kg grain/kg N)	FN recovery (%)
Conventional	11.3	39.8
LCC based	16.4	52.7

Source: Yadvinder-Singh et al. (2007)

The 3rd R of the 4 Rs nutrient stewardship implies the right time of application. It conveys nutrient supply as per crop uptake dynamics, nutrient supplying capacity of a soil, and mean annual rainfall. To rationalize fertilizer treatment as per crop growth subtleties, the FN is applied by dividing the total recommended dose in 3-4 equal split applications. This strategy of FN treatment at the time of sowing/planting and topdressings to a growing crop has proven to improve productivity but not necessarily to its fullest extent. This is because some flaws were noticed in this approach. Firstly, part of the FN applied at the time of sowing/planting is almost equal to the topdressings made to an actively growing crop. Research has confirmed lower use efficiency of basal FN treatment than that applied to an actively growing crop. It was excessively sensitive to NH_3 volatilization as established by Katyal *et al.* (1987) and Hong *et al*. (1992). Following these pioneering investigations, more credible evidence emerged favouring zero basal treatment. This shift produced additional benefit equal to ~15 per cent rise in agronomic efficiency (kg foodgrain/kg FN) (Singh *et al*., 2007; Subasinghe and Angus, 2009). Secondly, findings from China, IRRI and elsewhere suggested a quantum leap in NUE/agronomic efficiency by lessening share of basally applied FN to ≤ 10 per cent in high intensity farmed areas, like N-W India (Peng *et al*., 2006, http://knowledgebank.irri.org and Reetz, Jr., 2016). And thirdly, Sitthaphanit *et al*. (2010) showed that delaying basal application up to 14 days after sowing produced more yield (≤ 10%) and gain in NUE (up to 20%) (Fig. 30) of maize cultivated on a sandy soil of Thailand. Subsequently, Ali (2017) validated these findings with maize in Egypt.

While it has been established that omitting basal application enhances NUE, management of top-dressed FN on that count is, however, less explored. Katyal *et al*. (1987) found that replacing the then existing practice of FN broadcast on wet surface of standing wheat crop after irrigation by top-dressing FN to dry surface before irrigation improved yield by about 25 per cent and NUE by almost 50 per cent (Fig. 31). They attributed the economic and environmental benefits

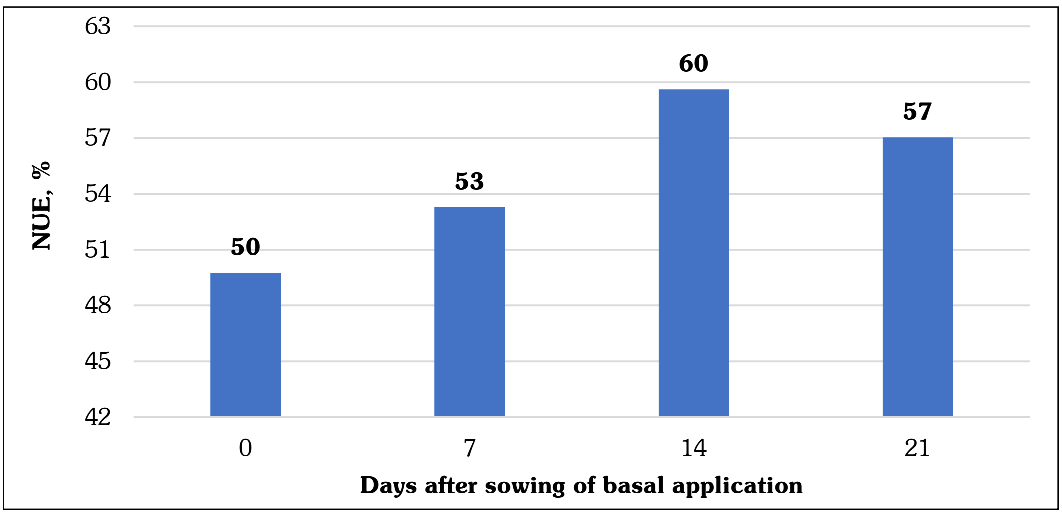


Fig. 30. *Effect of delayed basal FN application to maize on NUE (%).*

(Data Source: Sitthaphanit *et al*., 2010; Author's calculation)

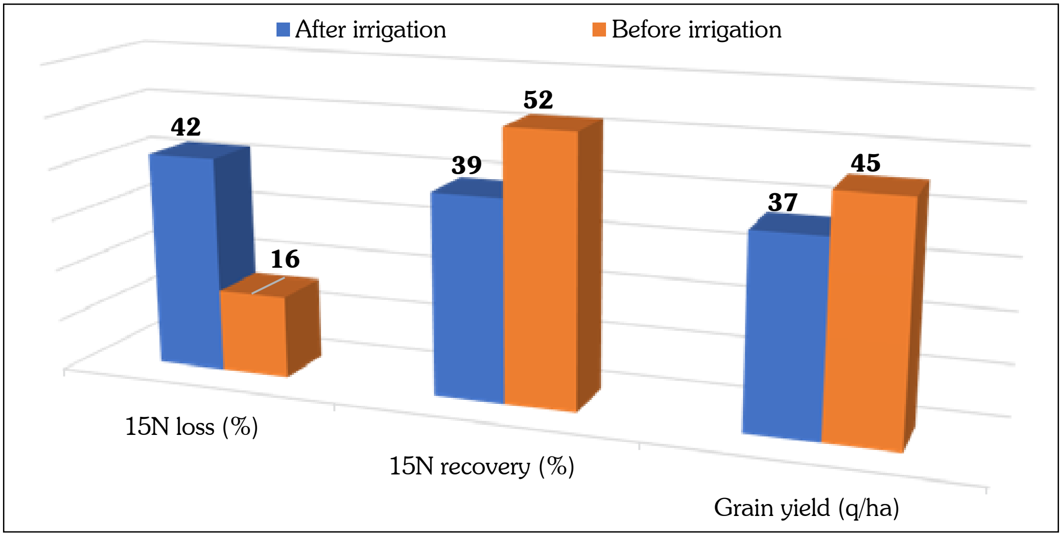


Fig. 31. *Influence of timing of top dress urea treatment vis a vis irrigation*

(Data Source: Katyal *et al.*, 1987)

of FN treatment before irrigation to its placement happening automatically with infiltrating water. Even with the lowland rice, after flooding cycle, FN top-dress application is spread on drying surface followed by irrigation to initiate flooding cycle. Subasinghe and Angus (2009) proved the efficiency of this practice and suggested the necessity of making pre-flood application to sustain biomass production. Pan *et al.* (2012) projected greater NH_3 volatilization when FN was broadcast on wet surface after irrigation than that on a dry surface before irrigation.

The 4thR of the 4Rs addresses root-soil proximity, manages inter-field spatial variability to meet the site-specific nutrient needs minimizing nutrient losses. In pursuance, fertilizers nutrients are placed where the crop roots have effective reach to absorb. In essence, the purpose is to maximize the crop feeding and minimize the soil fixation to contain the loss. Type of crop, cropping systems, and soil properties, no doubt, dictate the method of application.

Indian farmers, in general, follow broadcast method of FN treatment. Placing it deep in the soil by incorporation after broadcast is somewhat better strategy to enhance fertilizer use efficiency. Nevertheless, placing FN below the seed furrow by drilling or a few centimeters to the side was found to be superior to incorporation. With FN, in whose case far bigger share is applied as top dress to the standing crop placement by machines poses challenge. As explained above, FN application to a standing crop must be broadcast on drying surface followed by irrigation. Besides timing fertilizer application with reference to irrigation, FN (and other nutrients) is also applied by, what is called fertigation. It is a highly efficient way of feeding crops, but as the acceptance of drip irrigation itself is limited so is the acceptance of fertigation. Concentrated FN (i.e., liquid ammonia), or water soluble fertilizers, whose popularity is projected to increases in future (https://www.marketsandmarkets.com/pdfdownloadNew.asp?id=1055), for higher use efficiency must be injected below the soil surface. This method of placement is common in the developed world.

The extent of benefit to deep placement versus the common farmers' practice (combine of broadcast followed by basal broadcast and 2-3 top dressings) was studied in China (Li *et al*., 2021). In this investigation, involving a one-time 10 cm mechanical deep placement as basal and farmer's practice were compared. One-time deep placement of FN (+FP and FK) produced between 12 to 20 per cent more yield and 42 to 52 per cent higher NUE than the prevalent practice of split applications by broadcast. More importantly, the former practice reduced CH_4 and N_2O induced global warming potential, respectively up to 25 per cent and 12 per cent compared to the latter method of FN management. In India, where direct seeded rice is going to be more popular in future, one time deep placement seems to be a viable option to maximize NUE and yield and minimize rise of environmental adversaries. First, requirement would be to validate experimentally the trustworthiness of the results obtained in China. If confirmed, the second imperative would be to make farmers aware of the benefits of one-time application. For effecting deep placement of fertilizers, assured supply of low cost drills, or provisioning right machines by establishing custom-hiring centres would be the third prerequisite guarantying success.

Import Substitution of K and P Fertilizers

K Substitution potential

India, currently, imports entire amount of fertilizer K (FK) at huge cost to foreign exchange, ~US $ 1,700 million - during 2022. Apparently, it is necessary to bring down import bill by intervening with indigenous K resources. One such resource is plant-, animal- and human-based manures. According to Katyal and Chaudhary (2021), organic resources available for agriculture have potential to supply ~3.5 mt K. Even if 30 per cent of this potential is agronomically effective, it may probably complement one third of the imports. Additionally, India possesses rich resource of K bearing minerals and ores. Glauconite is one such resource, which is an iron-potassium-silicate clay mineral embedded in the rock called 'greensand'. This rock is found near the surface without over-burden. Its K content ranges between 5 per cent and 8.5 per cent K_2O, and is also a rich source of iron (12 to 19%), Mg (2 to 3%), and a host of trace elements like zinc (Zn), copper (Cu), molybdenum (Mo), etc. Some glauconites are rich in Ca and P and can potentially be effective to control soil acidity and K deficiency, which is a typical feature of acid soils. Glauconite is suitable for direct field application without any chemical treatment, except pounding if rock mass is lumpy. Unlike most other clay minerals, glauconite exists as sand sized particles (0.02 to 0.05 mm) and shows shades of green to bluish green color. However, glauconite does not behave like sand as its structure is saturated with hundreds of micro-pores. These tiny apertures play a vital role in binding the sand particles and enhancing water storability of poor water-holding light textured sands and loamy sands. On the other hand, being non-expandable, glauconite treatment helps manage sticking together of clay particles, which enhances aeration and free drainage of otherwise impervious black clay soils. Improvement in physical properties indirectly stimulates soil biology and help increase efficient use of nutrients other than K also. Armed with these complex physical, chemical, and biological features, glauconite qualifies both as a fertilizer and a soil conditioner (NAAS, 2017).

According to the Indian Minerals Yearbook (2015), compared to other K rich minerals - polyhalite, and sylvite, ease in mining of glauconite is its asset. Also, its proven benefits as K source and soil conditioner make it most favoured K resource for direct application. India has known reserves of unexploited 1900 Mt of glauconite, occurring primarily in Rajasthan, Madhya Pradesh, Uttar Pradesh, and Gujarat. However, due to lack of clear utilization policy driven by its non-inclusion in the minor minerals listed in the 'Mineral Concession Rules 1960' and 2016 (contained in the 'Mines and Mineral Development Regulation Act 1957), the greensand/glauconite mines currently lie commercially unexploited. Glauconite is not the only potash mineral that has been evaluated as an alternative to widely used K fertilizers. Potash-rich feldspars (13% K_2O) and occurring in far greater abundance is not of much agronomic value. Exceedingly slow availability of its K impedes agronomic usefulness, which is also the case of profusely found mica minerals. On the other hand, glauconite, because of its inherent ability to additionally work as soil ameliorant, outstands other K minerals for direct application as K source. Glauconite has been used as K source and soil amendment since the 18th century in the USA (https://www.ugaoo.com/knowledge-center/green-sand-forgardening-glauconite-greensand/). Like in the USA, India also ignored exploiting the potential of glauconite due to availability of relatively low-priced imported potash. In 2001, Technology, Information, Forecasting and Assessment Council (TIFAC) proposed to expand inclusion of glauconite as a potash source (http://tifac.org.in/index.php?option=comcontent&view=article&id=729&Itemid=2054/) to substitute imported potash. In 2014, Ministry of Mines GoI (Indian Minerals Yearbook 2015: Potash) stated that glauconite has potential for direct application to soils in a pro-environment manner. In support, the report stated that glauconite mixes homogeneously with the soil and provides potash as nutrient for plants. It also increases soil fertility and improves soil texture, porosity, and permeability due to more or less uniform grain size. Cited from TIFAC, the studies conducted by Bidhan Chandra Krishi Vishwavidyalaya (BCKV) and Banaras Hindu University (BHU) got encouraging results on direct application of glauconitic sand originating from Uttar Pradesh (http://tifac.org.in/index.php?option=com_content&view=article&id=729&Itemid =205 4/). Srinivasarao and Subba Rao (1999) confirmed that K release from glauconite was influenced by the particle size and accordingly dry matter yield and K uptake increased as the coarseness of the mineral matter decreased. To create an upgraded product, Chinese have developed a K fortified glauconite product by blending it with a complex of soluble potassic carriers and other nutrient sources. In small field plot tests, the compound potash fertilizer outyielded a comparable product, but without glauconite (https://www.google.com/ patents/CN101575231A?cl=en…). Beneficiation is a process to manufacture K fertilizers from glauconite, which refers to removing gangue minerals (materials of little commercial value) from the ore to synthesize a high grade or concentrated nutrient source. However, beneficiation does not seem commercially viable. This explains the necessity to make direct use of pounded material for direct application. The need for potassic fertilizers is on the rise due to rising K deficiency in Indian soils (Srinivasarao *et al*., 2010) . The focus is largely on high K demanding sugarcane, oilseed crops (sunflower), horticultural (banana), vegetable and plantation crops. Currently, K deficient acid soils supporting plantation and other crops in South and NE regions consume ~50 per cent of the total FK. The slow-release character of the glauconite-K is a boon in minimizing K leaching and maximizing use efficiency in acid soils. Replacement of at least 25 per cent of FK used in acid soil dominated regions is possible without any productivity loss. But before this reduction in consumption is realized, it would be essential that:

i) GoI declares glauconite in the schedule of minor minerals; currently, it is not included in the list of Associated Minerals, which renders this valuable resource as a waste.

ii) SAUs and ICAR's research institutes launch field experiments to identify niche soils and crops, requiring high intensity K treatment (plantation/horticultural crops), evaluate its value for direct application as source of K, soil conditioner and acid neutralizing material.

P Substitution potential

India possesses ~313 mt of rock phosphate (Indian Minerals Yearbook, 2018). Of this, only ~46 mt are commercially utilizable. This reserve can only be utilized as P source if finely-ground and contains around 16 per cent P_2O_5 (range 11-25%). In quantitative terms, this class of rock phosphate constitutes merely 20 per cent of the total resources. It means, ~5 mt rock containing ~0.8 mt P_2O_5 can complement the phosphatic fertilizers.

Rock phosphate has been successfully utilized for treating P deficient acid soils, pastures, and perennial grasses. Inoculation with P mineralizing microbes, composting with organic resources, application to green manure crops help solubilization and improvement in availability of otherwise unavailable P. Partial acidulation is another route to add value to utilize rock phosphate. Additionally, mixing dry powder of rock phosphate and a soluble fertilizer (single super phosphate) followed by granulation (compaction) showed promise to enhance importance as fertilizer of the former. Nevertheless, more R&D is needed to effectively exploit the potential of indigenous rock phosphate reserves.

Fertilizer Saving Value of Alternative Systems of Farming

To diminish dependence on chemical fertilizers without affecting productivity and environmental health, from time to time, several alternative systems of farming (ASF) have been evolved. A common focus of ASFs was to replace energy-dense inputs (fertilizers) with conventional farming practices and natively generated products. Various ASFs include: i) organic farming involving only organic sources and processes, ii) low input sustainable agriculture (LISA) focuses on maximum use of on-farm generated inputs with minimum dependence on off-farm bought fertilizers, iii) natural farming (NF) stresses avoidance of manufactured inputs and equipment and mimics how nature supports crop growth and development, iv) zero budget natural farming (ZBNF) espouses natural growth and production of crops without chemical inputs but with cow dung plus urine-based decoctions smeared on seed or applied to soil, v) conservation agriculture (CA) advocates minimum tillage, crop diversification and mulching, and vi) regenerative agriculture (RA) utilizes best inputs of conventional farming, Among the ASFs, RA, specifically, emphasizes biologically enhanced agriculture management (BEAM) plus concept of integrated farming i.e., fusion of crop and livestock farming. Soil biology is the pivot of BEAM as it harnesses the immense untapped potential of tiny flora and fauna. In fact, microbes constitute nature's nutrient factory complementing chemical fertilizer factory for achieving the goals of ecological intensification. In essence, information available thus far has established that ASFs like RA that allowed integration of fertilizer treatment with organics assured sustainable growth but not the systems that barred the use of chemical fertilizers.

Introduction of natural farming on ~ 30 per cent acreage is the current policy of GoI. Consequences of moving ~30 per cent farm area (www.financialexpress.com/economy/india-can-switch-30-of-agri-acreage-to-natural-farming...) to NF as envisaged is evaluated**.** NF, also called *Bhartiya Prakritik Krishi Paddhati* (BPKV) is defined as application of indigenous knowledge and practices focusing on on-farm biomass recycling with major stress on biomass mulching; use of cow dung–urine formulations; and exclusion of all synthetic chemical inputs either directly or indirectly. The yield penalty because of this shift is projected to be 30 to 35 per cent (equivalent of ~20 mt of foodgrains). This slide in yield is seen to happen due to slow speed of release, typically soil/manure held N by the soil microbes. This temporary immobilization promotes initial growth shock from which crops are hardly able to recover when nutrient availability improves. Had a small dose of fertilizer FN (no more than 10% of the total) been applied, it might have popped initial tardy growth. Complementarity of FN treatment in a small dose hastens mineralization of organic-N, leading to enhancement of availability. This approach symbolizes a win-win approach as it substantially reduces fertilizer use and maintains growth in productivity. To describe this phenomenon McLaren *et al.*, (2021), based on meta-analysis of yield data from 30 long-term experiments (Africa, Europe), confirmed that organic manure treatment jointly with small FN treatment substantially increased yield (McLaren *et al.*, 2021; http://dx.doi.org/10.1038/s41893-022-00911-x). The term coined by them was 'ecological intensification' (EI) which seems to be a superior pathway to sustainable agriculture. It is because EI describes no yield penalty and zero generation of negative outputs (aquifer pollution, soil health decline, air quality change, etc.. They also found that this pro-economic and pro-nature. The advantage of EI was lost if high doses of FN replaced small application rates. On this ground, India's NF concept (https://naturalfarming.dac.gov.in/NaturalFarming/Concept#:~:text=Natural%20Farming%20is%20a%) is recommended to be modified to the extent that no more than 10 kg FN/ha is blended with organic manure application. Another shift in NF would be infusion of cover crops in mono-crop rotations.

Fertilizer policy reforms and development extension

To strengthen existing way of handling fertilizers to enhance NUE and to infuse evidence-based findings on best management practices, joint action of technology (explained adequately throughout this paper), Hence, necessary actions on policy and technology transfer are detailed below in Fig. 32.

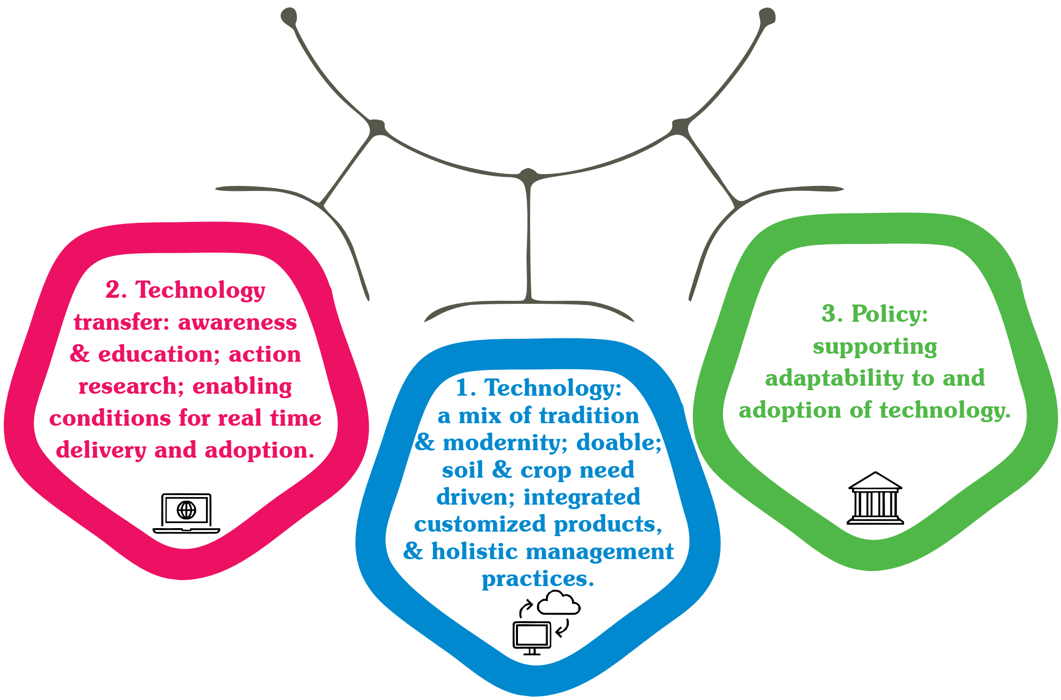


Fig. 32. *Fundamental elements of enhancing NUE*

Policy

Existing provisions of NBS promote overuse of FN – a noted cause of falling productivity growth, soil health deterioration and containment of climate change. AS reported earlier, findings of a German study (Gurumurthy and Goedeccle, 2015) confirmed that just 1 per cent reduction in urea-N subsidy would decrease soil health degradation by 3 per cent. Preferential focus on urea-N consumption seems to be the cause of excessive government support. With that incline, price of urea for farmers is the lowst compared to FP and FK. No doubt, recent corrections in NBS effecting reduction in retail price of FP and FK have been narrowed the price disparity to some extent. However, these corrections have hardly been able to remove distortions in N: P: K use ratio. Particularly, the imbalance persists in respect of K use. One reason is continuing higher price of subsidized FK than DAP. The other factor is the major diversion of FK (~50%) towards plantation crops (area ~30 Mha) that have high hunger for K and are grown primarily across K deficient acid soils. As a result, disproportionality less is left for food-basket crops - rice and wheat occupying 80 mha area. In this scenario, corresponding to raising imports to fill the need, a more viable solution would be to induct the use of native K bearing mineral glauconite. Use of this mineral would have to be preferably diverted to natively acid soils occupied largely by the plantation crops. As mentioned in a previous section, treatment with glauconite to manage K deficiency is more efficient than MOP in acid soils and specifically for plantation crops. Besides controlling K deficiency, glauconite will improve the structure and water holding capacity, the properties in which acid soils are inherently weak. In pursuance to make glauconite as part of soil fertility management, it is recommended that GoI through a policy instrument get it included in the schedule of associated minerals to open commercial exploitation. Once that happens, there will be a need to simultaneously launch research to establish set of management practices and to evaluate agronomic efficiency. To expand the ambit of its use, need would also be to develop crop and soil-specific multi-nutrient products by compacting together sparingly soluble glauconite and readily soluble MOP, urea, TSP, and some critical micronutrients. Proposed induction of R&D interventions overarched by a policy instrument, it is estimated to annually complement the existing imports of FK with at least 1 m tons of glauconite-K. Savings would be equivalent to ~US $ 590 million in foreign exchange spent on imports (@CFR or Cost and Freight Rate, Jan 2023) (https://www.fert.nic.in/sites/default/files/2020-082023-02/Monthly%20Bulletin...) and Rs 1,518 million savings in fertilizer subsidy because of complementary use of glauconite.

Experimental evidence, available thus far, confirms redemption of at least 25 per cent FN (FP and FK) due to integrated use of organic manures and chemical fertilizers. It is recommended to facilitate farmers to organize as 'INSAM Practitioner Groups' with village as a unit and village level worker as a change agent for local advice to produce quality organic manure. Formation of such groups may be supported and incentivized provided there is verifiable saving in fertilizers. For this analysis, if an 'INSAM Practitioner Group' can continuously cut fertilizer use by minimum 20 per cent and harvests no less yield than what was being produced with higher fertilizer application, should be given a cash prize and a commendation certificate. Award amount may be adjusted based on whether a group lowers NPK consumption and C footprint measured as rise in SOC over a period of at least

3 years. Proposed incentive and reward scheme on production of quality organic manures may also be made part of the upcoming 'Policy on Promotion of Organic Fertilizers' (https://www.fert.nic.in/node/2434). Since the policy ensures assistance of Rs 1,500/ton to organic fertilizer manufactures, it is recommended to financially support 'INSAM Practitioner Groups' also who undertake professional production of organic manures and use these to integrate with chemical fertilizers for efficient FN management.

Thus far, the focus of technology transfer agents has been to ensure that farmers use recommended dose of fertilizers. In general, they prescribe a common RDF for a regionally practiced cropping system without any consideration of crop- and soil-specific requirements. Also, advisories seldom emphasize using fertilizers efficiently. Accordingly, the focus of farmers' field demonstrations has, primarily, been to popularize fertilizer use to increase yield and not productivity (extra yield/kg FN) by efficient fertilizer use. In fact, as repeatedly highlighted in this paper, efficient fertilizer use is the need of the hour. To correct the situation, so that efficient use of fertilizers becomes a practice, firstly the extension agents must be educated on the value of SSNM, crop need-based and time-right applications, and managing these competently. Secondly, for making science-driven recommendations on efficient fertilizer management, the technology transfer agents must be trained in the art and science of Nutrient Expert (NE) based SSNM. In turn, SSNM, as echoed earlier, advocates fertilizer treatment coinciding with plant demand and soil nutrient supplying capacity. Alternatively, a simple tool like Leaf Colour Chart can also be popularized to make SSNM-driven fertilizer use decisions. To convince the farmers on the value of SSNM, need would be for inducting and conducting farmer-participated, and extension agent facilitated demonstrations – what is called action research. In pursuance, side by side trial plots, one each on farmer's method of fertilizer management and NE guided SSNM, are established. With this approach, farmers will have opportunity to judge for themselves the superiority of fertilizer saving and yield enhancing capability or otherwise of NE guided SSNM. GoI may, hence, consider induction of a policy popularizing SSNM-based fertilizer used advisories given in the Soil Health Card reports, which are prepared with the application of NE or leaf colour chart procedures.

To sum up, the technologies on enhancing NUE would become infructuous if the research to begin with does not provide space for farmers' concerns and address those with their participation. Necessary dialogue with farmers is likely to drive ownership when a technology is introduced for farmer participatory or adaptive research. Before transfer of a technology, it would also be essential to lay out wellconceived field research or pilots to validate adaptive research findings. Farmers' representatives would invariably be a part of the monitoring and evaluation team. Shared suggestions on making further refinements will facilitate scaling-up of a technology thus developed. The elements of research-extension model to scale-up adoption of NUE technologies are presented in Figure 33.

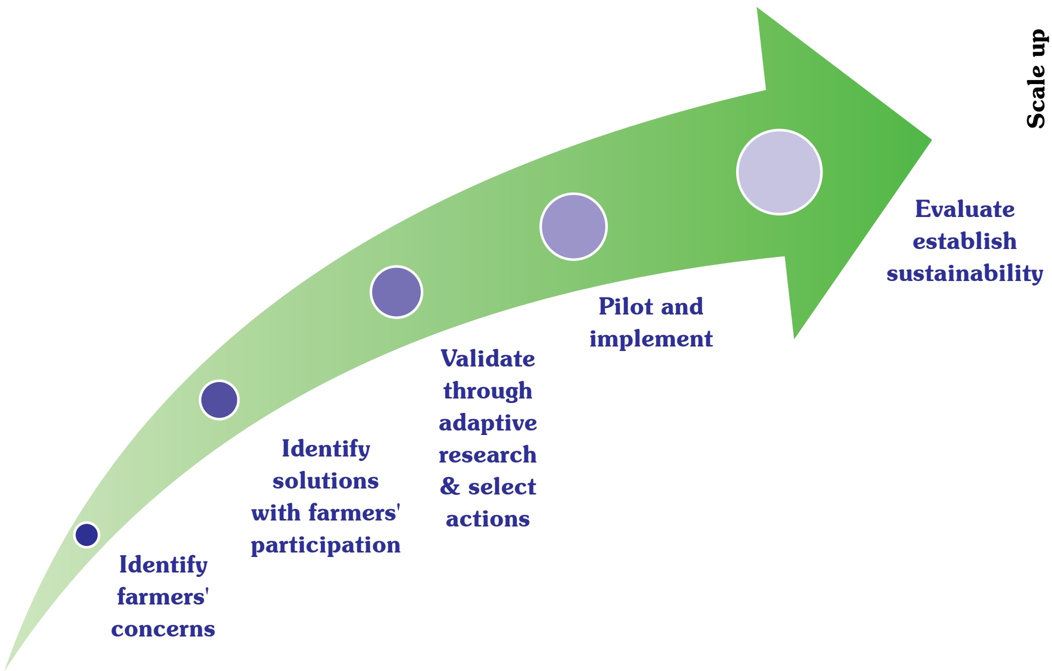


Fig. 33. *Research-extension model to scale-up adoption of NUE technologies*

Summary and Conclusions

Fertilizers (also referred to as fertilizer N, P, and K or FN, FP, and FK) are one input that farmers can't do without and the country cannot afford to slacken their supply in adequate amounts, in a timely fashion, and at affordable prices. Farmers willingly use fertilizers, if pricewise these are affordable and economically viable. GoI on its part, makes fertilizer use affordable, inspiring sustained use. It offers major N, P, and K fertilizers to farmers at subsidized rates based on time-to-time notified retail fertilizer prices. This responsive alliance paid good dividends as the country became self-sufficient in foodgrains from a deficit state. Not only did that happen, but also it turned India as an exporter from a net-importing nation.

The subsidized rate is the difference between the market price (cost incurred by the manufacturer or importer) and the retail value paid by the farmers. The extant

'Fertilizer Subsidy Policy' governs the payment as per this formula. Primarily, urea, DAP and MOP fall under the ambit of subsidy policy. Country, in 2022, spent Rs 2.25 lakh crore (~0.7% of the GDP) on fertilizer subsidy (urea 64%, DAP 26%, and MOP 10%). The subsidy policy for urea is different than that for DAP, and MOP. With the previous or existing arrangement, urea gets preferential subsidy support, which insulates the price farmers pay from the fluctuations in market price. On the other hand, nutrient based subsidy (NBS), launched in 2010, regulates support to DAP and MOP. The retail price of these two fertilizers varies with manufacturer/ importer cost, meaning thereby limited protection from the market fluctuating price. With the result, retail price of urea has remained far lower than the DAP or MOP. Low-cost urea attracts over-use and costly DAP, being popular is used in nearly optimum amounts. More specifically, expensive MOP suffers neglect and is a source of imbalanced use. In either way, the manner FN, FP, and FK are being consumed promote inefficient use and loss, which pose serious challenge both from economic (falling productivity and profitability) and environmental (soil health deterioration, climate change…) angles. The main plank of this strategy paper is to enhance fertilizer use efficiency (+native supplements and complements) to maximize nutrient crop uptake and minimize loss to effect saving in consumption without affecting target food production and environmental health. It must be assured that with decreasing fertilizer consumption there will be automatic containment of subsidy budget unless there is violent price jump of imported finished products or raw materials.

Synthesis of the available information established that among NPK fertilizers, FN use efficiency (NUE) is dismally low (<35%) because it suffers maximum loss (~50%). Apparently, FN offers the maximum opportunity to minimize loss by elevating use efficiency. Furthermore, as FN dominates in consumption (~60 of the total NPK consumption) relatively larger FN savings are possible. Then, FN is crucially important to sustain target food production, nurture soil health and mitigate climate change. FN is also the one nutrient on whose subsidy government bears the maximum burden. Research, development, and innovations to improve NUE, irrefutably, nucleate around FN.

The concept NUE, in general terms, refers to ensuring more output (say foodgrain production) with less input (say fertilizers). While doing that, it would be essential to ensure ecological sustainability, which means reducing use of fertilizers without affecting the productivity growth and no cost to health of soil, water, and air. Additional epicenter of the entire strategy is to enhance fertilizer subsidy financing efficiency. In pursuance, the following four routes are recommended to approach it:

- Management of FN to enhance use efficiency; '4Rs nutrient stewardship' of IFA was the focus of best fertilizer management practices.
- Integration of natural complements and supplements; the focus was on the integrated use of chemical fertilizers and organic fertilizers.
- Partial substitution of conventional fertilizers with minimally processed ores; focus was on glauconite K mineral.
- Alternative methods of farming; focus was on natural farming.

The outcome on value of these approaches to effect fertilizer saving was only possible if there was an aggressive extension to popularize standard agronomic practices and involving farmers in testing and action research. An umbrella policy element is necessary to hasten application of suggested innovations.

Potential savings in FN use with possible changes in the exiting practice and proposed actions are as follows:

- Replace general recommendation on fertilizer use with soil-test based and crop-specific recommendations (SSNM). Farmers must place fertilizer deep by avoiding broadcast. Needed action would be to educate farmers on the value of SSNM as per soil test data of their field and crops being grown and provisioning oflow-cost drills or through custom hiring centers. The possible saving in FN using this approach will be 20 per cent (NUE enhancement 15-25%).
- Zero or no more than 10 per cent of the recommended FN dose to be applied as basal. First top dress to standing crop after 10-14 days of sowing/transplanting to dry soil followed by irrigation (same procedure for other top dress applications). Through this approach, the minimum saving in FN will be 20 per cent (NUE gain ~20 to 25%).
- NPK use to be integrated with organic manure (75% FN+25% organic manure N, no more than 10% of the FN and entire amount of organic N to be applied at the time of sowing/planting, remainder FN to be top dressed before irrigation). Minimum saving in FN will be 25 per cent (NUE gain ~35-40%).
- Make possible use of glauconite-K mineral to save FK at least for plantation crops raised in acid soils. Induction of a policy instrument facilitating inclusion of glauconite in schedule of minerals is a must which will result in possible saving of 25 per cent FK.
- Use of organic manures spiked with ~10 kg N/ha, is likely to result in savings of FN by ~3 m tons each of FK and FP

It is emphasized that projected savings in FN and improvement in NUE would not be possible without the application of precision agronomic practices. Also, extension must adopt a holistic approach of education and farmers-involved testing and demonstration of each of the technologies in unison.

Finally, it is concluded that if NUE is enhanced from the current 35 to 60 per cent by 2030, there will be a possible reduction of about 4 mt in FN consumption. Additionally, it will be possible to save ~3 mt FN by adopting integrated use of organic and chemical fertilizers. On an overall basis, it is possible to bring down NPK fertilizer use, typically FN use, to one half by 2030 with the infusion of five doable approaches given above.

References

Ali, M. 2017. Effect of time of application of the first dose of nitrogen on yield and fertilizer use efficiency in maize grown in calcareous soils. *Communications in Soil Science and Plant Analysis* 48: 1733-1740.

Bijay-Singh and Craswell, Eric. 2020. Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem. SN Applied Sciences. 3:518 | https://doi.org/10.1007/s42452-021-04521-8

Bijay-Singh and Katyal, JC. 1985. Relative efficacy of some new urea-based nitrogen fertilizers for growing wetland rice on a permeable alluvial soil. Journal Agric Sci, Cambridge 109: 27-31.

Bumb, B, Katyal, JC and Singh, U. 2022. Building bridges between natural nutrient sources and fertilizers for soil health and food security. In *Soil Organic Carbon and Feeding the Future* (Rattan Lal, Ed.), pp. 64-97. CRC Press, Taylor and Francis Group, Boca Raton.

CAG Audit Report. 2011. Performance Audit of Fertilizer Subsidy in India of Union Government, Ministry of Chemicals and Fertilizers. Report # 8. https://cag.gov.in/en/audit-report/details/2521

Chen, Zhaoming, Wang, Qian, and Ma, Junwei. 2020. Impact of controlled-release urea on rice yield, nitrogen use efficiency and soil fertility in a single rice cropping system. Scientific Reports. https://doi.org/10.1038/s41598-020-67110-6

Cui, Z., Zhang, H, and Chen, X. 2018. Pursuing sustainable productivity with millions of small holder farmers. Nature 555: 363–366. https://doi.org/10.1038/nature25785

FAI 2021-22. *Fertiliser Statistics 2020-21*, 67th Edition. The Fertilizer Association of India, New Delhi.

Fixen, Paul E. 2020. A brief account of the genesis of 4R nutrient stewardship. Agronomy J (online) DOI: 10.1002/agj2.20315.

Goswami, N. N., Prasad, Rao D. M. V., *et. al*. (1988) Studies on effect of green manuring in Nitrogen economy in a rice-wheat rotation using ^{15}N technique. J. Agric. Sci. Cambridge. 111: 413-17

Gurumurthy, M and Goedeccle, Jann. 2015. *Economics of land degradation: A study of India*. ZEF Policy Brief #15. Centre for Development Research, Bonn, Germany.

Hong, CW, Katyal, JC and Vlek, PLG. 1992. Losses and utilization of nitrogen by sorghum as affected the depth of swelling clay soil. *Journal of Agronomy and Crop Science* 168: 263-271

Indian Minerals Yearbook. 2015. *Indian Minerals Yearbook 2013*. Part III. Mineral Reviews, Potash. 54th Edition. Indian Bureau of Mines, Ministry of Mines, GoI, Nagpur, Maharashtra.

Indian Minerals Yearbook. 2018. *Indian Minerals Yearbook 2018*. Volume III. Mineral Reviews. Indian Bureau of Mines, Ministry of Mines, GoI, New Delhi.

Isherwood, KF. 2000. *Mineral Fertilizer Use and the Environment*, IFA, Paris, France and UNEP, Division of Technology, Industry, and Economics, Paris, France.

Katyal, JC, Singh, Bijay, Vlek, P. L. G., *et al*. 1987. Efficient nitrogen use as affected by urea application and irrigation sequence. *Soil Science Society of America Journal* 51: 366370.

Katyal J.C., Bijay-Singh, Vlek, P.L.G. *et al*. 1985. Fate and application of nitrogen fertilizers applied to wetland rice. II. Punjab, India. *Fertilizer Research* 6: 279-290

Katyal, JC. 2016. Fertilizer nitrogen in Indian agriculture – retrospective and prospective. *Indian Journal of Fertilisers* 12(4): 16-33.

Katyal, JC. 2019. Fertilizer use efficiency research: looking back to move forward. *Indian Journal of Fertilizers* 15: 1384-1401.

Katyal, JC and Chaudhari, SK. 2021. Do fertilizers protect or punish soil health? *Indian Journal of Fertilisers* 17: 1242-1281.

Katyal, JC. 2022. Beating the current international fertilizer price rise and moderating India's subsidy bill: Innovations in fertilizer use and management are a Way forward. *Indian J. Fertilisers* 18 (7): 624-644.

Khan, S. A., R. L. Mulvaney, T. R. Ellsworth and C. A. 2007. The myth of nitrogen fertilization for soil carbon sequestration. *J. Environ. Qual*. 36:1821-1832.

Khind, C.S. and Datta, N.P. 1975. Effect of method and timing of nitrogen application on yield and fertilizer nitrogen utilization by lowland rice. *Journal of the Indian Society of Soil Science* 23: 443-446.

Kundu, S, Adhikari,T., Vassanda Coumar M., *et al*. 2018. Enhancing N use efficiency and reducing N_2O emission by coating urea with newly identified bio-molecule ($C_{20}H_{30}O_2$), nano-Zn oxide and nano-rock …Energy and Environment: Select Proceedings of ICWEES-2016, 2018. Springer. https://link.springer.com/chapter/10.1007/978-981-10-5798-4_9.

Ladha, JK, Tirol-Padre, A, and Reddy, CK. 2016. Global nitrogen budgets in cereals: A 50-year assessment for maize, rice, and wheat production systems. *Sci. Rep*. 6: 1-9. https://doi.org/10.1038/srep19355

Lassaletta, L, Billen, G, Grizzetti, B, Anglade, J and Garnier, J. 2014. 50-year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environmental Research Letters* 9(10): 1-9.

Li, Lin, Tian, Hua, and Zhang, Minghua. 2021. Deep placement of nitrogen fertilizer increases rice yield and nitrogen use efficiency with fewer greenhouse gas emissions in mechanical direct-seeded cropping system. *The Crop J*. 9: 1386-1397.

McLaren C., Mead Andrew , Derk van Balen, *et al*. 2021. Long-term evidence for ecological intensification as a pathway to sustainable agriculture. *Nature Sustainability*. 5: 770-779.

Mankunnummal, A. 2022. Containing the fertilizer subsidy in India: An analysis of subsidy containing strategies and its outcome. Centre for Development Studies, Thiruvananthapuram. Kerala. 30 p.

Malhi, SS, Oliver E, and Mayerle G. 2003. Improving effectiveness of seed row-placed urea with urease inhibitor and polymer coating for durum wheat and canola. *Commun. Soil Sci. Plant Anal.* 34:1709–1727. doi: 10.1081/CSS-120021307.

Menegat, S, Ledo, A and Tirado, R. 2021. Greenhouse gas emissions from global production and use of nitrogen synthetic fertilizers in agriculture. Scientific Reports 12:14490 https://doi.org/10.1038/s41598-022-18773-w

Moraghan, JT, Rego, TJ and Buresh, RJ. 1984a. Labeled nitrogen fertilizer research with urea in semi-arid tropics. II. Field studies on a Vertosol. *Plant and Soil* 80: 21-33

Moraghan JT, Rego, TJ, Buresh, RJ. 1984b. Labeled nitrogen fertilizer research with urea in semi-arid tropics. III. Field studies on an Alfisol. *Plant and Soil* 82: 193-203

Mustaffa, Ayesha, Athar Fareeha, Khan, Imran, *et al*. 2022. Improving crop productivity and nitrogen use efficiency using sulfur and zinc-coated urea: A review. Frontier of Plant Science. https://doi.org/10.3389/fpls.2022.942384

NAAS. 2017. Strategy on utilization of glauconite mineral as source of potassium. *Strategy Paper* 6: 1-12. National Academy of Agricultural Sciences, New Delhi.

Olk, D, Cassman, KG, and Simbahan, G. 1999. Interpreting fertilizer-use efficiency in relation to soil nutrient supplying capacity, factor productivity, and agronomic efficiency. *Nutri. Cycling Agroecosystems* 53: 35-41.

Omara Peter, Lawrence Aula, Fikayo Oyebiyi, *et al*. 2019. World Cereal Nitrogen Use Efficiency Trends: Review and Current Knowledge. *Agrosyst. Geosci. Environ*. 2: 1-8.

Park, S, Croteau, P, Boering, KA, and Etheridge, DM. 2012. Trends and seasonal cycles in the isotopic composition of nitrous oxide since 1940. *Nature Geoscience* 5(4): 261-265.

Pan, Sheng-gang, Huang, Sheng-qi, and Zhai. 2012. Effects of N Management on Yield and N Uptake of Rice in Central China, *J. Integrative Agriculture*. 11 (12): 1993-00.

Peng, Shaobing, Buresh, RJ, and Huang, J. 2006. Strategies for overcoming low nitrogen use efficiency in irrigated rice systems in China. *Field Crops Research* 96: 37-47.

PIB. 2023. Press Information Bureau Reports, Government of India, 2023.

Purakayastha, TJ and Katyal, JC. 1998. Evaluation of compacted urea fertilisers prepared with acid and nonacid producing chemical additives in the soils varying in pH and cation exchange capacity. 1, NH_3 volatilization. *Nutri. Cycling Agroecosystems* 51: 107-115.

Reetz Jr., and Harold F. 2016. Fertilizers and their Efficient Use. IFA, Paris, France.

Ritchie, Hannah. 2017. How many people do fertilizers feed? https://ourworldindata.org/how-many-people-does-synthetic-fertilizer-feed

Sapkota, Tek B, Jat, Mangi L, and Rana, Dharamvir S. 2021. Crop nutrient management using Nutrient Expert improves yield, increases farmers' income and reduces greenhouse gas emissions. Scientific Reports, 11: 1564. https://doi.org/10.1038/s41598-020-79883-x

Shinde, J. E., Krishnappa, K, Rao, KV and Gandhi, G 1985. Transformation of ^{15}N labeled urea in rice-wheat cropping system. *Plant and Soil* 88: 345-351.

Singh, Yadvinder, Bijay Singh, and Ladha, JK. 2007. On-farm evaluation of leaf color chart for need-based nitrogen management in irrigated transplanted rice in north-western India. *Nutrient Cycling Agroecosystems* 78: 167–176.

Sitthaphanit, Suphasit, Limpinuntana, Viriya, and Toomsan, Banyong. 2010. Growth and Yield Responses in Maize to Split and Delayed Fertilizer Applications on Sandy Soils Under High Rainfall Regimes. *Kasetsart J.* (*Nat. Sci*.) 44: 991-1003.

Srinivasarao, Ch. Subbarao, A., Magen, H. 1999. Characterization of indigenous glauconite sandstone for its potassium supplying potential by chemical, biological and electroultrafiltration methods. *Commn. Soil Sci. Plant Anal*. 30(7&8): 1105-1117.

Srinivasarao, Ch., Subba Rao, A, and Rao, KV. 2010. Categorization of districts based on the non-exchangeable potassium: implications in efficient K fertility management in Indian agriculture. *Indian Journal of Fertilizers* 6(7): 40-55.

Subasinghe, R and Angus, J. 2009. Increasing productivity and water use efficiency in Australia's rice industry through nitrogen management. Rural Industries and Development Corporation. PO Box 4778, Kingston, Australia.

TIFAC. 2016. Technologies for Agricultural Application of Glauconite A Potash Mineral. http://tifac.org.in/index.php?option=com_content&view=article&id=729&Itemid=205

Timsina, J. 2018. Can organic sources of nutrients increase crop yields to meet global food demand? *Agronomy* 8: 214(1-20).

Year-end Review of the Department of Fertilizers. 2022. Ministry of Chemicals and Fertilizers. https://pib.gov.in/PressReleaseIframePage.aspx

Zheng, Yong-Mei, Ding, Y. Feng, Zheng H. Liu, *et al*. 2010. Effects of Panicle Nitrogen Fertilization on Non-Structural Carbohydrate and Grain Filling in Indica Rice. *Agricultural Sciences in China*. 9(11): 1630-1640.

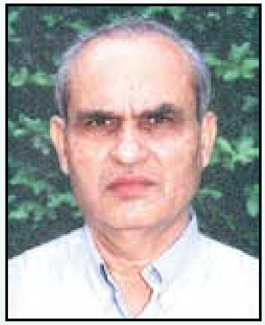
Zhang, X, Davidson, Eric A., Mauzerell, Denise L., *et al*. 2015. Managing nitrogen for sustainable development. *Nature* 528 (7580): 1-9.

Recent TAAS Publications

1. Enhancing Fertilizer Use Efficiency for Sustainable Soil Health - Policy Brief, November, 2023.
2. Strengthening National Agricultural Education System - A Road Map, 30 October, 2023.
3. Navara Rice - A Success Story by P Narayanan Unny, July 2023.
4. Policy and R&D Interventions to Increase Cotton Production and Industrial Growth – Policy Brief, March 2023.
5. National Dialogue on Harnessing the Potential of Floriculture in India - Proceedings & Recommendations, 16-17 February, 2023.
6. National Dialogue on Sustainable Growth and Development of Indian Dairy Sector – Proceedings and Recommendations, 16-17 December, 2022.
7. National Symposium on Food, Nutrition, and Environmental Security: Towards Achieving SDGs – Proceedings and Recommendations, 29-30 August, 2022.
8. Resilience in Dairy Farming – A Success Story by Nikki Pilania Chaudhary, November 2022.
9. National Dialogue on Innovations in Agricultural Extension: A Way Forward, 8-9 April, 2022.
10. Towards Secure and Sustainable Agriculture - Strategy Paper by Dr RS Paroda, August, 2022.
11. Expert Consultation on Promoting Efficient Irrigation Technologies for Water Saving Across Scales and Sectors, 25 February, 2022.
12. Expert Consultation on Accelerating Export of Seed Spices: Challenges and Opportunities - Proceedings and Recommendations, 22 November 2021.
13. National Workshop on Bridging the Yield Gaps to Enhance Foodgrain Production: A Way Forward - Proceedings and Recommendations, 26 August, 2021.
14. Report on Policies and Action Plan for a Secure and Sustainable Agriculture in Hindi, October, 2021.
15. Youth as Advisory Agents, Input Providers and Entrepreneurs – Article by Dr RS Paroda, September, 2021.

16. Brainstorming Session on Regenerative Agriculture for Soil Health, Food and Environmental Security - Proceedings and Recommendations, 26 August, 2021.
17. Stakeholders Dialogue on Enabling Policies for Harnessing the Potential of Genome Editing in Crop Improvement - Proceedings and Recommendations, 17 March, 2021.
18. Harnessing Genome Editing for Crop Improvement – An Urgency: Policy Brief, May, 2021.
19. Accelerating Science-Led Growth in Agriculture: Two Decades of TAAS, May, 2021.
20. A Road Map on Stakeholders Dialogue on Strategies for Safe and Sustainable Weed Management, January, 2021.
21. Fish Farming in North India-A Success Story by Dr Sultan Singh, December, 2020.
22. A Road Map on Stakeholders Dialogue on Current Challenges and Way Forward for Pesticide Management, September, 2020.
23. A Road Map on Stakeholders Dialogue on Way Forward for the Indian Seed Sector, June, 2020.
24. Biofertilizers and Biopesticides for Enhancing Agricultural Production – A Success Story by Dr Basavaraj Girennavar, June, 2020.
25. A Road Map on Policy Framework for Increasing Private Sector Investments in Agriculture and Enhancing the Global Competitiveness of Indian Farmers, December, 2019.
26. Crop Biotechnology for Ensuring Food and Nutritional Security – Strategy Paper by Dr JL Karihaloo and Dr RS Paroda, December, 2019.
27. A Road Map on Efficient Land Use and Integrated Livestock Development, November, 2019.
28. National Dialogue on Land Use for Integrated Livestock Development - Proceedings & Recommendations, 1-2 November, 2019.
29. Horticulture for Food & Nutritional Security - Strategy Paper by Drs KL Chadha and VB Patel, October, 2019.
30. Urgency for Scaling Agricultural Innovations to Meet Sustainable Development Goals (SDGs) – Strategy Paper by Dr RS Paroda, April, 2019.

Brief Resume



Dr JC Katyal, born on 04 March 1944, was educated at Vaish High School Rohtak 1957-60; PAU, 1960-64; IARI, 1964-69; Post-doctoral Fellow, IRRI, 1970-72. BSc- Ag (1964), MSc- Soil Science (1966) and PhD 1969. Dr Katyal began his professional career as Soil Scientist, AICRIP, Hyderabad, 1972-77 and went on to become Project Coordinator, AICRIP (Micronutrients), PAU 1977-85; Principal Scientist and Head, Division of SS&AC, IARI, New Delhi 1988-1991; Director, CRIDA, 1991-1997; Director NAARM, 1997-2002; and DDG (Agricultural Education) ICAR 2002-05. Following superannuation he served as Director, Centre for Extension Education and Professor School of Agriculture, IGNOU, New Delhi (2005); Vice-Chancellor, CCS HAU, Hisar (2006-09); and Director-Consultant Cargills (Ceylon), Colombo, Sri Lanka (2009-2012). He also served as Visiting Scientist IFDC, USA (1985-1988) and Senior Research Fellow, Center for Development Research, University of Bonn, Germany (1999-2000).

Dr Katyal has a rich and diverse experience of over 50 years in research, institutional and policy issues, teaching, training, and extension. His special areas of research include Soil Chemistry and Fertilizers, Micronutrients, Dryland Agriculture, Desertification and Land Degradation. Dr Katyal has about 250 research and other publications to his credit. He has also served as Chairman/Member/Convener of numerous National/International Committees and has represented India on foreign missions. For his professional contributions, he has been conferred with several awards and recognitions. Some of them are: FAI Excellence in Agricultural Research 1984, IFDC Best Visiting Scientist 1986, Borlaug Award, 1995, ICAR Best Institute Award 1996, Rafi Ahmad Kidwai Award 1996, Life Time Achievement Award for Micronutrient Research by Ranade Trust 2001, Rajiv Gandhi Award for leadership in Science by Haryana Government, 2007; Life time Excellence in Agricultural Research and Development, IFFCO/FAI, 2019. He is Fellow of the Indian Society of Science and National Academy of Agricultural Sciences (NAAS). In 2016, he was conferred the Honorary Fellowship of the Indian Society of Soil Science. He has been President, Indian Society of Soil Science and Indian Society of Dryland Agriculture and served as Member Executive Council/Editor/Vice president, NAAS, New Delhi.

taas

Progress Through Science

Trust for Advancement of Agricultural Sciences (TAAS)

Avenue II, ICAR-Indian Agricultural Research Institute (IARI)
Campus, New Delhi - 110012, India
Ph.: +91-11-25843243; +91-8130111237
E-mail: taasiari@gmail.com; Website: www.taas.in