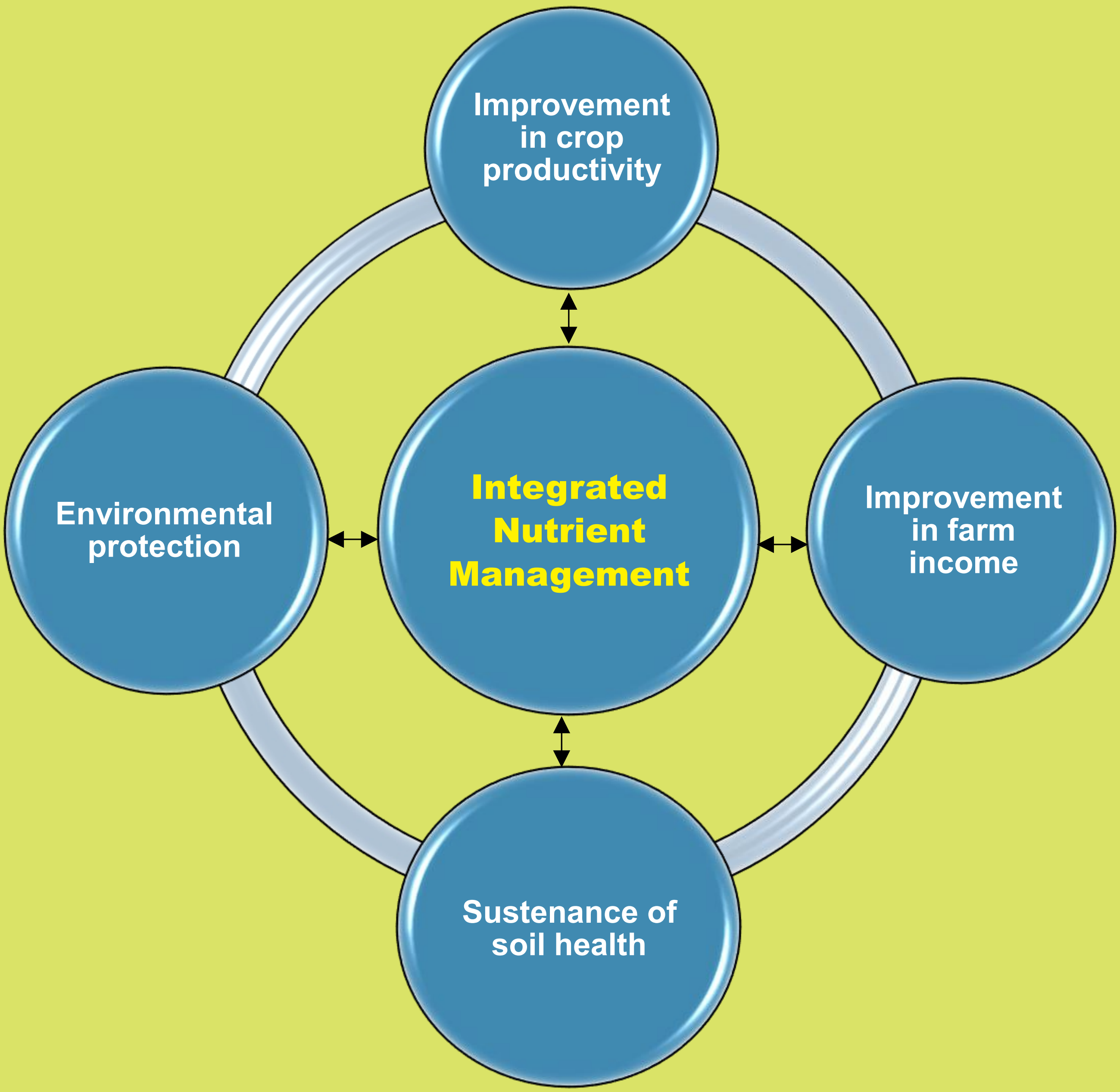
ISSN 0973-1822 Vol.16 No.4 pp 289-408 April 2020 Price Rs.100 per copy Annual Subscription Rs. 1000

FAI ENSURING FOOD SECURITY

# INDIAN JOURNAL OF FERTILISERS

Monthly Journal of The Fertiliser Association of India

## AGRICULTURE SPECIAL



# The Fertiliser Association of India
(Founded in 1955)

## FAI BOARD OF DIRECTORS

*Chairman*

| | | |
|---|---|---|
| K.S. RAJU | : | Nagarjuna Fertilizers and Chemicals Ltd., Hyderabad |

*Directors*

| | |
|---|---|
| AJAY S. SHRIRAM | DCM Shriram Ltd., New Delhi |
| A. VELLAYAN | Coromandel International Ltd., Chennai |
| P.S. GAHLAUT | Indian Potash Ltd., New Delhi |
| RAKESH KAPUR | Indian Farmers Fertiliser Cooperative Ltd., New Delhi |
| R.K. CHOPRA | KRIBHCO Fertilizers Ltd., Noida |
| M.S. DAGUR | Gujarat Narmada Valley Ferts. & Chems. Ltd., Bharuch |
| ASHIM KUMAR GHOSH | BVFCL, Namrup |
| SAMEER GOEL | Coromandel International Ltd., Secunderabad |
| ASHVINI HIRAN | IRC Agrochemicals Pvt. Ltd., Kolkata |
| A.K. JAIN | Kanpur Fertilizers and Cement Ltd., Noida |
| SANJIV KANWAR | Yara Fertilisers India Pvt. Ltd., Gurgaon |
| ANIL KAPOOR | Chambal Fertilisers and Chemicals Ltd., New Delhi |
| K.K. KAUL | DCM Shriram Ltd., New Delhi |
| SHAILESH KHAITAN | Khaitan Chemicals & Fertilizers Ltd., Indore |
| N. SURESH KRISHNAN | Mangalore Chemicals and Fertilizers Ltd., Gurgaon |
| PRAVEEN K. MAHESHWARI | Hindalco Industries Ltd., Mumbai |
| S.C. MEHTA | Smartchem Technologies Ltd., Pune |
| MANOJ MISHRA | National Fertilizers Ltd., Noida |
| S.C. MUDGERIKAR | Rashtriya Chemicals and Fertilizers Ltd., Mumbai |
| MANISH NAGPAL | Greenstar Fertilizers Ltd., Chennai |
| SUNDEEP KUMAR NAYAK | NCDC, New Delhi |
| AKSHAY PODDAR | Zuari Agro Chemicals Ltd, Gurgaon |
| D.S. SUDHAKAR RAMAIAH | PDIL, Noida |
| S.R. RAMAKRISHNAN | Southern Petrochemical Industries Corpn. Ltd., Chennai |
| KISHOR RUNGTA | FACT, Udyogmandal |
| C. NARASIMHA REDDY | JACPL, Greater Noida |
| U. SARAVANAN | Madras Fertilizers Ltd., Chennai |

*Director General* :

| | |
|---|---|
| SATISH CHANDER | FAI, New Delhi |

*Registered Office :*

**THE FERTILISER ASSOCIATION OF INDIA**
FAI House, 10 Shaheed Jit Singh Marg
New Delhi - 110 067
CIN : U85300 DL 1955 NPL 002999
Tel : 91-11-26567144 Fax : 91-11-26960052 46005213
E.mail : dg@faidelhi.org, secy@faidelhi.org
Website : www.faidelhi.org

# INDIAN JOURNAL OF FERTILISERS

Vol.16 No.4 April, 2020



## CONTENTS



No. of Pages 120 (289-408)

### Our Cover

**Cover depicts components of INM and their importance in agriculture**

Previous issue : Vol.16 No.3, pp.185-288

**Annual Subscription** : **Rs.1000/-**
**Single copy** : **Rs.100/-**

7

All the papers published in Indian Journal of Fertilisers are peer-reviewed.

The opinions expressed by contributors do not necessarily reflect the views of The Fertiliser Association of India

Indian Journal of Fertilisers **16** (4) : 294-295, April 2020

Frank Notes

**Satish Chander**

# Integrated Nutrient Management: Key to Sustainable Soil Health and Crop Productivity

India achieved spectacular growth in agricultural production during the last 50 years with its march from 'ship to mouth situation' of mid-1960s to 'current net export surplus' on food production front. Country's dependence on agriculture is more than 10,000 years old. Organic manures were the sole source of nutrients as well as organic matter in the Indian soils up to the beginning of 20th century. Soils supported precarious low yield levels. In 1928, diagnosing poor fertility of soils as the cause of lower yields, Royal Commission on Agriculture observed, "Indian soils have been depleted to the extent that no further depletion is possible". Inadequacy of organic manures in meeting the crop nutrient requirements led to a search for other/ alternative nutrient sources.

Historically, production of single superphosphate by Liebig and chemical fixation of atmospheric nitrogen as ammonia by Haber-Bosch process heralded the era of chemical fertilizers. In India, fertilizer started with the EID-Parry company setting up a single superphosphate (SSP) factory at Ranipet, Tamil Nadu in 1906. Chemical fertilizers introduced in first half of 20th century started supplementing the nutritional requirements of the crops. With heralding of the Green Revolution era, chemical fertilizers emerged as the dominant sources of plant nutrient supply to high yielding varieties of crops. With increase in crop intensity, more land area put under cultivation, and more reliance on farm machinery replacing draught animals, availability of organic manures as nutrient source declined gradually. In this scenario, fertilizers assumed a key role in strengthening the national food security. Currently, 50% of the food production both globally as well as in India is attributed to fertilizer use.

While agricultural intensification model helped in achieving self-sufficiency in the food grain production by the close of 20th century, issues related to soil health degradation (particularly, soil fertility depletion) became more critical. Indian soils are plagued by abysmally low soil organic carbon of less than 0.5%. More than 90% of the Indian soils are deficient in available nitrogen (N). Deficiencies of phosphorus (P), potassium (K), sulphur (S), zinc (Zn), boron (B), iron (Fe) and manganese are 80%, 50%, 41%, 36%, 23%, 13% and 7%, respectively. Consequences have been the low nutrient use efficiencies: 30-50% for N, 15-25% for P, 50-60% for K, 8-12% for S, and 2-5% for micronutrients. Decline in fertilizer response ratio from 12.1 kg grain per kg NPK in 1960-69 to 5.1 kg grain per kg NPK in 2010-17 reflects on the deterioration of soil fertility. Imbalanced fertilizer use, unabated burning of crop residues and climate change pose further challenge to the sustenance of soil health.

The increased nutrient uptake under high yielding crop varieties and intensive agriculture has exerted pressure on soil fertility. Although, annual fertilizer (NPK) consumption increased from 0.78 million tonnes (Mt) in 1965-66 to a record level of 28.12 Mt in 2010-11, the problem of soil nutrient mining has continued unabated. As per the FAI estimates, the annual uptake of primary nutrients (NPK) by crops during 2015-16 was 36.6 Mt against application of 26.8 Mt, leaving a gross nutrient gap of 9.8 Mt. By taking into consideration the nutrient use efficiencies, the net gap between nutrient uptake by the crops and addition through fertilizers widened to 13.0 Mt. Nutrient-wise analyses revealed that the whopping gap between nutrient uptake and application of fertilizer nutrients was largely on account of K, leading to its over-mining from the soil.

The nutrient needs of Indian agriculture are so huge that no single source by itself, be it fertilizer or organic manure or bio-fertilizer, can meet the entire nutrient demand. Integrated nutrient management (INM) *i.e.* combined use of fertilizers, organic manures and bio-fertilizers is the only practicable, efficient, economically feasible and environmentally benign way of managing nutrients. Concept of INM first originated in late 1980s or beginning of 1990s due to widespread emergence of multi-nutrient deficiencies and deterioration of physical and biological health of the soil. Its basic objective was the maintenance of soil fertility, sustenance of crop productivity and improvement of the farmers' profitability.

Integrated nutrient management, combining the age-old and modern methods of nutrient management, is designed to derive benefits from usage of all possible organic and inorganic sources in a judicious, efficient and integrated manner. The combined use of inorganic, organic and biological sources of plant nutrients is not only important for nutrition of crops but also in improving physical and biological health of soils. Several researchers have

**Integrated nutrient management *i.e.* combined use of fertilizers, organic manures and bio-fertilizers is the only practicable, efficient, economically feasible and environmentally benign way of managing nutrients.**

reported that the combined application of chemical fertilizers and organic manures increased soil organic matter (SOM) more effectively than did the application of fertilizers or organic manures alone. The INM-induced SOM build up brings about improvement in soil physical properties such as soil structure and water holding capacity.

Chemically, SOM enrichment enhances the capacity of soil to resist changes in the pH, increases cation exchange capacity, reduces phosphorus fixation and serves as reservoir of nutrients, including micronutrients. Soil health- related microbial indicators such as soil microbial biomass, soil bacterial community diversity and soil enzyme activities also improve significantly under the INM practice. Biologically, SOM favours growth of fauna and micro-organisms which disrupt the nutrient cycles operating in the soil and facilitate the release of minerals in the ecosystems. Conjoint use of organic and inorganic sources helps improve the nutrient use efficiency by increasing synchrony between soil nutrient availability and crop demand.

Farmers are aware of benefits of organic manures; however, the real challenge is the scant availability or non-availability of organic manures. Shifting of animal-based farming to mechanized agriculture, and burning of crop residues and their diversion for other purposes are some of the reasons for low availability of biomass for compost preparation. All these practices singly or together are major hindrances to the adoption of INM technology by the farming community.

Crop residues constitute a good nutrient source; however, the quality of residues is often low and the amounts are generally insufficient. In India, an estimated 500-550 Mt of crop residues are produced annually. After accounting for multiple competitive uses, about 140 Mt are surplus most of which are burnt *in situ*. Burning of straw poses phenomenal pollution problems in the atmosphere and is a reason for huge nutritional and physical health deterioration to the soil.

Biogas plant integrated with low cost cattle sheds and rural toilets may be a viable option for proper recycling of crop residues, cow dung and urine, human excreta, weed biomass, and kitchen wastes. It will help in supplementing rural fuel and fodder needs besides generating valuable biogas manure for agricultural use.

Promotion of city compost can serve twin objectives of supporting Swachh Bharat Abhiyan of the Government of India and providing valuable manures to the farmers. To encourage the use of city compost, the Department of Fertilizers, Ministry of Chemicals and Fertilizers, GOI has started providing a market development assistance of Rs.1500 per tonne of city compost. However, it seems to be inadequate and therefore has not yielded desired results. Ministry of Agriculture and Farmers Welfare is promoting the concept of INM through various programmes and schemes. However, the adoption of INM technology at the farmers' fields is still abysmally low.

The existing nutrient based subsidy (NBS) policy of the Government keeping urea out of this policy and maintaining artificially very low retail price works against the promotion of balanced and integrated use of nutrients. With heavy subsidy on urea, farmers are encouraged to overuse urea, leading to the excessive-N use related risks of ground water pollution with nitrates, eutrophication of surface water bodies, nitrous oxide emissions-induced climate change, etc. Lower or scant use of other nutrients like P, K, secondary and micronutrients reduce the use efficiency of applied N resulting in low crop response and degradation of environment. Accelerated appearances of multi-nutrient deficiencies arising out of this imbalance are threatening the sustainability of soil and crop productivity. Therefore, there is a need for immediate correction in retail prices of fertilizers. This can early be done by brining urea under NBS policy. Fertilizer manufacturing companies should be encouraged to produce and promote organic fertilizers and bio-fertilizers so that these fertilizers contribute 15% of fertilizer basket of the farmers. Awareness among farmers should be created to adopt the improved agricultural management practices like crop diversification including legumes, crop residue retention, mulching, cover crop, use of organics in conjunction with chemical fertilizers as a wholesome package.

Although location-specific relevant INM packages to address soil health related issues are available, the outcome is far below the expectations mainly because the INM activities are being implemented in isolation through different developmental schemes/programmes by different Ministries/Agencies. There is a need for convergence of all the related programmes/schemes to address nutrient management issues. Needless to say that all policies related to the fertilizer and agriculture sectors should promote integrated nutrient management. These steps are necessary to maintain soil health, sustain water quality, protect the environment, and make the country food and nutrition secure. ■

# Carbon-Centric Integrated Nutrient Management : A Solution for Enhancing Farm Productivity and Carbon Sequestration in India

**Rattan Lal**

Carbon Management and Sequestration Center

The Ohio State University, Columbus, OH 43210, USA

Received : 06/01/2020 Accepted : 09/03/2020

## Abstract

The global success story of India's agriculture, indicated by increase in cereal production between 1950 and 2019 by a factor of 5.6 *versus* growth in population by a factor of 3.6, is partly due to intensive input of chemical fertilizers used at the rate of less than 1 kg $ha^{-1}$ in 1951-52 compared with 165.8 kg $ha^{-1}$ in 2018-19. In conjunction with expansion of the area under irrigation and use of dwarf high-yielding varieties, the use of chemical fertilizers transformed India from a food-importing to a food-exporting country. While 196 million people (14.5% of the total population in 2019) remain vulnerable to food insecurity, there are also serious environmental issues with regards to depletion and contamination of natural waters, pollution of air, dwindling of biodiversity, and severity of soil degradation. Therefore, there is a need for a paradigm shift in favour of adopting a carbon-centric approach based on the strategy of integrated nutrient management (INM) and restoration of soil health through sequestration of soil organic carbon (SOC) in croplands of India. Severe depletion of SOC content, aggravated by accelerated erosion and in-field burning of crop residues along with its removal for other uses, may be an important cause for the low use efficiency of fertilizers, water, and other inputs. Rather than increasing the rate of fertilizer, the goal is to improve its use efficiency through adoption of 4-R and 4-S systems of fertilizer and soil management. While fertilizers cannot be completely replaced by manuring or enhancing soil health, the strategy is to produce more from less by restoring degraded soils so that land and water resources can be saved for nature, gaseous emissions reduced and environment quality improved. Rather than NPK, the focus should be on the use of CNPK. Input of biomass-carbon (C) in a depleted soil may restore its health, improve the environment, and increase the use efficiency of fertilizers. The goal is to reconcile the need for meeting the food demands of the growing and progressively affluent population of India with the absolute necessity of improving and sustaining the environment. Rights-of-soil must be respected.

**Key words:** Soil health, soil organic carbon sequestration, fertilizer use efficiency, nutrient use efficiency, soil degradation, integrated nutrient management, food and nutritional security

## Introduction

Increase in India's cereal production, from 50.8 million tonnes (Mt) in 1950 to 285 Mt in 2019, is a global success story. While the net cultivated land area remained relatively constant at 140 million hectares (Mha) and under cereals at 100 Mha since 1970 (Tian et al., 2014), increase in production occurred due to a strong growth in productivity. Between 1950 and 2019, crop yield (kg $ha^{-1}$) increased from 668 to 2000 for rice, 663 to 3600 for wheat, and 441 to 779 for pulses. Furthermore, the rate of increase in food grain production was more than that of population growth; thus the per capita grain production has also kept ahead of the population growth (**Figure 1A & 1B**). In addition to the adoption of improved varieties, the growth in agricultural production was also due to drastic increase in input. The cropland area under irrigation increased from 18.1% in 1950 (20.2 Mha) to 34.5% in 2013-14 (48 Mha) (World Bank, 2013; FAO, 2014). While canal irrigation was championed by the British government (Shah, 2011), micro-irrigation is gaining momentum in India since 2015 (Harsha, 2017; Narayanamoorthy, 2019). Similar to irrigation, the rate of fertilizer input in India increased from less than 1 kg $ha^{-1}$ in 1951-52 to 165.8 kg $ha^{-1}$ in 2018-19. Total fertilizer consumption in India increased from 0.066 Mt in 1950-51 to 1.98 Mt in 1969-70, 18.07 Mt in 1999-2000, and 26.7 Mt in 2017-18. Along with the use of chemical fertilizers, the use of pesticides also increased. There are 275 registered pesticides in India (Kumar and Reddy, 2017).

The Green Revolution (GR) in India, based on the use of high-yielding varieties grown in irrigated land with high input of fertilizer and pesticides, saved hundreds of millions from starvation and transformed India from the status of a "hungry nation" to that of a "food exporting nation" (Siegel, 2018). However, even greater challenges lie ahead, and there is no cause for complacency. First, hunger and malnutrition persist, and prevalence of undernourishment remains to be serious at 195 million people in 2018 compared with that of 256 million for the entire continent of Africa, and India ranks 103rd among 119 countries in the

lal.1@osu.edu

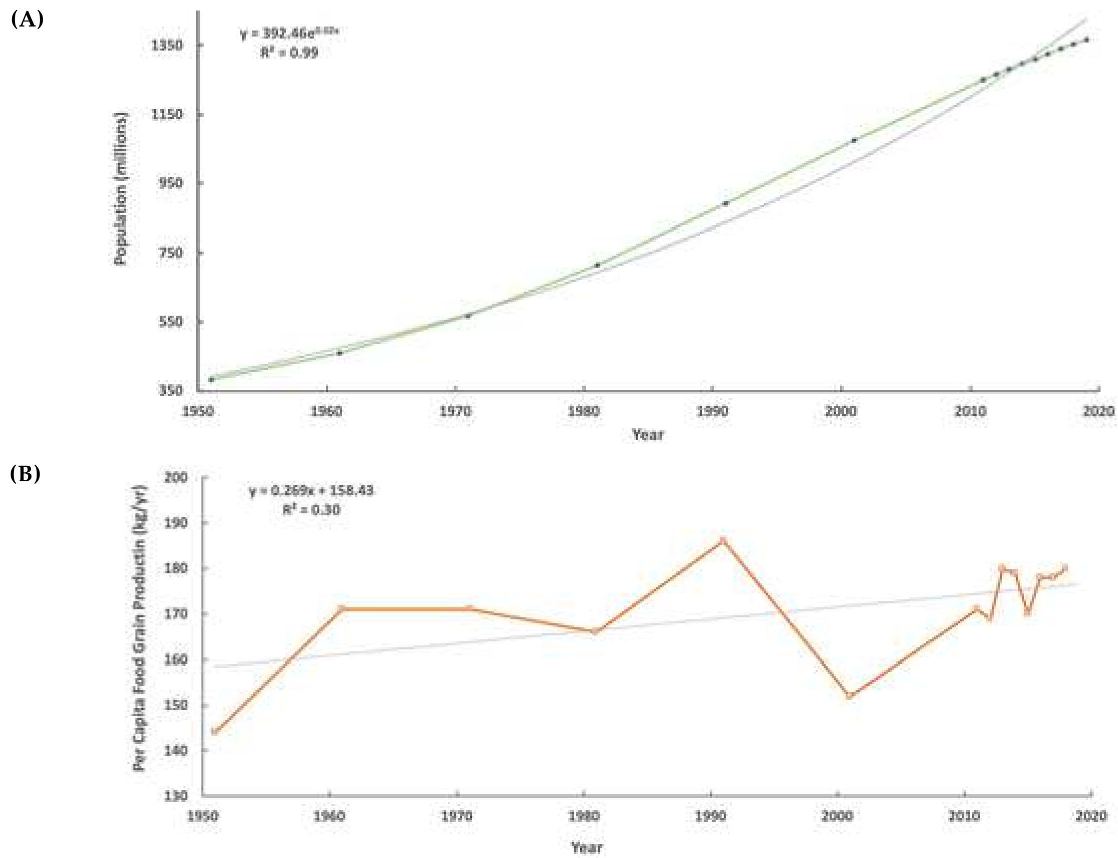



**Figure 1. Population (A) and per capita annual food grain production (B) over a period of time**

prevalence of undernutrition (FAO et al., 2019). Second, the yield of cereals in India has been stagnating since 2010. For example, yield (kg $ha^{-1}$) of wheat in India has stagnated at about 3500 since 2012; of rice at 2500 since 2011; and that of corn has decreased from 3100 in 2017 to 2840 in 2019. Third, the ecological footprint of agriculture - in terms of water contamination, air pollution and deterioration of the overall environment - is staggering (Singh, 2000). The adverse environmental impact of the GR technology is indicative of low use efficiency of fertilizer (especially nitrogen) and water. Fourth, there is a serious problem of soil degradation, which is simultaneously limiting the agronomic productivity, degrading the environment, and adversely affecting the human wellbeing. Finally, there exists a large yield gap - the difference between the achievable and the actual yield of most crops in India. There also exists a large difference in the agronomic yield of major crops between China and India (**Figure 2**), which is indicative of low use efficiency of inputs, poor quality of soil resources, and land misuse and soil mismanagement. The soil organic carbon (SOC) content, an important indicator of soil functionality and health of cropland soils, is low (Bhattacharyya et al., 2000; Manna et al., 2003), and is regressively declining over time because of the prevalence of extractive practices. The SOC content can be as low as 2.8 to 6.1 g $kg^{-1}$ under traditionally managed control treatment in the surface layer compared with only 4.9 to 15.6 g $kg^{-1}$ with integrated nutrient management (INM) involving judicious use of chemical fertilizers and organic manure (NAAS, 2018). Indeed, there are strong declining trends in the fertility status of cropland soils of India (Pathak, 2010).

Yet the food production must be enhanced and sustained to meet the ever-growing demands of the increasing and progressively affluent population of India. Whereas the chemical fertilizers may never be completely replaced by biofertilizers nor by restoration of soil health through increase in SOM content, the use efficiency of fertilizers (and other inputs such as irrigation) must be enhanced and adverse impacts on environment minimized through judicious and discriminate use of fertilizers and restoration of soil health. Thus, the objective of this article is to discuss strategies of reconciling on the need for increasing food production with the necessity of improving the environment and restoring the quality of natural resources by improving use efficiency of inputs through adoption of soil-centric technologies.

## Food Demand in India

India's population, which increased from 410 million

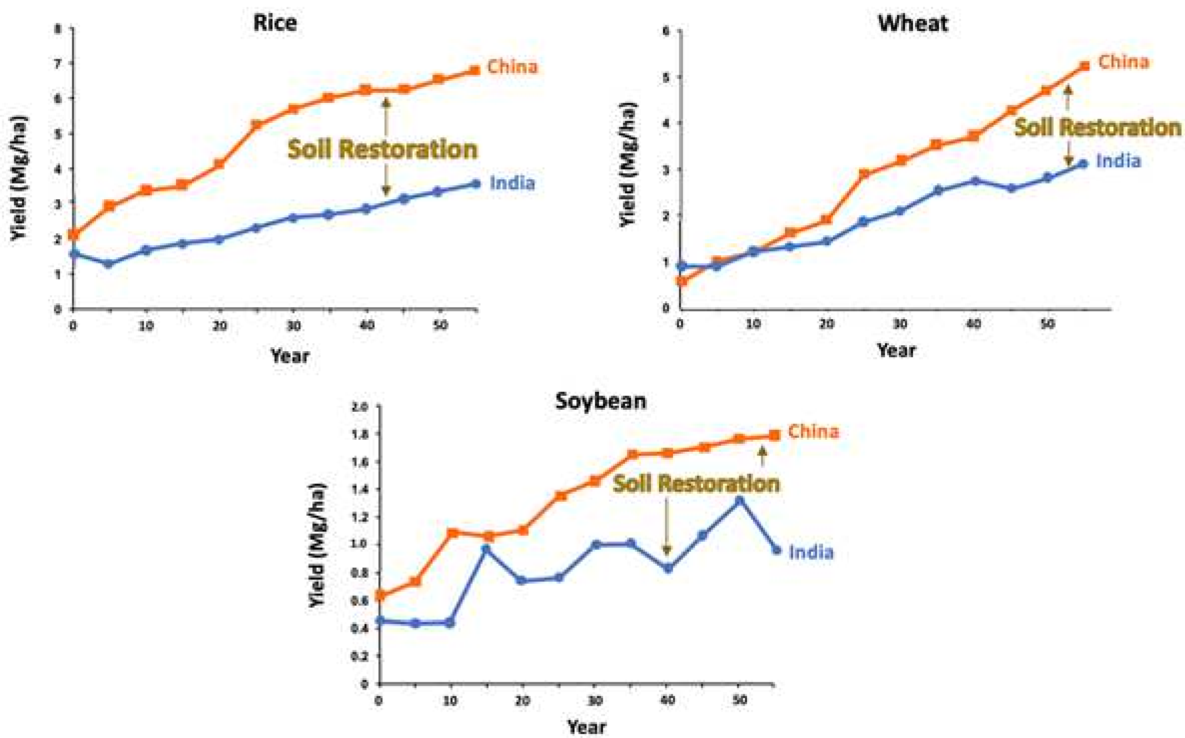



**Figure 2. Trends in grain yield of rice, wheat and soybean for China and India (data from FAOSTAT, 2017)**

in 1955 to 1369 million in 2020, is increasing at the rate of 1.19% per year, and is projected at ~1680 million by 2050 (United Nations, 2019). Therefore, the per capita soil and water resources will decrease because of increase in population and conversion to non-agricultural land uses (*e.g.*, urbanization, industrial uses, recreational land use, infrastructure development). With the technical annual food grain production potential of India at 550 Mt, food grain production can be almost doubled (193%) by 2050 through increase in yield of rice, wheat, corn and pulses, especially under rainfed conditions. Rather than increasing the inputs (*i.e.*, fertilizer, irrigation, pesticides, energy for tillage), the strategy must be to enhance their use efficiency and "produce more from less." The latter implies that eco-efficiency and eco-effectiveness of inputs must be enhanced by restoring soil functionality/quality and health by increasing quality and quantity of SOC pool in croplands of India.

## Use Efficiency of Fertilizers

Globally, more than 50% of the fertilizers applied to cropland are transported into the environment (Lassaletta et al., 2014) with severe adverse impacts on the quality of water, soil, air, biodiversity and ecosystems. The cereal nitrogen use efficiency (NUE) in 2015 was 35, 41, 30, and 21% for the world, USA, China, and India, respectively (Omara et al., 2019). The low NUE in China and India is due to high N use, low use of other fertilizers (P, K, and micro-nutrients), and due to the prevalence of degraded and depleted soils. Li et al. (2017) conducted an experiment across China from 1980 to 2010 to determine if fertilizers could be completely replaced by manure and yet maintain a high yield. Li and colleagues concluded that NPK fertilizers could be at least partially replaced by manure to sustain a high yield of maize. In addition to a favourable soil health, a high NUE in the USA may be due to precision fertilizer management (Omara et al., 2019). The crop yield response to fertilizer use in India between 1961 and 2009 followed a classical law of diminishing returns because some other limiting factors (*i.e.*, soil degradation, micronutrient deficiencies, nutrient imbalance, drought stress) restricted the increase in crop yield and imposed a ceiling to agronomic productivity. The rate of N fertilizer use (kg N $ha^{-1}$ $yr^{-1}$) was much lower for India than of that for China and Egypt: 51, 118, and 343, respectively (Lassaletta et al., 2014). Bijay-Singh (2017, 2018) reported the saturating N fertilizer level for cereal production in India at 51-59 kg N $ha^{-1}$ $yr^{-1}$. Further, there may be no benefit in expected yield by increasing the rate of N fertilizer unless the agronomic improvement of the cropping system is realized (George, 2014). The extra N is lost into the environment often at a high rate of 50 kg N $ha^{-1}$ $yr^{-1}$ in the EU, Middle East, USA, Central America, China, and India (Lassaletta et al., 2014). The NUE is also low in Pakistan (Shahzad et al., 2019). Use of precision agricultural tools can enhance NUE (Sharma and Bali, 2017), but this is not a substitute to restoring soil quality. Soil degradation reduces crop yield and forces farmers to add extra fertilizers and other inputs (Gomiero, 2016).

### Drought Stress and Fertilizer Use Efficiency

Use efficiency of chemical fertilizers, and especially the NUE, also depends on the soil moisture (and soil temperature) regime. The water use efficiency (WUE) refers to the amount of carbon synthesized as biomass or the grain produced per unit of water used by the crop (Hatfield and Dold, 2019). Extremes of soil moisture regime affect NUE by increasing losses caused by leaching under wet conditions and by volatilization under dry conditions. Drought stress, in combination with high soil temperatures, reduces the NUE because the grain yield strongly depends on the availability of soil water at critical stages. For example, grain yield can be represented as a product of four factors (Stewart and Lal, 2018) as shown in Eq.1:

$$GY = ET\left(\frac{T}{ET}\right)\left(\frac{I}{TR}\right)HI \qquad \text{(Eq.1)}$$

Where, GY is grain yield, ET is evapotranspiration: $\left(\frac{T}{ET}\right)$ *is* ET ratio, TR is the units of water required to produce 1 unit of biomass, and HI is the harvest index or the weight of grain divided by the weight of aboveground biomass. Thus, fertilizer use influences GY only as it affects one of the four factors outlined in Eq. 1, and the common variable in all these four factors is water. In other words, grain yield is totally dependent on water (ET) regardless of whether the crop is irrigated or rainfed and grown under arid or humid conditions. For rainfed agriculture, ET is the amount of precipitation received during the growing season. For irrigated agriculture, ET is the amount of water added by irrigation during the growing season. Therefore, FUE can only be increased by increasing the WUE, these two are intricately interconnected.

Closely interacting with water is the temperature regime, and the latter is becoming important with the current and projected climate change. For India, the projected increase in temperature is 0.50-1.20 ºC by 2020, 0.88-3.16 ºC by 2050, and 1.56 to 5.44ºC by 2100 (IPCC, 2007; Kumar et al., 2017). In general, a 1ºC increase in temperature may reduce wheat production by 4-5 Mt in India (Kumar et al., 2017) and lead to a 17% loss in yield of most crops. Thus, drought stress and heat wave management are critical to enhancing NUE. In addition, enhancing WUE at the canopy level necessitates adoption of recommended management practices (RMPs) that reduce losses of water by soil evaporation and divert more water into transpiration (Eq. 1 above). Important among these are conservation agriculture (CA) comprising of no-till (NT), crop residue management (complete elimination of in-field burning or its removal for other uses), retention of crop residue as mulch, optimum crop stand and row spacing, micro-irrigation (drip-sub irrigation) and precision farming (Hatfield and Dold, 2019). Improved management of drylands (rainfed agriculture) is critical to achieving Sustainable Development Goals (SDGs) in India. Soil moisture conservation, through soil surface management that reduces losses by water runoff and evaporation, is vital to improving and sustaining rainfed agriculture (Bradford et al., 2017; Stewart and Thapa, 2016; Stewart and Lal, 2018). Enhancing the WUE in rainfed agriculture is also critical to improving the use efficiency of fertilizers.

### Soil Degradation in Agroecosystems of India

Crop yields are increasing globally, yet the trends of increase in crop yields are insufficient to double the required production by 2050. Ray et al. (2013) reported that yields of key global crops - maize, rice, wheat and soybean - are increasing annually at the rate of 1.6%, 1.0%, 0.9%, and 1.3%. The required rate of increase for the production to double by 2050 is 2.4% $yr^{-1}$ (Ray et al., 2013). In contrast, growth of crop yield in India is rather stagnant. The north-western region, the center of the GR for wheat and rice, registered the lowest growth rate for 3 decades from 1980 to 2008 (Rada, 2013). The average annual growth rate of agricultural production of 2.1% between 1980 and 2008 ranged from the lowest of 1.0% in the north-east to the highest of 2.7% in the south (Rada and Schimmelpfennig, 2016). There are patterns of yield stagnation of major crops in India. The analysis of yield records from 1961 to 2008 indicates that, in India, maize yield has stagnated across 31% of the maize growing areas, rice across 36% of the rice-growing areas, wheat across 70% of the wheat growing areas, and soybean across 1 Mha of the area under soybeans (Ray et al., 2012). The principal cause of yield stagnation is degradation of soil health (NAAS, 2018; Agribusiness, 2018).

Risks of soil degradation may be exacerbated by high density of human and livestock population. India supports 18% of the world's human population and 15% of the livestock population on merely 2.4% of the world's land area (Bhattacharyya et al., 2015). Demands of the human and livestock population have caused severe soil degradation affecting a total of 147 Mha, including 94 Mha by water erosion,16 Mha by acidification, 14 M ha by flooding, 9 Mha by wind erosion and 7 Mha by other processes (Bhattacharyya et al., 2015; Kurrey et al., 2016; Kumar, 2019). The present rates of soil erosion can be orders of magnitude higher than the rate of natural soil formation (Wuepper et al., 2019). Accelerated soil erosion has been a major problem ever since the pre-independence era. The average soil erosion rate across the country is 16 Mg $ha^{-1}$ $yr^{-1}$, which is more than 3 times the tolerable rate of 4-5 Mg $ha^{-1}$ $yr^{-1}$ (Awasthi, 2015). The areas of severe soil erosion rates (>20 Mg $ha^{-1}$ $yr^{-1}$) include the Shivalik hills, northwestern Himalayas, western coastal Ghats, and Vertisols in central India (Singh et al., 1992). Severe degradation is adversely affecting the agronomic productivity (ICAR/NAAS, 2010; Aulakh and Sidhu, 2015; Saroha et al., 2017), and is the primary cause of low NUE/FUE.

By 2011-2013, soil degradation in India affected as much as 29.3% of the land area (Jain, 2018). The problem of soil degradation in India is being exacerbated by the current and projected climate change, and the ever-increasing environmental crisis that has been evident since the 1990s (Negi, 1991). Risks of soil degradation are exacerbated by land misuse and soil mismanagement such as in-field burning of crop residues in the north-west India and slash-and-burn agriculture in Nagaland. The positive feedback by climate change on soil degradation and desertification is through severe decline in productivity (Florida, 2019) and the attendant reduction of the input of biomass carbon into the soil. The projected temperature increase would reduce crop yield globally (Zhao et al., 2017; Schlaepfer et al., 2017; Gabbatiss, 2018), but especially in small holder farms of India. The cost of inaction can exceed the current economic loss being incurred by soil degradation in India (Mythili and Goedecke, 2016). The economic cost is severe in arid and semi-arid regions where the severity of environmental degradation is approaching irreversible levels (Reddy, 2003).

Thus, policy interventions are needed to reverse soil degradation trends and make agriculture an integral solution to adaptation and mitigation of climate change in India. In addition to the widespread adoption of recommended package of practices (RMPs), protection of prime farmland against competing uses (*e.g.*, urbanization) is an absolute necessity (Inani, 2019). The present land use in India involves 51.1% cropland, 21.8% forest, 3.9% pasture, and 12.3% of urban and other land uses (National Institute of Hydrology, 2009). By 2001, the buildup land area covered 8.04 Mha (Tian et al., 2014), and it has and is increasing because of rapid urbanization between 2000 and 2020. *Ad-hoc* and subjective horizontal expansion of housing and infrastructure development on prime farmland deserve an objective and urgent consideration (Sharma, 2018). The pledge of restoring 26 Mha of degraded land by 2030 (Tripathi, 2019; Srinidhi, 2019) must be implemented by taking appropriate policy action for integrating effective land and water management schemes (Jadhav, 2019) with the objective of achieving land degradation neutrality by 2030.

**Depletion of Soil Organic Matter Content**

Severe degradation - caused by physical, chemical, and biological processes - depletes soil organic matter (SOM) content. In soils prone to water and wind erosion, SOM is preferentially removed because it is a light fraction (bulk density of 0.25-0.35 Mg $m^{-3}$), and it is concentrated in the surface layer, the epicenter of accelerated erosion. Manna et al. (2007) observed that depletion of SOM occurs even in soil receiving the recommended rate of N and P but without input of farmyard manure (FYM). Degradation-induced depletion of SOM occurs in any system that leads to decline in production of biomass (especially the root biomass) and its return into the soil. Therefore, the highest rate of SOM buildup is often observed in soils receiving FYM at the rate of 10 Mg $ha^{-1}$ $yr^{-1}$ (Anantha et al., 2018).

There is an optimal range of SOM content below which the use efficiency of inputs (*i.e.*, fertilizer, irrigation, improved varieties) is severely jeopardized. The optimal range of SOC varies among soils, ecoregions and cropping/farming systems and can be 2-3% of SOM (or 1-1.5% of SOC) for soils of the tropics (Aune and Lal, 1997). Maintaining SOM content at an optimal range is necessary to enhance and sustain agronomic production. However, the exact response function of crop yield and SOM content depends on site-specific factors (soil type, climate, landscape) and management (tillage, fertilizer, crop rotation) (Oldfield et al., 2019). In general, yield increase levels off at about 2% SOM content (1.1% of SOC content) for soils of the tropics (Aune and Lal, 1997) and at about 4% (2% SOC content) for soils of temperate climate (Loveland and Webb, 2003). Globally, two-thirds of croplands have SOM content at the sub-optimal level, and in India SOM content of arable lands of the northwestern region (*i.e.*, Punjab, Haryana, Rajasthan, Western U.P.) is often lower than 0.2% (<0.1% SOC). Sub-optimal levels of SOM adversely affect crop yields through reduction in NUE and WUE. Beneficial impacts of SOM on agronomic productivity are often attributed to improvement of soil structure, total porosity and relative proportion of macropores, water infiltration and retention, and increase in activity and species diversity of soil biota, especially macro-biota such as earthworms (Lal, 2004, 2009, 2010). Rather than on the yield, the focus must be on nutrients harvested per hectare, and on nutrient sensitive agrculture.

**Management of Soil Organic Matter Content**

The rate of fertilizer application in India (kg NPK $ha^{-1}$) is already more than that of the cropland in the U.S. Rather than increasing the rate of input of fertilizer, the focus should be on improving : i) the FUE by reducing the losses through high leakage into the environment, ii) the balanced use of both macro (N, P, K, Ca, Mg) and micro nutrients (Fe, Mn, Zn, Cu, B, Mo), iii) soil quality/functionality and specifically soil health by restoring SOM content, and iv) resilience of soil and agroecosystems to drought stress by enhancing the climate-resilience of soils. These and other soil physical constraints (structure, erodibility, porosity, compaction, crusting, PAWC, infiltration rate) can be alleviated through restoration of SOM content by adoption of a soil-centric strategies of restoring soils of agroecosystems. Therefore, the strategy in India must be of increasing productivity by enhancing the FUE and reducing the adverse effects on the environment by adopting eco-technologies (Ayala and Rao, 2002).

There are many examples from India of improvements in SOM content with adoption of conservation agriculture (CA) and complex farming systems (Srinivasarao et al., 2012a, b, c, d,e; 2013a, b; 2014; Chaudhari and Biswas, 2017). Thus, long-term sustainability of cropping systems can be achieved by use of agro-forestry, agro-horticultural, agro-pastoral, and agro-silvopastoral systems. Sapkota et al. (2017) also reported that sequestration of SOC is an important strategy to restore soil quality through adoption of CA in the rice-wheat system of the eastern Indo-Gangetic Plains. Sapkota and colleagues reported that CA with residue retention increases the SOC concentration by 3 to 4.7 Mg C $ha^{-1}$ to 0.6 m depth over a seven-year period. Prasad et al. (2016) reported that after 10 years of using a CA system, SOC concentration in Alfisols of southern India was 11% higher in 0-20 cm layer than that under the conventional system. The rate of SOC sequestration was 62-186 kg $ha^{-1}$ $yr^{-1}$, and the rate was higher with organic sources of nutrients than that with inorganic fertilizers. Indoria et al. (2018) identified several alternative sources of organic amendments of about 300 MT $yr^{-1}$. These sources can be used for composting, vermiculture, etc. Adoption of climate-resilient agricultural systems -techniques which restore soil health by conserving soil and water and enhancing SOC concentration and stocks - is critical to increasing sustainability of the rice-wheat system (Jat et al., 2019). Thus, India must have a very well-organized programme on "Soil Health" restoration and sustainable management through sequestration of SOC in the root zone (NAAS, 2018). The success of such an initiative depends on payments to farmers for provisioning of ecosystem services on the basis of the societal value of SOC (Lal, 2014).

## Improving Fertilizer Use Efficiency by Restoring Soil Health

There is a growing and widespread awareness about the need to improve the FUE in India's agroecosystems. Whereas the on-farm NUE ranges from 20 to 40%, those of researcher-managed experiments range from 46-65% (Roberts, 2008). Thus, adoption of RMPs is critical to enhancing the NUE. The knowledge about site-specific RMPs exists for rice (De Datta et al., 1990) and upland crops for rainfed areas (Singh et al., 2004; Lal, 2008; Wani et al., 2011; Venkateswarlu and Prasad, 2012) and other crops through management of organic amendments (Gupta, 2005). The overall FUE must be specifically improved in less developed regions of rainfed agriculture (Sagar, 1995). The FUE can be enhanced by combining the use of inorganics with organic amendments (Hati et al., 2007). It is argued that the yield of wheat in India is stagnating because of the conventional blanket application of chemical fertilizers rather than in combination with organic manures.

Thus FUE in India must be enhanced by: i) improving soil quality through SOC sequestration, ii) alleviating drought stress by soil-water management, iii) controlling soil erosion, iv) managing soil temperature by mulch farming and CA system, v) increasing crop diversification by adopting complex rotations, and vi) adopting the 4-R concept of fertilizer management. The latter comprises of the: i) right fertilizer source, ii) right rate, iii) right time, and iv) right place (Johnston and Bruulsema, 2014). The 4-R concept must be combined with the 4-S concept that comprises of soil management to: i) sequester carbon, ii) restore soil health, iii) conserve soil water, and iv) manage soil temperature through the adoption of a system-based CA (Lal, 2015). While the plant water status affects the NUE, plant nutrient status affects the WUE (Fixen et al., 2015), and both must be managed simultaneously.

## Mechanisms of Enhancing Fertilizer Use Efficiency by Restoring Soil Organic Carbon

Soil health moderates FUE through multifarious and complex interactions among biophysical processes at the pedon, soil scape, and the landscape level (**Figure 3**). These processes, which reverse soil degradation trends, are set in motion by sequestration of SOC through use of CA and other site-specific RMPs. Improvements in soil physical properties (*e.g.*, aggregation, porosity and pore continuity and stability, aeration, water retention, and transmission, soil heat capacity, soil strength, and erodibility) are critical to rhizosphere processes that enhance the availability, absorption, and assimilation of nutrients. Soil biodiversity, activity, and species diversity is also critical to improving the FUE through its effects on nitrification-denitrification, methanogenesis, volatilization, leaching and run-off. Increase in net primary productivity (NPP), through improvement in soil health, would result in greater input of biomass-C (especially that of the root biomass) into soil, create a positive soil-C budget, and enhance the SOC stock. Restoring soil health through SOC sequestration also enhances NUE/FUE indirectly by creating climate-resilient soils and agro-ecosystems. Indeed, sequestering the excess atmospheric $CO_2$ within the terrestrial biosphere is the most natural and land-based solution for India and the world for a successful outcome of India's tryst with the anthropogenic climate change.

Soils of India, similar to anywhere else in the world

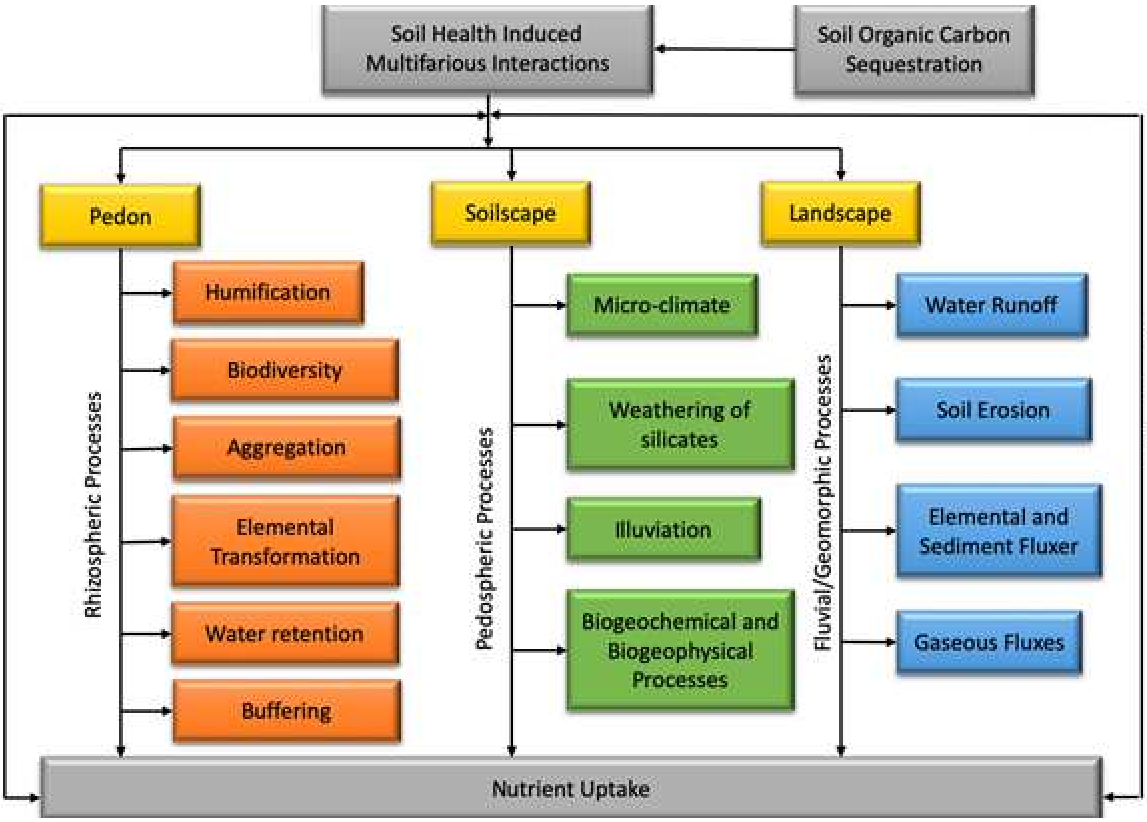



**Figure 3. Factors affecting use efficiency of nutrients at different spatial scales**

and that of any other living organism, have the right to be protected, restored, and thrive through a judicious land use and an appropriate management system (Lal, 2019). Since soils are one of the five critical elements (Kashti, Jal, Pavak, Gagan, Sameera) according to the *Prasanna Upanishad*, it is humanity's moral and ethical duty to restore, use and enhance the soil productivity and functionality forever. Judicious and discriminate use of fertilizer is a critical element of that strategy.

## Soil Organic Carbon Sequestration while Reducing Gaseous Emissions from Agroecosystems

The per capita $CO_2$ emission (Mg person$^{-1}$ yr$^{-1}$) of India was 0.27 in 1960, 0.35 in 1970, 0.45 in 1980, 0.74 in 1990, 0.98 in 2000, 1.40 in 2010, and ~2.3 in 2018 (IEA, 2018). The cumulative emission from India between 1850 and 2002 is merely 2.2% of the world total and ranks 9$^{th}$ among all the countries. However, the total national emission has increased by a factor of 18.5 from 120 Mt in 1960 to 2239 Mt in 2014 (Boden et al., 2016). Total $CO_2$ emission (Mt yr$^{-1}$) was 120 in 1960, 195 in 1970, 314 in 1980, 619 in 1990, 1032 in 2000, 1720 in 2010, and 2300 in 2018, which was a 4.8% increase over 2017 (IEA, 2018). India is the 4$^{th}$ highest emitter of $CO_2$ in the world and accounted for 7% of the global emissions in 2011. Doubling of India's $CO_2$ energy-related emissions from 2012 to 2030 is likely the upper bound in relation to the Paris Pledge (Dubash et al., 2018). India's total emission of 3202 Mt in 2014 (6.55% of the global emissions) comprised of 68.7% from the energy sector, 19.6% from agriculture, 6.0% from industrial processes, 3.8% from land use change and forestry, and 1.9% from waste. Between 1990 and 2014, India's GDP increased by 357%, and its GHG emissions by 180%. However, India is signatory to the 2015 Paris Climate Accord (Patra, 2017) for sequestering SOC at the rate of 0.4% per year to 40 cm depth. In this context, adoption of RMPs in agriculture can play an important role, especially in regard to improving soil health, sequestering SOC, enhancing NUE/FUE, and also advancing SDGs and achieving land degradation neutrality of UNCCD.

Emissions from the agricultural sector in India also comprise of $CH_4$ and $N_2O$ with the relative global warming potential of 21 and 310, respectively. While livestock and rice paddies are major sources of $CH_4$, use of fertilizer and biomass burning are important contributors of $N_2O$. By 2030, with business as usual, GHG emissions from agriculture in India would be 515 Mt $CO_2$e yr$^{-1}$. However, adoption of RMPs, especially those which enhance NUE/FUE, can mitigate 55.5 Mt $CO_2$e yr$^{-1}$ without jeopardizing food production and human nutrition (Jain, 2018).

The desired emission reduction from agriculture in India could be accomplished by: i) increasing FUE, ii)

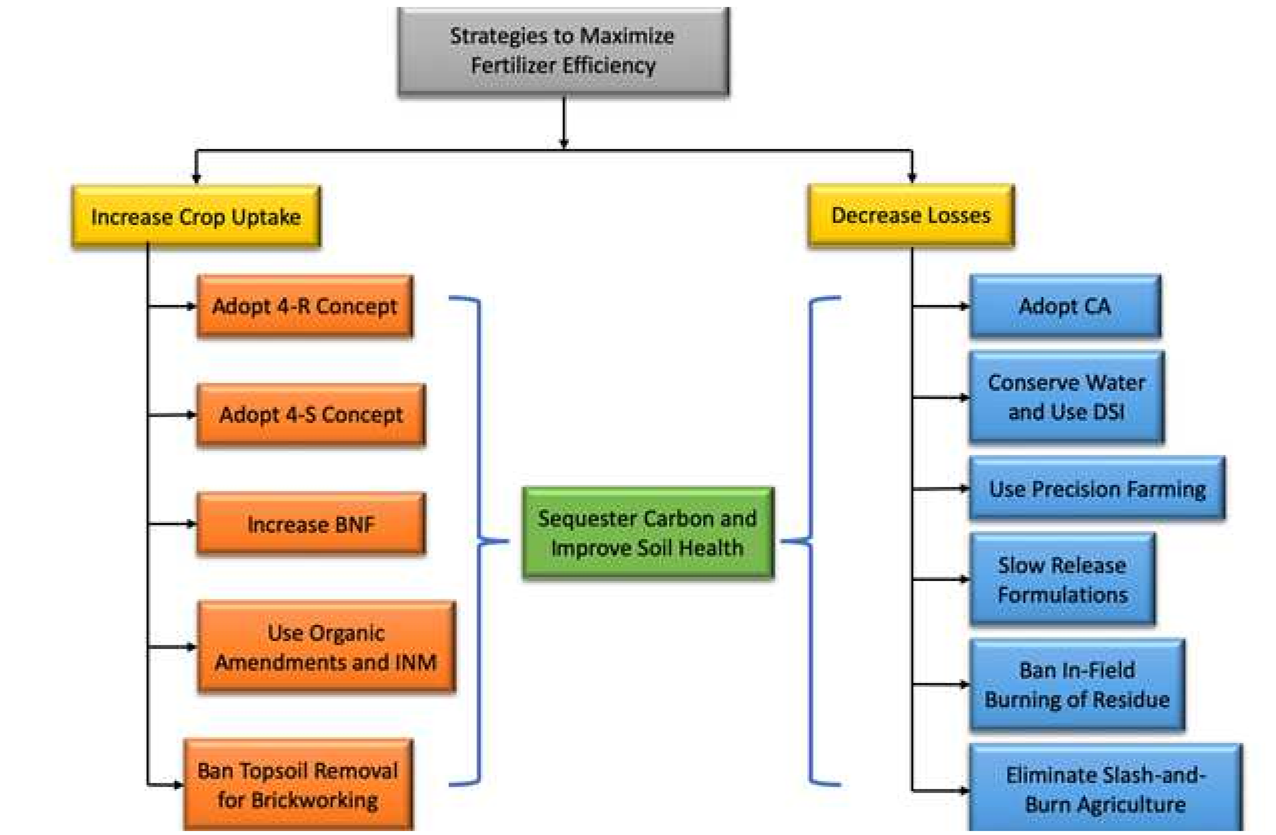



**Figure 4. Strategies to maximize the fertilizer use efficiency (DSI : Drip sub-irrigation)**

expanding adoption of CA, and 3) improving WUE for rice paddy cultivation. In all these measures, improvement of soil health by SOC sequestration is the most critical factor. Techniques to enhance NUE/FUE are outlined in **Figure 4**. Livestock and rice cultivation are the primary emitters (Vetter et al., 2017); the impact of soil erosion and low FUE must be addressed through adoption of site-specific RMPs. Recycling of biomass (crop and livestock residues, city wastes, and gray/black water) are critical to building soil organic matter content (Lal, 2017). Thus, there is a strong need of a paradigm shift for adoption of soil-centric RMPs; restoration of degraded soils, and sequestration of SOC which enhance eco-efficiency; make soil and agriculture climate-resilient; and restore the environment quality by making soil and agriculture integral to advancing the SDGs of the United Nations (Lal et al., 2018).

## Conclusions

The uniquely iconic increase in agricultural production in India between 1970 and 2020 can be even a more success story if its environmental footprint can be reduced and the soil degradation trends reversed. The mutually reinforcing interconnectivity between the environmental crisis in India and the low FUE can be reversed through restoration of soil health by sequestration of SOC in severely depleted soils of agroecosystems through widespread adoption of soil-centric RMPs (**Refer Table 1**). The basic strategy is to increase FUE by restoring soil health, increasing crop yields, and restoring degraded soils through the concept of 4-R and 4-S (**Figure 5**).

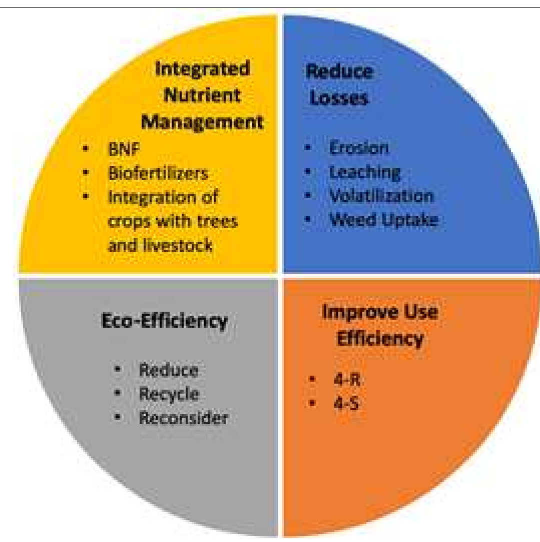



**Figure 5. Approaches to enhance fertilizer and water use efficiency**

**Table 1. Desired and hypothetical trends for fertilizer consumption and rate, cereal yield along with total and per capita production, manure use, and land area affected by soil degradation**

| Parameter | Year | | | |
|---|---|---|---|---|
| | **2017** | **2030** | **2050** | **2100** |
| Population ( × $10^6$) | 1339 | 1513 | 1659 | 1517 |
| Total grain production (Mt) | 273 | 320 | 370 | 400 |
| Per capita production (kg $person^{-1}$) | 204 | 212 | 241 | 330 |
| Fertilizer nutrient use (Mt) | 30 | 25 | 20 | 15 |
| Cereal yield (t $ha^{-1}$) | 2.1 | 2.7 | 2.8 | 4.0 |
| Agronomic efficiency (kg grain $kg^{-1}$ fert.) | 9.1 | 12.8 | 18.5 | 26.7 |
| Mean SOC content in 0-20 cm (g $kg^{-1}$) | 5.0 | 7.5 | 10.0 | 12.5 |
| Total manure use (Mt $yr^{-1}$) | 200 | 300 | 400 | 500 |
| Soil degradation (Mha) | 96 | 90 | 50 | 20 |

The strategy is to reduce losses and increase effectiveness by adopting a holistic/nexus approach of integrated nutrient management and using chemicals as supplemental materials by precision agriculture. Whereas the fertilizer cannot be replaced, the use efficiency must be strongly increased, gaseous emissions reduced, and productivity (yield) enhanced and sustained through restoration of soil health by improvement of SOM content and greater reliance on recycling of agricultural wastes and by-products.

Policy interventions are also needed for: i) promoting the balanced use of nutrients through a judicious combination of organic and inorganic sources of nutrients; ii) increasing SOC content in soils of agro-ecosystems by adoption of system-based CA and integration of crops with trees and livestock; iii) paying farmers for provisioning of ecosystem services (rather than subsidies) for carbon sequestration, reducing gaseous emission, avoiding in-field burning of crop residues, saving land and water for nature, and increasing biodiversity; iv) focusing more on effectiveness, efficiency and productivity rather than on rate of input of fertilizers; and v) encouraging farmers to produce more from less so that land, water, energy and other natural resources can be saved for nature conservancy. In addition, rjghts-of-soil, as a living entity must be respected. Ultimately focus must be on nutrition sensitive agriculture.

## References

Agribusiness. 2018. Stagnation in production, degrading soil major concerns: ICAR. The Hindu Business Line. January 9. https://www.thehindubusinessline.com/economy/agri-business/stagnation-in-production-degrading-soil-major-concerns-icar/article9992135.ece

Anantha, K.C., Majumder, S., Padhan, D., Badole, S., Datta, A., Mandal, B. and Reddy, G. 2018. Carbon dynamics, potential and cost of carbon sequestration in double rice cropping system in semi-arid Southern India. *Journal of Soil Science and Plant Nutrition* **18**, 418-434.

Awasthi, K. 2015. Losing ground: high rates of soil erosion trouble India. *DownToEarth.org*. July 4. https://www.downtoearth.org.in/news/losing-ground-10579

Ayala, S. and Rao, E. 2002. Perspectives of soil fertility management with a focus on fertilizer use for crop productivity. *Current Science* **82**, 797-807.

Aulakh, M.S. and Sidhu, G.S. 2015. Soil degradation in India: causes, major threats, and management options. In *MARCO Symposium 2015 - Next Challenges of Agro-Environmental Research in Monsoon Asia*, pp. 151-156. National Institute for Agro-Environmental Sciences (NIAES), Tsukuba, Japan.

Aune, J. and Lal, R. 1997. Agricultural productivity in the tropics and critical limits of properties of Oxisols, Ultisols and Alfisols. *Tropical Agriculture Trinidad* **74**, 96-103.

Bhattacharyya, R., Ghosh, B.N., Mishra, P.K., Mandal, B., Rao, C.S., Sarkar, D., Das, K., Anil, K.S., Lalitha, M., Hati, K.M. and Franzluebbers, A.J. 2015. Soil degradation in India: challenges and potential solutions. *Sustainability* **7**, 3528-3570.

Bhattacharyya, T., Pal, D.K., Mandal, C. and Velayutham, M. 2000. Organic carbon stock in Indian soils and their geographical distribution. *Current Science* **79**, 655-660.

Bijay-Singh. 2017. Management and use efficiency of fertilizer nitrogen in production of cereals in India - issues and strategies. In *The Indian Nitrogen Assessment: Sources of Reactive Nitrogen, Environmental and Climate Effects, and Management Options and Policies* (Y.P. Abrol, T.K. Adhya, V.P. Aneja, N. Raghuram, H. Pathak, U. Kulshrestha, C. Sharma and Bijay-Singh, Ed.)., 149–162. Elsevier.

Bijay-Singh. 2018. Are nitrogen fertilizers deleterious to soil health? *Agronomy* **8** (April 14, 2018).

Boden, T.A., Marland, G. and Andres, R.J. 2016. *Global, Regional and National Fossil Fuel $CO_2$ Emissions*. Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6290, U.S.A. (doi: 10.3334/CDIAC/00001_v2016).

Bradford, J.B., Schlaepfer, D.R., Lauenroth, W.K. et al. 2017. Future soil moisture and temperature extremes imply expanding suitability for rainfed agriculture in temperate drylands. *Scientific Reports* **7**,12923 doi:10.1038/s41598-017-13165-x.

Chaudhari, S.K. and Biswas, P.P. 2017. Assessment, monitoring and managing soil organic carbon (SOC) for climate change mitigation and adaptation: An Indian perspective. *FAO Global Symposium on Soil Organic Carbon*, FAO Rome, Italy, held on March 21-23, 2017. http://www.fao.org/3/a-br960e.pdf

De Datta, S.K., Buresh, R.J. and Mamaril, C.P. 1990. Increasing nutrient use efficiency in rice with changing needs. *Fertilizer Research* **26**, 157–167.

Dubash, N.K., Khosla, R., Rao, N.D. and Bhardwaj, A. 2018. India's energy and emissions future: an interpretive analysis of model scenarios. *Environmental Research Letters* **13(7)**, 74018.

FAO. 2014. *India - History of Irrigation*. http://www.fao.org/nr/water/aquastat /countries_region/ind/index.stm

FAO, IFAD, UNICEF, WFP, and WHO. 2019. *The State of Food Security and Nutrition in the World 2019. Safeguarding Against Economic Slowdown and Downturns*, pp. 1-212. FAO, Rome, Italy (ISBN; 978-92-5-131570-5).

Fixen, P.E., F. Brentrup, T. Bruulsema, F. Garcia, R. Norton, and S. Zingore. 2015. Nutrient/fertilizer use efficiency: measurement, current situation and trends. In *Managing Water and Fertilizer for Sustainable Agricultural Intensification* (P. Drechsel, P. Heffer, H. Magen, R. Mikkelsen, D. Wichelns, Eds.), pp. 8-37. IFA, IWMI, IPNI and IPI, Paris, France.

Florida, R. 2019. Researchers study how climate change affects crops in India. *Phys.Org*. June 17. https://phys.org/news/2019-06-climate-affects-crops-india.html

Gabbatiss, J. 2018. Crop yields set to drop by tenth as nearly all Earth's land area is degraded within coming decades, report warns. Independent. June 22. https://www.independent. co.uk/environment/land-degradation-deserts-farming-agriculture-cattle-world-atlas-eu-europe-a8411856.html.

George, T. 2014. Why crop yields in developing countries have not kept pace with advances in agronomy. *Global Food Security* **3**, 49-58.

Gomiero, T. 2016. Soil degradation, land scarcity and food security: reviewing a complex challenge. *Sustainability 2016*, **8(3)**, 281: doi:10.3390/su8030281.

Government of India. 2017 Pocket Book of Agriculture Statistics (pp 1-115). Directorate of Economics and Statistics. Ministry of Agriculture and Farmers Welfare, New Delhi.

Gupta, A.P. 2005. Nitrogen use scenario in India. *Science in China Series C: Life Sciences* **48(2)**, 921–927.

Hati, K.M., Swarup, A., Dwivedi, A.K., Misra, A.K. and Bandyopadhyay, K.K. 2007. Changes in soil physical properties and organic carbon status at the topsoil horizon of a Vertisol of Central India after 28 years of continuous cropping, fertilization, and manuring. *Agriculture, Ecosystems and Environment* **119**, 127-134.

Harsha, J. 2017. Micro-irrigation in India: An assessment of bottlenecks and realities. *Global Water Forum*. June 13. http://www.globalwaterforum.org/2017/06/13/micro-irrigation-in-india-an-assessment-of-bottlenecks-and-realities/

Hatfield, J. L. and Dold, C. 2019. Water-use efficiency: advances and challenges in a changing climate. *Frontiers in Plant Science*. 19 February. https://doi.org/10.3389/fpls.2019.00103

ICAR/NAAS. 2010. *Degraded and Wastelands of India: Status and Spatial Distribution*. NASC, Pusa, New Delhi.

IEA. 2018. *World Energy Outlook*. International Energy Agency (OECD/IEA, www.iea.org).

IPCC. 2007. *Climate Change, Synthesis Report. Inter-Government Panel on Climate Change*. Cambridge, U.K.

Inani, R. 2019. As land degrades, India struggles to save its farms. *Scientific American.* September 19, 2019. https://www.scientificamerican.com/article/as-land-degrades-india-struggles-to-save-its-farms/

Indoria, A., S. K.L., K. Reddy, S. Ch, S. Karlapudi, S. S. Balloli, M. Osman, P. Gudapaty, and N. S. Raju. 2018. Alternative sources of soil organic amendments for sustaining soil health and crop productivity in India - impacts, potential availability, constraints and future strategies. *Current Science* **115(11)**, 2052–2062.

Jadhav, R. 2019. Govt. plans to integrate land and water schemes to tackle land degradation. The Hindu BusinessLine. August 6. 2019. https://www.thehindubusinessline.com/economy/govt-plans-to-integrate-land-and-water-schemes-to-tackle-land-degradation/article28830722.ece

Jain, N. 2018. Why land degradation in India has increased and how to deal with it. *Mongabay*. October 3, 2018. https://india.mongabay.com/2018/10/why-land-degradation-in-india-has-increased-and-how-to-deal-with-it/

Jat, H.S., Datta, A., Choudhary, M., Sharma, P.C., Yadav, A.K., Choudhary, V., Gathala, M.K., Jat, M.L. and McDonald, A. 2019. Climate smart agriculture practices improve soil organic carbon pools, biological properties and crop productivity in cereal-based systems of North-West India. *Catena* **181**:104059.

Johnston, A.M. and Bruulsema, T.W. 2014. 4R nutrient stewardship for improved nutrient use efficiency. *Procedia Engineering* **83**, 365-370.

Kumar, D. and Reddy, D.N. 2017. High pesticide use in India: health implications. Pesticide Action Network (PAN) India. http://www.pan-india.org/wp-content/uploads/2017/08/High-pesticide-use-in-India-health-Implications_Health-Action-August-2017-1.pdf

Kumar, S.V. 2019. *Reversing Soil Degradation in India*. TERI, The Energy and Resource Institute in India, New Delhi.

Kumar V., Sharma, A., Soni, J.K. and Pawar, N. 2017. Physiological response of C3, C4 and CAM plants in changeable climate. *The Pharma Innovation Journal* **6(9)**, 70-79.

Kurrey, D., Singh, R. and Rajput, R. 2016. *Status of Soil Erosion or Land Degradation in India*.

Lal, R. 2004. Soil carbon sequestration in India. *Climatic Change* **65**, 277-296.

Lal, R. 2008. Managing soil water to improve rainfed agriculture in India. *Journal of Sustainable Agriculture* **32(1)**, 51-75 (doi: :10.1080/10440040802121395).

Lal, R. 2009. Soil degradation as a reason for inadequate human nutrition. *Food Security: The Science, Sociology and Economics of Food Production and Access to Food* **1(1)**, 45-57.

Lal, R. 2010. Enhancing eco-efficiency in agroecosystems through soil C sequestration. *Crop Science* **50**, S120-S131.

Lal, R. 2014. Societal value of soil carbon. *Journal of Soil and Water Conservation* **69 (6)**, 186A-192A.

Lal, R. 2015. A system approach to conservation agriculture. *Journal of Soil and Water Conservation* **70(4)**, 82A-88A.

Lal, R. 2017. Restoring soil and water resources and mitigating climate change in India by judicious management of agricultural and urban waste. *Journal of the Indian Society of Soil Science* **65**, 105-117.

Lal, R. 2019. Rights-of-soil. *Journal of Soil and Water Conservation* **74(4)**, 74A-79A.

Lal, R., Horn, R. and Kosaki, T. (Editors). 2018. *Soil and Sustainable Development Goals*. Catena - Schweizerbart, Stuttgart, Germany, 196 pp.

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)**, 105011.

Li, H., Feng, W., He, X., Zhu, P., Gao, H., Sun, N. and Xu, M. 2017. Chemical fertilizers could be completely replaced by manure to maintain high maize yield and soil organic carbon (SOC) when SOC reaches a threshold in the Northeast China Plain. *Journal of Integrative Agriculture* **16**, 937–946.

Loveland, P. and Webb, J. 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. *Soil and Tillage Research* **70**, 1-18.

Macrotrends, 2020. India Population Growth 1950 to 2012 (https ://...macrotrends.net/countries/india/population-growth-rate)

Manna, M.C., Ghosh, P.K. and Acharya, C.L. 2003. Sustainable crop production through management of soil organic carbon in semiarid and tropical India. *Journal of Sustainable Agriculture* **21(3)**, 85–114.

Manna, M.C., Swarup, A., Wanjiri, R.H., Mishra, B. and Shahi, D.K. 2007. Long-term fertilization, manure, and liming effects on soil organic matter and crop yields. *Soil and Tillage Research* **94**, 397-409.

Mythili, G. and Goedecke, J. 2016. Economics of Land Degradation in India. In *Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development* (E. Nkonya, A. Mirzabaev and J. von Braun, Eds.), pp. 431–469. Springer Open.

NAAS. 2018. *Soil Health: New Policy Initiatives for Farmers Welfare*. **Policy Brief #3**. National Academy of Agricultural Sciences, NASC Complex, Pusa, New Delhi, 19pp.

Narayanamoorthy, A. 2019. Tap drip irrigation to save water. *The Hindu BusinessLine*. June 07. https://www.thehindubusinessline.com/opinion/tap-drip-irrigation-to-save-water/article27688289.ece

National Institute of Hydrology. 2009. Land use map of India: *National Institute of Hydrology. India Waterportal*. August 18, 2009. https://www.indiawaterportal.org/

articles/land-use-map-india-national-institute-hydrology

Negi, S.S. 1991. *Environmental Degradation and Crises in India*. Indus Publishing Company, New Delhi.

Oldfield, E., Bradford, M. and Wood, S. 2019. Global meta-analysis of the relationship between soil organic matter and crop yields. *SOIL* **5** (January 15, 2019), 15–32.

Omara, P., Aula, L., Oyebiyi, F. and Raun, W.R. 2019. World cereal nitrogen use efficiency trends: review and current knowledge. *Agrosystems, Geosciences and Environment* **2**,180045. doi:10.2134/age2018.10.0045

Pathak, H. 2010. Trend of fertility status of Indian Soils. *Current Advances in Agricultural Sciences* **2(1)**, 10-12.

Patra, A.K. 2017. Trends and projected estimates of GHG emissions from Indian livestock in comparisons with GHG emissions from world and developing countries. *Asian Australasian Journal of Animal Sciences* 27, 592–599.

Prasad, J.V.N.S., Rao, C.S., Srinivas, K., Jyothi, C.N., Venkateswarlu, B., Ramachandrappa, B.K., Dhanapal, G.N., Ravichandra, K. and Mishra, P.K. 2016. Effect of ten years of reduced tillage and recycling of organic matter on crop yields, soil organic carbon and its fractions in Alfisols of semi-arid tropics of southern India. *Soil and Tillage Research* **156**,131–139.

Rada, N.E. 2013. *Agricultural Growth in India: Examining the Post-Green Revolution Transition*. 2013 Annual Meeting of Agricultural and Applied Economics Association, August 4-6, 2013, Washington, D.C. 149547.

Rada, N.E. and Schimmelpfennig, D.E. 2015. Propellers of Agricultural Productivity in India. *Economic Research Report* **203**. USDA Economic Research Service.

Ray, D.K., Ramankutty, N., Mueller, N.D., West, P.C. and Foley, J.A. 2012. Recent patterns of crop yield growth and stagnation. *Nature Communications* **Volume 3**, Article No. 1293. doi:10.1038/ncomms2296.

Ray, D.K., Mueller, N.D., West, P.C. and Foley, J.A. 2013. Yield trends are insufficient to double global crop production by 2050. *PLoS One* **8(6)**, e66428. https://doi.org/10.1371/journal. pone.0066428.

Reddy, V. 2003. Land degradation in India: extent, costs and determinants. *Economic and Political Weekly* **38** (January 1, 2003), 4700–4713.

Roberts, T.L. 2008. Improving nutrient use efficiency. *Turkish Journal of Agriculture and Forestry* **32**, 177–182.

Sagar, V. 1995. Fertiliser use efficiency in Indian agriculture. *Economic and Political Weekly*, **30(52)**, A160-A180. Retrieved from www.jstor.org/stable/4403619.

Sapkota, T.B., Jat, R.K., Singh, R.G., Jat, M.L., Stirling, C.M., Jat, M.K., Bijarniya, D., Kumar, M., Saharawat, Y.S. and Gupta, R.K. 2017. Soil organic carbon changes after seven years of conservation agriculture in a rice–wheat system of the eastern IndoGangetic Plains. *Soil Use and Management* **33**, 81-89.

Saroha, N.J. 2017. Soil erosion: causes, extent and management in India. *International Journal of Creative Research Thoughts (IJCRT)* 1704172. November 5(4): 1321-1330. ISSN:2320-2882.

Schlaepfer, D., Bradford, J., Lauenroth, W. et al. 2017. Climate change reduces extent of temperate drylands and intensifies drought in deep soils. *Nature Communications* **8**:14196. doi:10.1038/ncomms14196.

Shah, T. 2009. Past, present, and the future of canal irrigation in India. In *India Infrastructure Report 2011*, pp. 69-89. Infrastructure Development Finance Company, Mumbai.

Shahzad, A.N., Qureshi, M.K., Wakeel, A. et al. 2019. Crop production in Pakistan and low nitrogen use efficiencies. *Nature Sustainability* **2**, 1106–1114. doi:10.1038/s41893-019-0429-5.

Sharma, L.K. and Bali, S.K. 2018. A review of methods to improve nitrogen use efficiency in agriculture. *Sustainability* **10**, 51.

Sharma, R.K. 2018. Soil loss setbacks to Indian agriculture. *Acta Scientific Agriculture* **2.6**, 95-97.

Siegel, B.E. 2018. *Hungry Nation: Food, Famine and Making of Modern India*. Cambridge University Press.

Singh, G., Babu, R., Narain, P., Bhushan, L.S. and Abrol, I.P. 1992. Soil erosion rates in India. *Journal of Soil and Water Conservation* **47(1)**, 97-99.

Singh, H.P., Sharma, K.P., Reddy, G.S. and Sharma, K.L. 2004. Dryland agriculture in India. In *Challenges and Strategies of Dryland Agriculture* (S.C. Rao and J. Ryan, Eds.), **Special Publication 32**, 67-92. Crop Science Society of America, Madison, WI, USA.

Singh, R.B. 2000. Environmental consequences of agricultural development: a case study from the Green Revolution state of Haryana, India. *Agriculture, Ecosystems and Environment* **82**, 97–103.

Srinidhi, A. 2019. India's target to combat land degradation and desertification. *India Waterportal*. October 1. https://www.indiawaterportal.org/articles/indias-target-combat-land-degradation-and-desertification.

Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A.K., Vittal, K.P.R., Kundu, S., Singh, S.R. and S.P. Singh.

2012a. Long-term effects of soil fertility management on carbon sequestration in a rice-lentil cropping system of the Indo-Gangetic Plains. *Soil Science Society of America Journal* **76**, 168-178.

Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A.K., Vittal, K.P.R., Kundu, S., Gajanan, G.N. and Ramachandrappa, B. 2012b. Soil carbon sequestration and agronomic yield of groundnut based systems on an Alfisol in southern India. *European Journal of Agronomy* **43**, 40-48.

Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A.K., Vittal, K.P.R, Sharma, S.K., Jain, M.P. and Ravindra Chary, G. 2012c. Sustaining agronomic productivity and quality of a Vertisolic soil (Vertisol) under soybean-safflower cropping system in semi-arid central India. *Canadian Journal of Soil Science* **92**, 771-785.

Srinivasarao, Ch., Deshpande, A.N., Venkateswarlu, B., Lal, R., Singh, A.K., Vittal, K.P.R., Mishra, P.K., Prasad, J.V.N.S., Mandal, U.K. and Sharma, K.L. 2012d. Grain yield and carbon sequestration potential of post-monsoon sorghum cultivation in Vertisols in semi-arid tropics of central India. *Geoderma* **175/176**, 90-97.

Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A.K., Kundu, S., Vittal, K.P.R., Singh, S.R., Ramachandrarappa, B.K. and Gajanan, G.N. 2012e. Long-term effects of crop residues and fertility management on carbon sequestration and agronomic productivity of groundnut-finger millet rotation on an Alfisol in southern India. *International Journal of Agricultural Sustainability* **10(3)**, 1-15.

Srinivasarao, Ch., Kundu, S., Ramachandrappa, B.K., Reddy, S., Lal, R., Venkateswarlu, B., Sahrawat, K.L. and Naik, R.P. 2013a. Potassium release characteristics, potassium balance, and finger millet (*Eleusine coracana* G.) yield sustainability in a 27-year-long experiment on an Alfisol in the semi-arid tropical India. *Plant and Soil* **374**, 315–330.

Srinivasarao, Ch., Kundu, S., Venkateswarlu, B., Lal, R., Singh, A.K., Balaguravaiah, G., Vijayasankarbabu, M., Vittal, K.P.R., Reddy, S. and Manideep, V.R. 2013b. Long-term effects of fertilization and manuring on groundnut yield and nutrient balance of Alfisols under rainfed farming in India. *Nutrient Cycling in Agroecosystems* **96**, 29–46.

Srinivasarao, Ch., Lal, R., Kundu, S., Prasad, M.B.B., Venkateswarlu, B. and Singh, A.K. 2014. Soil carbon sequestration in rainfed production systems in the semi-arid tropics of India. *Science of the Total Environment* **487**, 587-603.

Stewart, B.A. and Lal, R. 2018. Increasing world average yields of cereal crops: it's all about water. *Advances in Agronomy* **151**, 1-44.

Stewart, B.A. and Thapa, S. 2016. Dryland farming: concept, origin and brief history. In *Innovations in Dryland Agriculture.* (Muhammad Farooq, and, Kadambot H.M. Siddique, Eds.), pp. 3-29. Springer International Publishers.

Tian, H., Banger, K., Bo, T. and Dadhwal, V.K. 2014. History of land use in India during 1880–2010: Large-scale land transformations reconstructed from satellite data and historical archives. *Global and Planetary Change* **121**, 78–88.

Tripathi, B. 2019. India's pledge to restore 26 Mn hectare degraded land could fuel land conflicts. *IndiaSpend.com.* October 5. https://www.indiaspend.com/indias-pledge-to-restore-26-mn-hectare-degraded-land-could-fuel-land-conflicts/

United Nations. 2019. *The World Population Prospects 2019: Highlights*. Dept. of Economics and Social Affairs, Population Division, U.N. New York (ST/ESA/SER.A/423), ISBN: 978-92-1-148316-1, 39pp.

Venkateswarlu, B. and Prasad, J.V.N.S. 2012. Carrying capacity of Indian agriculture: issues related to rainfed agriculture. *Current Science* **102**, 282-288.

Vetter, S.H., Sapkota, T.B., Hillier, J., Stirling, C.M., Macdiarmid, J.I., Aleksandrowicz, L., Green, R., Joy, E.J.M., Dangour, A.D. and Smith, P. 2017. Greenhouse gas emissions from agricultural food production to supply Indian diets: implications for climate change mitigation. *Agriculture, Ecosystems and Environment* **237**, 234–241.

Wani, S.P., Rockstrom, J. and Sahrawat, K.L. (Editors). 2011. *Integrated Watershed Management in Rainfed Agriculture*. Taylor and Francis, Boca Raton, FL.

Wuepper, D., Borrelli, P. and Finger, R. 2019. Countries and the global rate of soil erosion. *Nature Sustainability (2019)* doi:10.1038/s41893-019-0438-4.

World Bank. 2013. *Agricultural irrigated land (% of total agricultural land).* https://data.worldbank.org/indicator/AG.LND.IRIG.AG.ZS/countries.

Zhao C., Liu, B., Piao, S., Wang, X., Lobell, D., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., et al. 2017. Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences USA* **114**, 9326–9331. ■

Indian Journal of Fertilisers **16** (4) : 316-338, April 2020

# Integrated Nutrient Management Strategies for Food Security, Improving Nutrient Use Efficiency and Soil Health in Irrigated Agriculture

**Yadvinder-Singh**

INSA Honorary Scientist, Department of Soil Science, P.A.U., Ludhiana, Punjab

Received : 22/03/2020 Accepted : 28/03/2020

## Abstract

During the past 50 years (1969–2019), the 3.4-fold increase in Indian agricultural food production can be partly attributed to 13.7-fold increase in fertilizer (NPK) use. With the increasing use of chemical fertilizers, post-Green Revolution period witnessed a gradual decline in factor productivity and soil health, worsened by the progressively decreasing additions of organic manures. Increasing crop production by preserving environment and mitigating climate change should be the main goal of today's agriculture. New advances for sustainability of agriculture using integrated nutrient management (INM) approach are the need of the hour. This review captures and highlights different facets of INM in irrigated agriculture. Results from a large number of studies conducted in India revealed that INM enhances crop yields with reduced consumption of chemical fertilizer, increases the economic returns, while improving soil health and sustainability compared with conventional practices. Strong and convincing evidence indicates that INM practice could be an innovative and environment-friendly strategy for sustainable agriculture in India and other parts of the globe.

**Key words**: Integrated nutrient management, irrigated agriculture, soil health, sustainability, nutrient use efficiency

## Introduction

Fertilizers have played a key role in the success of India's Green Revolution and subsequent self-reliance in food-grain production. India supports 17% of the world's population on merely 2.3% of world's land area and 4.4% of world's fresh water resources. However, due to the increasing use of chemical fertilizers to increase the production of food and fiber, post-Green Revolution period witnessed a gradual decline in factor productivity and soil health, and appearance of multi-nutrient deficiencies in soils and plants mainly due to imbalanced use of fertilizers exacerbated by the progressively decreasing additions of organic manures. Persistent decline in soil health and related problems are major constraints coming in the way of achieving sustainability in Indian agriculture.

India has nearly achieved its food grain demand with production of around 285 Mt in 2018-19 (FAI, 2019). This could become possible with the accelerated use of chemical fertilizers. However, it may be kept in mind that the excessive use of fertilizers may actually result in decreased nutrient use efficiency (NUE) in the crops and also contribute to soil degradation, pollution and the greenhouse gas (GHG) emissions (Hoben et al., 2011). India is the second-largest consumer of fertilizers in the world with an annual consumption of more than 55.0 Mt. As per the statistics of Government of India, total nutrient consumption ($N+P_2O_5+K_2O$) was 27.29 Mt in 2018-19 and it is likely to increase to around 48.0 Mt by 2050. It is projected that in the year 2050, food grain production (estimated at 405 Mt) would remove about 58 Mt of $N + P_2O_5 + K_2O$ with an addition of 48 Mt of fertilizer nutrients if the current linear trend in fertilizer consumption observed over the last 25 years continues for the next 30 years. This would leave a negative gap of 10 Mt between nutrient removal by crop production and additions through fertilizers per annum of plant nutrients every year. India has vast potential of plant nutrients locked up in organic, biological and industrial by-products which can be used for INM but they are bulky and vary widely in chemical composition (Indoria et al., 2018). It is, therefore, vital for us to consider efficient utilization of all available organic wastes including biofertilizers as valuable sources of plant nutrients to bridge the gap and meet the challenges for ever-Green Revolution in agriculture. Major reasons for utilizing all the organic sources include: (i) poor soil organic matter cotent and ill soil health, (ii) imbalance in fertilizer use, (iii) emerging multi-nutrient deficiencies, (iv) negative soil nutrient balance, (v) declining nutrient use efficiency, and (vi) declining crop response ratio.

Based on current pricing policy and growth trends, it is estimated that the demand and supply of N alone in India by 2030 would be about 23.5 and 18.8 Mt, respectively, leaving a gap of 4.7 Mt (Tewatia and Chanda, 2017). The N use efficiency for cereal

yadvinder16@rediffmail.com

production is quite low and a large part of the fertilizer not taken up by the crop is emitted into the water bodies as nitrate ($NO_3$) and as nitrous oxide ($N_2O$), a potent greenhouse gas (GHG). The need for combining organic, inorganic, and biological nutrient sources through integrated nutrient management (INM) is being increasingly realized as a means of meeting crop nutrient needs, and improving nutrient use efficiency (NUE) and soil health and minimizing the environmental pollution. Importance of INM practices has been mentioned in several researches in the Indian subcontinent (Sharma et al., 2019; Bijay-Singh and Ali, 2020).

It is estimated that organic resources would have a total nutrient ($N + P_2O_5 + K_2O$) potential of around 32.4 Mt by 2025, of which about 7.75 Mt could be tapped (Tandon, 1997). The INM concept is being broadened to make it more context-specific for local environmental conditions, increasing mechanization, expanding popularity of conservation agriculture, and renewed focus on recycling of available organic nutrient flows (Wu and Ma, 2015). Incorporation of these new interventions in an INM system has developed new dimensions in the INM system. This review examines various INM approaches. Perspectives for further development of INM in the near future are also proposed and discussed. It also deals with constraints in the adoption and provides future research trends for INM in irrigated agriculture.

## Integrated Nutrient Management (INM): Meaning, Concept and Goals

The basic concept of INM or integrated plant nutrient system (IPNS) is the maintenance or adjustment of soil fertility and supply of plant nutrients to an optimum level for sustaining desired crop productivity through optimization of benefits from all possible sources of plant nutrients in an integrated manner. INM is viewed as an important framework for boosting crop productivity while improving soil health. It concentrates on a holistic approach of optimizing plant nutrient supply from all the sources in a cropping system as a whole rather than individual crop in the system and farming system. INM uses all possible sources of nutrients to: (i) optimize their input; (ii) matche soil nutrient supply with crop demand spatially and temporally; and (iii) reduce N losses while improving crop yields. According to Zhang et al. (2012), overall principle of INM is to maximize biological potential for improving crop productivity and resources use efficiency through root zone/rhizosphere management. In cropping systems, rhizosphere/root-zone nutrient management is a key component of INM for achieving high grain yields and high NUE at the same time.

Concept of INM originated in late 1980s or beginning of 1990s to arrest the widespread emergence of multi-nutrient deficiencies and deterioration of soil health. According to Kumar and Shivay (2010), INM concentrates on a holistic approach of plant nutrient management based on three fundamental principles for example, maximizing the use of organic materials, ensuring access to mineral fertilizers, and achieving high NUE along with minimal losses of nutrients from the soil–plant system. The basic objectives of INM are to: i) reduce the use of chemical fertilizers, ii) restore organic matter content in soil, iii) enhance NUE, iv) maintain soil health in terms of optimization of physical, chemical and biological properties, (v) minimize potentially adverse impacts of chemical fertilizers on the environment by using most efficient soil, water and crop management practices, and (vi) ensure productive and sustainable agriculture.

Steps involved in developing INM include, determining soil productivity potential for various crops through assessment of soil health, calculating crop nutrient requirements for the specific site and yield goal, quantifying nutrient value of on-farm resources such as manures and crop residues, calculating supplemental nutrient needs (total nutrient needs minus on-farm available nutrients) that must be met with"off-farm" nutrient sources, and developing a programme to optimize nutrient utilization through selection of appropriate nutrient sources, application timings and placement.

## Major Organic Sources and their Nutrient Potentials

Organic materials most commonly used as soil amendments and fertilizers to improve nutrient supply include animal manures [farmyard manure (FYM), slurry, animal wastes], composts (mixture of decomposed plant residues etc.), crop residues, urban organic wastes (either as such or composted), green manures, bio-gas spent slurry, microbial preparations, vermicompost, agro-industrial wastes (oilseed cakes, press mud cake, coir pith, rice husk and biomass ashes), residues from processing of animal products (blood, horn-and bone-meal). Sewage sludge and some of the industrial wastes also find application in agriculture. In India, out of 980 Mt of solid wastes produced annually, around 350 Mt are organic wastes generated from agricultural wastes. As the fertilizer use in most of the Indian farms is suboptimal, organic resources can supplement available fertilizer supply. The total nutrient ($N + P_2O_5 + K_2O$) potential of various organic resources was estimated at 14.85 Mt in 2000, which was projected to be around 32.41 Mt by 2025 (Tandon, 1997). Livestock population in India generates annually about 3 billion tonnes (Bt) of manure. This manure generates more than 4.0, 1.5 and

2.5 Mt of N, $P_2O_5$ and $K_2O$, respectively (a total of about 8 Mt) that is equivalent to one-third of the fertilizer currently consumed in the agriculture sector. Concentrated organic manures, such as non-edible oilcakes, bonemeal, slaughterhouse wastes, fishmeal and poultry manure are comparatively richer in NPK. Global estimates of N and P in the animal manure generated by livestock production exceed the global N and P fertilizer use (Bouman et al., 2010). However, use of all tappable nutrients would not be sufficient to produce the required food grains for the burgeoning human population. Approximately 25% of nutrient needs of Indian agriculture can be met by using various tappable organic sources. Despite their low nutrient value, organic manures improve soil health by increasing the soil carbon content and enhancing biological activity.

Proper use of organic manures on cropland may solve the problems (*e.g.*, observed yield decline) generated by the use of chemical fertilizers alone. Over the years, availability of traditional source of soil organic amendment, *viz*. cattle manure drastically declined due to mechanization and various competitive uses (*e.g.*, use of cattle dung for cooking). Cattle dung accounts for about 90% of the total animal dung and nutrients. Unless organic sources are managed carefully to minimize nutrient losses, it becomes a source of water pollution. Many of the organic materials are cheaply available but usually require handling and transporting, so it is best to use them on fields near to where they are produced. Human excreta is another valuable nutrient resource. About 16.5 Mt of material is available from 1000 million people in a year with an average NPK potential of 2 Mt $yr^{-1}$. Sewage and industrial wastes are often discharged into water bodies with adverse environmental and health consequences. Important criteria for organic fertilizers are: dry matter content, total and easily mineralizable humus, total and quick-acting N, C/N ratio, total nutrient (P and K) content, and content of substances detrimental to plant growth or product quality (heavy metals in particular which should be below the established critical limits).

### *Organic Manures*

Manure is the composted heterogeneous organic mixture that is made up by dung, various types of crop residues, and household wastes with various level of decomposition. It slowly releases the plant nutrients. So, the initial supply of plant nutrients can be done with chemical fertilizers for better plant growth. Manures (*e.g.*, FYM) contain all the plant nutrients needed for crop growth including micronutrients. Manure is the single largest waste flow of nutrients and provides over 70% of the current total recovered N and P from all sources. However, manure handling and application results in large amounts of nutrient losses through gaseous ($NH_3$) emis-sions, leaching and runoff. Proper handling and storage of manure requires large farm level investment which can be difficult in small scale operations, although imaginative farmer cooperatives are finding ways to surmount these challenges.

Due to higher prices of inorganic fertilizers, farmers in India could easily manage to prepare FYM in their farms and apply them in fields. The availability or efficiency of manure utilization by a crop is determined by the method of its application, time to incorporate and the rate of manure decomposition by microorganisms in soil. Currently, almost 2/3$^{rd}$ of the total cattle dung produced is burnt in the form of dung cakes. Organic manures like FYM and composts are the important components of INM and should be assessed for the quantity available. According to one estimate, nearly 800 Mt of organic manure available if spread over 329 Mha of the country's geographical area comes out to be around 2.5 t $ha^{-1}$ $yr^{-1}$.

### *Green Manures*

Leguminous green manures (GM) are good source of biologically fixed N and organic carbon. In India, the area under green manuring crops is limited to 7 Mha (Indoria et al., 2018). Area under green manuring crops has not expanded in India over the last few decades. Probably, land scarcity, intensification in crop production, relatively low price of urea N, significant cost involved in production and incorporation, scarcity of irrigation water for their cultivation are some of the main determining factors for the long-term reduction in GM use. In rice-wheat and maize-rice rotations, about 50-60 days' lag period is available after the harvest of wheat and before the transplanting of rice or sowing of maize. Short duration dual-purpose grain legumes like mungbean/cowpea or typical GM crops like *dhaincha*/sunnhemp can be grown. A 40-45 days old GM crop can supply 100-125 kg N which is almost equal to average N applied in most of the cereal crops (Yadvinder-Singh et al., 1991). But practicing of GM is restricted to regions where water is available during summer season. It is preferred to grow short duration dual purpose summer mungbean rather than growing sole GM crop, which provides an additional 0.5–1.0 t $ha^{-1}$ protein-rich grains. After harvesting pods, the residue can be incorporated into soil, which can save 60 kg N $ha^{-1}$ in succeeding rice or maize (Yadvinder-Singh et al., 1991, 2010a).

### *Crop Residues*

The annual production of crop residues in India is estimated to about 686 Mt with NPK potential of more than 12 Mt (Yadvinder-Singh and Sidhu, 2014;

Yadvinder-Singh et al., 2017). India has achieved a record foodgrain production of 285Mt in 2018-19 and crop residues production in the country is also huge. Total removal of plant nutrients by different crops is significantly higher than additions through fertilizers, resulting in continuous depletion of soil fertility. Indian soils are generally low in soil organic matter and poor in fertility. Retaining crop residue on the soil surface will improve nutrient cycling, ultimately leading to improvement in soil and environmental quality. Adopting the principles of conservation agriculture together with improved crop management practices would improve system productivity and overall resource-use efficiency. It will increase the profitability as well as sustainability of different crops and cropping systems. There are numerous direct and indirect adverse impacts of residue removal on ecosystem services, including depletion of the SOC pool. Important among direct adverse impacts of residue removal for various off-farm purposes (except for composting and use as fodder) are low input of biomass C, reduction in nutrient cycling representing an economic loss in the short term, decrease in food/ energy source and habitat for soil biota along with the long-term negative effect on soil health and agriculture sustainability (Yadvinder-Singh and Sidhu, 2014). About 30-40% of N, 25–35% of P, 70–85% of K, and 35–45% of S absorbed by cereals remain in the vegetative parts at maturity (Yadvinder-Singh et al., 2017).

About two-third of all available crop residue is used as animal feed and the remaining one-third is available for direct recycling on the land amounting to 229 Mt, and if used it can supply about 5 Mt of N, $P_2O_5$, $K_2O$, annually. As much as 12.5–25.0 kg $K_2O$ can be added to the soil through one tonne of cereal straw. Crop residues fed to animals get recycled through FYM whereas residues placed in compost pits are recycled as rural compost. Incorporation of N-poor cereal residues (having wider C:N ratios) are known to temporarily immobilize soluble soil N and thus temporarily create a deficiency of plant available N. If such residues are incorporated 10-20 days before the crop is sown, the N immobilization effect can be reduced (Yadvinder-Singh et al., 2004a). Other study conducted in Punjab has shown that co-incorporation of green manure and wheat residue helped alleviate its adverse effect on rice yield (Yadvinder-Singh et al., 2004b).

Of late, residue burning has become a serious problem in the Indian sub-continent. This apart from contributing to GHG emissions, deprives the soil of several benefits associated with recycling of crop residues. Burning the residue causes loss of precious organic matter, plant nutrients and creates environmental pollution. The entire amount of C, approximately 80-90% of N and more than 50% of S present in crop residues are lost upon burning. Burning of 23 Mt of rice residues in North-West India leads to a loss of about 9 Mt of C equivalent ($CO_2$-equivalent of about 34 Mt) per year and an annual loss of about 0.7 Mt of NPKS valued at Rs. 1000 crores (NAAS, 2017). Residue management has become an important component of conservation agriculture systems because surface residues help reduce soil water loss and soil erosion. Until recently, the availability of suitable machinery was a major constraint to direct drilling seeds into heavy rice stubbles. The development of a new line of machines for seeding into rice residues commenced with the construction of the Happy Seeder; this seeder works well for direct drilling in standing as well as loose residues, provided the residues are spread uniformly (Sidhu et al., 2015).

### *Sewage Sludge*

The number of sewage treatment plants is increasing day by day producing nutrient-rich waste, sludge, which needs disposal. Activated sewage sludge is obtained by repeated exposure of the sewage to atmospheric oxygen. The general composition of sewage sludge is 1.1–2.3% N, 0.35% P and 0.42–1.42% K. It also contains Na, Ca, S, several micronutrients and toxic heavy metals. Properly treated sewage effluent and processed products such as sewage sludge can serve as irrigation water and manure. Sewage sludge, often being high in P content, may lead to P accumulation in soils. There may be spatial constraints on the extent to which this material can be spread on land because of transport costs. There is some-times insufficient knowledge and specification of the plant-available nutrients present in the sludge to be applied to land. Secondly there are concerns about possible presence of pathogens, pharmaceuticals and complex organic compounds which could threaten plant, human and long-term soil health. Technological improvements in recovery techniques can address these concerns and increase societal confidence.

### *Urban Solid Waste*

There is considerable uncertainty about the quantities available of urban solid waste. If not recycled, it can be a direct and massive source of pollution and health hazard. According in one estimate in 2009, India generated about 69 Mt $yr^{-1}$ of municipal solid waste (MSW) (Sharma et al., 2017). It is estimated that 5-14 Mt of compost can be prepared from MSW depending upon the method of composting. The direct use of mixed city waste in agricultural soils is impossible as it contains almost 50% non-biodegradable material.

The biodegradable material needs to be segregated from the non-biodegradable, one at the household level. In few big cities mechanical composting plants are working. Urban waste needs to be treated carefully because it may contain heavy metals, parasites, and other pathogens. It must be comparatively cheap and have no detrimental or toxic effect, and it must be profitable. The buildup of heavy metal concentrations in the soil can be cause for concern. Supreme Court has directed the Government of India for conversion of biodegradable wastes of all urban municipal bodies into compost and to formulate a scheme for its use near cities. Stabilized municipal waste sludge typically contains about 3.3% N, 2.3% P and 0.3% K. Actual nutrient content, however, varies widely depending on the source of waste (Indoria et al., 2018). It is also a source of the secondary and micronutrients that are necessary for proper plant growth.

### *Organic Wastes from Agro-industries*

Large quantity of waste in solid form is generated by agro-based industries, food-processing industries, sugar mills, distilleries industry, etc. The wastes generated from agro-industries are mainly sugarcane bagasse and press mud, paddy husk, wastes of vegetables, food products, tea, vegetable oil production, jute fibre, groundnut shell, coconut husk, cotton stalk, etc. Researchers have shown that by-products of sugarcane industries (bagasse ash and press mud) are a good source of plant nutrients, and may improve soil properties and yield of sugarcane (Indoria et al., 2018). Main constraints in the use of agro industries waste by the farmers are transportation cost and other environmental issues. Coir pith is the by-product of coir industries. It is estimated that about 7.5 Mt of coir pith is produced annually in India, which requires safe disposal.

About 9 Mt of pressmud cake (PMC) is produced annually from the sugar industries in India (Yadvinder-Singh et al., 2008). The PMC typically contains about 1.8-2.3 % N, 0.8-1.2% P, 0.4-0.6% K in addition to several other plant nutrients including 2.5 g Fe $kg^{-1}$, 1.5 g Mn $kg^{-1}$, 0.27 g Zn $kg^{-1}$, and 0.13 g Cu $kg^{-1}$ besides S.

Bagasse and rice husk are the two important agro-industrial waste by-products that are generally used as fuel in sugar and rice mill industry, respectively. It is estimated that 45 Mt of bagasse are produced annually by the sugar factories in India (NAAS, 2008) and bagasse ash constitutes about 4.6% of the total bagasse production. Rice husk used as fuel produces 16 to 23% ash and its disposal causes serious environmental problems. Recycling of these ashes on to agricultural land can help improve the physical and chemical fertility of soil. In addition, approximately 25 Mt of rice husk produces about 4.5 Mt of ash. Biomass ashes also contain significant amounts of P, K and trace elements (Thind et al., 2012).

### *Biogas Slurry*

Estimates show that if a farmer generates biogas from cattle dung for cooking and uses the home-produced slurry, he can substantially reduce the purchase of chemical fertilizer from the market. Presently 3.2 million biogas plants are producing about 28 Mt of slurry. Avoiding the practice of using animal waste for burning in rural areas will save huge amount of electricity used in the manufacture of chemical fertilizer. One animal on an average produces about 3.65 t manure $yr^{-1}$. Dried biogas slurry contains 1.5-2.0% N, 1.1% P and 1-1.2% K (Yadvinder-Singh et al., 2003b). Biogas plant integrated with low cost cattle may be a viable option for proper recycling of crop residues, cow dung and urine, human excreta, weed biomass, and kitchen wastes supplementing thereby rural fuel besides generating valuable biogas manure for agricultural use. The Government's National Biogas and Manure Management Programme aims to set-up the Family Type Biogas Plants at rural and semi-urban/households level for recycling of rural wastes (http://mnre.gov.in/schemes/decentralizedsystems/schems-2/). It is estimated that if 75% of the total of annual production of cattle and buffalo dung in India is considered as collectable and the total dry matter (20% on an average) is 150 Mt, it will be capable of producing $30 \times 10^6$ $m^3$ of biogas and 112.5 Mt of digested slurry (dry matter). This move will save huge amount of electricity used for manufacturing chemical fertilizer.

### *Composts*

Composting and vermicomposting are the best strategies to convert the biomass of available alternative sources of organic amendments to plant nutrient-rich products. Composts are of three types *viz*., ordinary compost (rural and city), bio-enriched compost (compost fortified with rock phosphate, pyrites, waste mica and biofertilizers), and vermicompost. ICAR has developed technology to prepare various types of composts. Promotion of city compost can serve twin objectives of supporting the Government's Swachh Bharat Abhiyan and providing manures to farmers. The Department of Fertilizers, Ministry of Chemicals and Fertilizers, GOI has declared a subsidy of Rs. 1500 per tonne on city compost. Composts contain significantly higher contents of NPK compared to the unprocessed organic materials. For example, total N, P and K contents in pressmud compost are 3.10%, 1.95% and 3,5%, respectively (Indoria et al., 2018). Corresponding values reported for vermicompost are 1.59, 1.63 and 1.07%. Total K content in different composts ranges from 0.64% in biocompost to 2.03% in coir pith compost. Technologies for preparing microbial enriched and nutrient enriched composts are available to manage agro-industrial/ municipal wastes.

### *Biofertilizers*

Bio-fertilizers are bioinoculants or micro-organisms which play a vital role in mobilization of different nutrients (N, P and S) from organic and inorganic non-available forms to available forms. Introducing legumes into rotations can reduce fertilizer requirements by adding biologically fixed nitrogen into the soil. Nearly 40-48 Mt N $yr^{-1}$ is fixed biologically in agricultural crops compared to 83 Mt N $yr^{-1}$ fixed industrially for the production of fertilizer involving expenditure of huge amount of energy. The use of asymbiotic bacteria like *Azotobacter* and *Azospirillium* has not become a common practice because of competition under natural soil conditions. In general, *Azospirillum* is more appropriate for cereals and *Azotobacter* for non-foodgrain crops such as sugarcane, potatoes, cotton and vegetables. In terms of potential, *Azospirillium* is second only to blue green algae (BGA). However, application of improved strains of BGA inoculants has not made much headway due to dependence on rains, low availability of P and Fe in soils and its susceptibility to grazing by invertebrates that flourish in rice fields. *Azolla* is also a potential BNF system for wetland rice and is as efficient as BGA. However, BGA is more efficient in conjunction with higher amounts of mineral fertilizers. *Azolla* grows well in neutral soils and requires high availability of P and Fe with temperature range of 25-30 ºC of the standing water. It can fix up to 30 kg N $ha^{-1}$ $month^{-1}$ (Kundu, 2018). BGA is mainly practiced in eastern and north-eastern parts of the country. Biofertilizers can replace 25-30% chemical fertilizers (10-40 kg N $ha^{-1}$ and 10-35 kg $P_2O_5$ $ha^{-1}$) and generally increase grain yields by 10-40%. They help in decomposing plant residues, thereby improving C/N ratio of soil, improving soil structure and water holding capacity. Biofertilizers help in decomposing plant residues thereby improving C/N ratio of soil, improving soil structure, stimulating plant growth in general and root growth by secreting various growth hormones in particular, providing better nutrient uptake, and increasing tolerance towards drought and moisture stress.

Phosphate solubilizing bacteria like *Bacillus* spp. help in converting P from insoluble forms to soluble ones. Several studies report saving in N and P through use of biofertilizers, though the extent varies depending upon the soil and climate conditions (Rao, 2018). The phosphate solubilizing micro-organisms can be used successfully to increase the mobility of native and insoluble P applied through non-industrial grade rock-phosphate. Among the mycorrhizae, vesicular arbuscular mycorrhiza (VAM) is most promising in P cycling and enhancing P uptake by plants. Majority of the plant species are capable of colonizing the VAM. The success of biofertilizers, to a large extent, is governed by the level of organic matter in the soil and the survival of introduced organisms depends on the lability/ availability of adequate amounts of organic matter.

### *Mineralization of Organic Manures*

In studies on organic material decomposition and N release, plant material quality has often been characterized in terms of the material's content of N, lignin, and polyphenols, and also its C/N ratio (Yadvinder-Singh et al., 2005). The short-term release of N is largely determined by the presence and temporal pattern of decomposition of different plant components such as nonstructural and structural carbohydrates (free sugars, hemicellulose, cellulose) and N-rich compounds such as nucleic acids, amino acids and proteins. These compounds differ widely in decomposition kinetics, and their decomposition may result in net N mineralization or microbial assimilation of N (*i.e.* net immobilization).The decomposition of organic materials may result in either net N mineralization or microbial assimilation of N (*i.e.*, net immobilization) depending on their chemical composition. The mineralization-immobilization turnover (MIT) of manure and soil N availability in relation to crop response in the field has not been satisfactorily quantified. The C/N ratio has a major influence on MIT in soils, although its shortcomings have been recognized. Generally, if organic manure with a C:N ratio of >30 is added to a soil, there is immobilization of N during the initial decomposition process. For ratios between 20 and 30, the mineralization and immobilization may be equal. Release of mineral N early in the process is caused when organic matter with a C:N ratio of less than 20 decomposes. Manure-N generally comprises of three major fractions of agronomic importance namely, mineral N ($NH_4^+$-N and $NO_3^-$-N), easily mineralizable organic N, and more resistant organic N. The relative contents of these fractions in manure vary depending on methods of collection, handling and storage methods. Land application of organic sources high in C content and/or having wide C/N ratio will be metabolized by microorganisms within 10-15 days causing immobilization of mineral N. On the contrary, well-decomposed, *i.e.* composted or biogas digested, animal wastes generally contain small amounts of rapidly decomposable compounds, and short-term changes in N mineral concentrations are, therefore, small. If mineralization rate is slow, then a crop may not derive any benefit from the immobilized N during a normal growing season. This probably underlines the importance of time of incorporation of manure before seeding/planting of crop. The rate and timing of N release in manure-amended soils will be affected by type/chemical composition of organic manure and different site-specific factors, *e.g*., compost quality, composting conditions, temperature, soil moisture, soil properties and management practices during crop growing season. Mineralization of organic N fraction in organic manures may range from 40% to as high as 100% depending on the type/source of organic manure and soil and climatic conditions during crop growing season. Nitrogen mineralization rate is generally lower in surface-applied manure than for incorporated manure. Bitzer and Sims (1988) suggested that more than 60% of the organic N fraction may be mineralized during cropping and hence become available along with the mineral N fraction in the poultry manure, whereas only 38% of added organic N from swine and dairy cattle manure was apparently mineralized. Rate of N mineralization from poultry manure is much faster than FYM (Yadvinder-Singh et al., 1988). Mineralization rate of N is generally slower in surface-applied manure than for incorporated manure. Yadvinder-Singh (2009a) reported that about 46% of the N from poultry manure was released during 60 days of incubation. The release of P on 20 days after incubation accounted for 15–17% of the total P.

Yadvinder-Singh (2010) reported that total N release from incorporated residue containing 40 kg N $ha^{-1}$ was about 6-11 kg N (15-27% of initial) by the maximum tillering stage of wheat. In contrast, there was no release of N (rather N was immobilized) from the residues on the soil surface throughout the wheat growing season, thus suggesting that there is no direct N benefit to the growing wheat crop but it can benefit the following rice crop. Rice and wheat residues are rich sources of K and release about 70% of its K within 10 days of their incorporation into the soil.

***Nutrient Losses from Organic Manures***

Nutrient losses from organic manures occur during handling, storage and field application. Anaerobic storage conditions lead to concentrations of $NH_4^+$-N being much higher than those occurring under aerobic conditions, and sometimes $NH_4^+$-N may even make up for most of the total N in anaerobic manure. Aerobic conditions lead to a stabilization of N in organically bound forms, high pH values, and large gaseous losses of $NH_3$. Emissions of $NH_3$ amount to at least 25% of the initial N from composted manures, whereas losses are normally less than 10% during anaerobic storage because of reduced air exchange in the covered slurry tanks.

In the cropping systems where INM is implemented, organic nutrient sources generally represent an increased risk for N losses to the environment compared with N from mineral sources, even when excessive nutrient applications are avoided. This is because soil microbial activity leads to N release that is not in synchrony with plant nutrient demand. Thus, any N that may accumulate from mineral sources in the soil is prone to leaching and denitrification during the wet season, leading to low N use efficiency. Some of the gaseous N emissions could be reduced by improving field application of manure. To achieve high N use efficiency, farmers should replace simple land spreading with narrow band spreading or shallow injection techniques when applying a slurry, and they should rapidly incorporate solid manures following land application to prevent excessive losses of $NH_3$.There is also a scope to reduce $NH_3$ emissions and facilitate nutrient collection by better design and management of animal housing. Other strategies to reduce nutrient losses from manures include regulations on maximum permissible manure loadings and various best management practices. Improved synchronization between N net mineralization (N release) from organic materials and plant N demand has been advocated as a means of improving N use efficiency. It is essential that adequate amounts of N be present during periods of plant N uptake, whereas minimal amounts of N should be present during periods of no N uptake and when there is a high risk of leaching. There is, therefore, a need to improve our means of directing N release from organic nutrient sources, irrespective of the cropping system and origin of the organic materials.

The release of nutrients from organic amendments should be adequately controlled to match temporal crop demand with nutrient supply to minimize N losses. As decomposition of an organic material in soil proceeds, a net decrease in mineral N will lead to a net release of mineral N. If such is the case, then the question arises as to how net immobilization of mineral N followed by net mineralization will affect crop response in the field. The strategies to reduce nutrient losses from manures include regulations on maximum permissible manure loadings and various best management practices.

**Effects of Integrated Nutrient Management on Yield Responses and Sustainability**

Crop yield responses to addition of organic materials are highly variable and are dependent upon the crop, soil and climatic conditions, management practices and the quality of the organic manure used. Organic manures increase crop yields by improving soil nutrient supply and soil health. The beneficial use depends on choosing the best amount and frequency of manure application. Use of composts or other organic amendments in combination with mineral fertilizers enhanced crop yield in many cropping systems over more than 10 years, compared with organic manures alone (Yadvinder-Singh et al., 2003a; Sharma et al., 2019). Grain yield of wheat was highest where 10 t FYM $ha^{-1}$ was applied along with recommended NPK fertilizer for 34 years under maize–wheat cropping system (Brar et al., 2015). Similar yield trends with time were observed due to application of FYM in a 27-year maize–wheat long-term experiment at Ranchi (Swarup, 2002). This increase in yield potential is due to many components present in the organic manures and their effects on improved soil structure, water regime, trace element supply, and partly to synergism. Slow nutrient release from manures and composts provides stable supply of $NH_4$ and thus supports the maximal yields.

In a rice–wheat system, Yadvinder-Singh et al. (2009b) reported that applying poultry manure (5 t $ha^{-1}$, dry wt.) with fertilizer N (40 kg $ha^{-1}$) increased rice yield and nutrient uptake similar to that obtained with the recommended dose of fertilizer N (120 kg $ha^{-1}$). The residual effect of poultry manure in the following wheat was equivalent to 30 kg N + 30 kg $P_2O_5$ $ha^{-1}$. Behera et al. (2007) applied 2.5 t $ha^{-1}$ poultry manure along with 50% of the recommended NPK to wheat and recorded a significantly higher grain yield compared to the fertilizer-alone treatment.

In the annual soybean–wheat crop rotation, the combined application of mineral fertilizers and FYM on a long-term basis either to wheat (Bhattacharyya et al., 2010) or to soybean (Kundu et al., 2007) resulted in significant direct as well as residual effects on both the crops. In a number of rice-wheat studies from North-West India, incorporation FYM enhanced the productivity over the recommended NPK fertilizers. For example, at Pantnagar, application of FYM with 100% NPK for 34 years increased the productivity of rice and wheat by 14% and 18%, respectively over 100% NPK alone (Singh and Wanjari, 2018). Increase in yield on incorporation of FYM is not only due to additional supply of major nutrients but also of micro (Zn) and secondary nutrients, and overall improvement in soil health. Singh et al. (2018) reported that supplementing 25% N through vermicompost (VC) or *Sesbania* green manure (GM) plus 75% recommended dose of fertilizer N (RDN) resulted in rice yield similar to that obtained with 100% of RDN. Mondal et al. (2016) reported that application of 50% recommended dose of fertilizer (RDF) + 50% RDN through mustard oil cake (MOC) or 75% RDF + 25% RDN through MOC + biofertilizer recorded significantly higher grain yields, and higher partial factor productivity of applied nutrients than those of the crop having 100% RDF. Joshi et al. (2013) opined that the maize produced significantly higher crop yields with application of recommended dose of NPK + 10 t FYM $ha^{-1}$ compared to either inorganic fertilizers alone or organics sources alone.

Many other studies also reported that application of fertilizers supplemented through organic manure produced significantly higher yield of rice than fertilizers alone (Bijay-Singh and Ali, 2020 and references therein). According to Biswas (2018), responses to NPK+FYM were not distinctly different from NPK alone in the initial 5-6 years under long-term cropping, but later on responses to NPK alone became lower than those to NPK + FYM. This indicates that with time intensive agriculture relying mainly on NPK would accentuate deficiencies of secondary and micro nutrients such as S and Zn. The positive effects of FYM were more conspicuous in maize, perhaps because it improved the physical condition of the soil, besides supplying additional S and Zn. In a 30-year soybean–wheat long-term experiment, Kundu et al. (2007) also observed that application of FYM not only resulted in the highest soybean and wheat yields, but also reversed the negative yield trend in the 100% NPK treatment over time to a positive yield change.

From a recent meta-analysis of the data conducted on INM from Indian subcontinent for a period of 1989–2016, Sharma et al. (2019) deduced that there occurred a significant increase in the grain yield of both rice and wheat crops with the use of INM over inorganic fertilizers only and organic fertilizers only treatments. The yield differences in the INM treatment over inorganic fertilizers only were 0.05 and 0.13 t $ha^{-1}$, respectively in rice and wheat crops. The percent yield increases in INM treatment over inorganic fertilizers only and organic fertilizers were more in loamy soils compared to the clayey soils. The net returns increased by 9.3% (INM *vs.* chemical fertilizers) in wheat crop. On account of yield gain and maintenance of soil health, INM practice can be considered as a viable nutrient option over conventional chemical fertilizer treatments in rice-wheat system in the Indian subcontinent.

Experiments conducted at Ludhiana showed that application of pressmud cake (5 t $ha^{-1}$, dry weight basis) along with 60 kg fertilizer N $ha^{-1}$ produced rice grain yield equivalent to that produced under the recommended fertilizer treatment of 120 kg N $ha^{-1}$ (Yadvinder-Singh et al., 2008). Residual effect of PMC in the following wheat was equivalent to 40 kg N + 30 kg $P_2O_5$ $ha^{-1}$. Thirty-five years' data clearly indicated that integration of N, P and K sustained the yield at a higher level compared to application of N and NP in soybean-wheat rotation (Singh and Wanjari, 2018); however, the maximum average productivity was recorded with conjunctive use of NPK and FYM. The big jump in yield indicates that INM becomes more important in soils which have poor buffering capacity. Seven years' study on soybean-wheat at IISS Bhopal also demonstrated that integration of nutrient (FYM and fertilizer) sustained the yield at higher level compared to sole application of either organic manure or fertilizer (Rao et al., 1998).

Based on results from 7 long-term experiments (12–15 years) on rice–wheat system conducted at different locations in India, Yadav et al. (2000) reported a highly significant increase in yield of both rice and wheat with integrated supply of nutrients through fertilizers and manures (FYM, GM and crop residues), indicating the advantage of combined use of manures plus fertilizers over fertilizers alone in sustaining crop yields. Ladha et al. (2003) reported that average yield increase in rice was significantly higher with the application of organic manures along with 50% NPK as compared with the 100% NPK treatment. However, no significant change in yield trends was observed in following wheat. Sarkar et al. (2018) reported increase in the yield of maize over chemical fertilizers alone. Direct application to wheat of 10–20 t FYM $ha^{-1}$ along with 25–50% less than the locally recommended dose of NPK fertilizers resulted in the production of equal or higher grain yield than that obtained with the application of full dose of fertilizers (Behera et al., 2007; Bhattacharyya et al., 2010).

Application of vermicompost along with RDF and even sole application of vermicompost were found to enhance or maintain similar yield of pulses, cereals and vegetables (Padmavathiamma et al. 2008). However, it is always better to evaluate the beneficial effects of vermicompost in crop production in integration with chemical fertilizers and not alone.

From a 5-year study, Meena et al. (2019) reported that the grain yield of maize-chickpea system was significantly higher with 75% NPK of soil test based fertilizer recommendation + 5 t FYM $ha^{-1}$; an increase of 20.9% and 13.08% in mean grain yield of maize and chickpea was recorded, respectively over general recommended fertilizer dose. However, apparent nutrient balance was negative for N and K in all the treatments except higher level of FYM treatment (20 t FYM $ha^{-1}$) while P balance was positive under balanced and complete nutrition through organic and inorganic treatments over the years. The soil test based 75% NPK along with 5 t FYM $ha^{-1}$ treatment recorded highest sustainable yield index with maximum guaranteed yield of 6.19 and 1.99 t $ha^{-1}$ in maize and chickpea, respectively. The sustainable yield index (SYI) of the INM treatment was conspicuously higher than that for the fertilizer only treatment. From a 28-year (1984–2012) experiment, Das et al. (2014a) reported that sustainable yield index for the NPK and NPK + FYM for rice was 0.82 and 0.95, respectively. In a long-term (1984-1997) experiment on rice–wheat cropping sequence, Bhandari et al. (2002) observed a significant declining trend in the 100% NPK treatment but the declining trend was not observed in wheat yield when FYM was applied to the preceding rice crop.

Studies conducted at CRRI, Cuttack and Ludhiana showed that application of 60% N through BGS and 40% through fertilizer N to rice produced higher grain yield than the application of fertilizer N alone (Yadvinder-Singh et al., 2003a). Experiments carried out at New Delhi showed that N applied through BGS and urea was equally effective in increasing grain yields of both rice and wheat (Anonymous, 1994). Biogas slurry may also be applied directly with irrigation water. Studies showed that application of 40 t $ha^{-1}$ of wet slurry (5% dry matter) with first irrigation in conjunction with 60 kg N $ha^{-1}$ increased the wheat yield, which was at par with that obtained with 120 kg N $ha^{-1}$. Studies conducted at Ludhiana showed that application of 5 t $ha^{-1}$ of dried BGS supplied @40 kg N $ha^{-1}$ to rice and 30 kg N + 30kg $P_2O_5$ $ha^{-1}$ to the following wheat crop in RWS (R.K. Gupta and Yadvinder-Singh, unpublished data). Above results suggest that INM can contribute towards maintaining and enhancing the yield sustainability in the cropping system. Phosphocompost served as a P source for crops in acid as well as alkali soils, where Mussorrie rock phosphate was otherwise ineffective (Mishra, 1992).

Kumar et al. (2020) evaluated the direct and residual effects of organic manures (sewage sludge, vermicompost and sesbania GM) and chemical fertilizers on grain yield of rice and their residual effect on wheat grown in sequence at Varanasi, Uttar Pradesh. The mean rice grain yield and net returns recorded under 100% recommended dose of chemical fertilizers were higher compared to the organic treatments with similar N rates.

From extensive literature reviews, Yadvinder-Singh et al. (1991, 2010a,b) came across several examples from India where adoption of GM led to marked increases in rice/wheat/maize yields and could substitute 40-100 kg N $ha^{-1}$ depending the amount of N added and cropping system.

Das et al. (2014b) reported that under permanent beds with residue retention seed cotton yield was about 24 and 51% higher and wheat yield was 9 and 11% higher compared with permanent beds without residue retention and CT plots, respectively. The cotton–wheat system under permanent beds with residue retention under irrigated conditions in NW India increased the productivity, water use efficiency and profitability. Crop residues supplied 35-50 kg N $ha^{-1}$ which is a key consideration when attempting to optimize N fertility in conservation tillage systems. Nitrogen management for zero till system with residue retained as mulch may differ from that where residue has either been removed or burned *in-situ*. Unfortunately, it is poorly documented for the Indian conditions. Results from a long-term study on conservation agriculture (CA) practices (zero tillage + crop residues) in rice-wheat and maize-wheat systems showed that wheat after 4 years of continuous CA practices required 30% less N and 50% less K fertilizer compared to conventional-till systems with similar yields. This might be due to the addition of nutrients through residues which led to improved physical environment and microbial activity that helped in higher mineralization resulting in the enhanced availability of nutrients to crops and thus increased the soil N supply (Jat et al., 2018).

From a 4-year field study, Thind et al. (2019) reported that rice yield was significantly higher by 8% with 50% less fertilizer N application in GM compared with conventional puddled transplanted rice with no GM. Zero till (ZT) wheat sown into rice residue produced significantly higher mean wheat grain yield by 7.3% and 17.5% compared with CT and ZT wheat with no residue, respectively. GM in rice followed by ZT wheat + rice residue resulted in Rs 24,075 $ha^{-1}$ more net returns compared with the conventional RW system. Significant increases in soil organic carbon, available P and available K contents were recorded in ZT wheat + residue compared to CT wheat. Applying rice husk ash (RHA) and bagasse ash (BA) on agricultural land improves yield, nutrient uptake and chemical fertility of soil with special reference to available P and K. Thind et al. (2012) reported that using recommended NPK fertilizer doses, soil amendment with RHA and BA to wheat along with recommended NPK fertilizers increased wheat yields by 24% and rice yield by 10% compared to no soil amendment in the rice-wheat system. These increases in grain yield were accompanied by significant increase in the Olsen P content in soil. From another study, Thind et al. (2017) reported that significant response of wheat to fertilizer P was observed up to 30 kg $P_2O_5$ $ha^{-1}$ in the presence of BA and RHA compared to recommended 60 kg $P_2O_5$ $ha^{-1}$ applied to wheat on non-amended plots, thereby effecting 50% saving on fertilizer P. The application of recommended P without biomass ash yielded a negative P balance of 21 kg P $ha^{-1}$. On the other hand, application of BA alone and RHA along with 30 kg $P_2O_5$ $ha^{-1}$produced nil or positive P balance. Thus, recycling of biomass ashes with reduced application of fertilizer P, improves the system productivity and economic returns and will go a long way to reduce the environmental pollution.

A portion of organic manure applied along with mineral fertilizers to summer season crops such as rice, maize and soybean is mineralized slowly and this may have a residual nutrient benefit to crops like wheat grown in a subsequent winter season. Several researchers have observed significant residual effects of INM based on FYM, poultry manure, pig manure applied to rice, maize or soybean on the succeeding wheat (Maskina et al., 1988a,b; Kumar and Yadav, 1995;Yadvinder-Singh et al., 1995, 2004a; Bijay-Singh et al., 1997; Bhandari et al., 2002; Rupa et al., 2003; Manna et al., 2005;Behera et al., 2007; Kundu et al., 2007). Maskina et al. (1988a,b) reported that FYM and pig manure applied to rice or maize gave residual effect equivalent to 30 kg N and 30 kg $P_2O_5$ $ha^{-1}$ on the yield of succeeding wheat. Bijay-Singh et al. (1997) reported that application of poultry manure in rice also showed significant residual effect in wheat, which was equivalent to 40 kg N and 30 kg $P_2O_5$ $ha^{-1}$.

Several studies clearly indicate that inoculation with *Azotobacter*, *Azospirillum* and PSB gave yield increases in different crops by 5-10% over farmers' practice where no fertilizers are being used (Rao, 2018). In Jute-rice-green gram system in Odisha, jute yield increased by 19% due to biofertilization over RDF, rice by 8% and green gram by 12%. NPK recovery increased from 62.0% to 74.0% in recommended fertilizers + BF (Rao, 2018). Microbially enriched compost (5 t $ha^{-1}$) with biofertilizer or GM with biofertilizer or *Azolla* (0.5 t $ha^{-1}$) gave highest rice grain yield. A consortium of biofertilizers consisting of *Azospirillum lipoferum*, *Azotobacter chroococcum* and plant growth promoting *Rhizobacteria* (PGPR Mix I) has been developed and is being promoted by ICAR. From a 5-year survey, it was found that wherever rhizobial inoculation was practiced by farmers along with FYM and fertilizer application there was increased nodulation and grain yield of soybean compared to application of chemical fertilizers alone in Madhya Pradesh (Rawat et al., 2008). In India, against the total anticipated biofertilizers demand of 1 Mt in the country, the current supply position is very low (<100, 000 t) (Rao, 2018).

**Fertilizer N Equivalence of Organic Manures**

The fertilizer N equivalent approach includes estimation of the amount of fertilizer N that 1 t of manure replaces in terms of crop production. Determination of efficiency of manure N use requires an experimental approach in which the effects of manure N and fertilizer N on N yield or total N uptake

**Table 1. Fertilizer nitrogen equivalents (FNE) of organic manures (compiled from different sources)**

| Source | N added (kg $ha^{-1}$) | Fertilizer nitrogen equivalent (kg $ha^{-1}$) |
|---|---|---|
| Poultry manure (5 t $ha^{-1}$, dry wt.) | 75-100 | 60-80 |
| FYM (12 t $ha^{-1}$) | 60-80 | 40-50 |
| Green manures | 80-150 | 60-120 |
| Cereal residues | 25-50 | 20-30* |
| Legume (mungbean) residue | 80-100 | 60 |
| *Azolla* | 20- 50 | 30 |
| Pressmud cake (5 t $ha^{-1}$, dry wt.) | 90-120 | 60-80 |
| Biogas slurry (5 t $ha^{-1}$, dry wt.) | 50-100 | 50-80 |

**Note**: Above data apply mainly to rice-wheat system *3-5 years after application

of the crop are compared. Such field experiments compare several rates of fertilizer N and organic manures (including no N control) to determine the amount of total N in organic manure needed to obtain yields or N uptake by a crop equivalent to that obtained with fertilizer N. These experiments require ample supply of P and K to all plots, to avoid crop response to manure P or K, rather than to N. Evidently, the only property of manure in these experiments that is influencing yield is the N furnished by the manure. The efficiency of use of N from animal manure or chemical fertilizer can be expressed as apparent recovery of N (ANR) or apparent efficiency of N (ANE). Ratio of ANR or ANE of manure/ANR or ANE of fertilizer, expressed in %, is called the 'efficiency index of manure N' for yield or N uptake. An efficiency index of manure N of 50% means that 100 kg of manure total N has the same effect on crop N yield as 50 kg chemical fertilizer N. Results are also expressed in equivalent rates (kg N $ha^{-1}$) or as percentage of total N.

From a 3-year field study with rice-wheat rotation, Yadvinder-Singh et al. (1995) reported that fertilizer equivalence for cattle manure based on grain yield of rice ranged from 38 to 55% of manure total N and the fertilizer equivalence was 30-54% based on N uptake. Apparent recovery of N by rice was lower (20%) for manure as compared to 35-46% for urea. Bijay-Singh et al. (1997) reported that fertilizer equivalence for poultry manure ranged from 86 to 146 kg N $ha^{-1}$ depending on the amount of manure N applied. Field trials conducted on phosphocompost showed it to be comparable to superphosphate in wheat and several other crops (Mishra, 1992). Experiments showed that N applied through poultry manure, green manure, BGS and urea was equally effective in increasing grain yields of both rice and wheat (Yadvinder-Singh et al., 2003a). The fertilizer N equivalents cannot be calculated when the factors limiting yields with and without manure are different. Total nutrient supply and fertilizer equivalents of different organic manures depend on their chemical composition, quantity applied and the cropping system and climate season. Some of examples of the fertilizer N equivalents are provided in **Table 1**.

Nutrient supply from the manure varies according to the fractions of the nutrients (inorganic and organic) in the manure and their transformations. Organic N is only available after mineralization. About 30-40% of manure organic N becomes available for crop uptake in the first year after application in the '*rabi*' crops and 50-70% in '*kharif*' crops and the rest may gradually mineralize afterwards in the following seasons depending on the source and quality of manure. From a literature review, Yadvinder-Singh et al. (2003a) reported that on alluvial soil, integrated use of 12 t FYM and 60 kg N $ha^{-1}$ gave as much rice yield as 120 kg N $ha^{-1}$ resulting in a substitution of 60 kg N $ha^{-1}$. But on red and yellow soils, a saving of 60 kg N $ha^{-1}$, 60 kg of $P_2O_5$ $ha^{-1}$and 60 kg of $K_2O$ $ha^{-1}$ was obtained. Organic manures applied to rice also have significant residual effects on the succeeding crop (s) (see previous section). One important aspect is how the application rates are determined. If application rate of animal manure is based on N content, then P is usually applied in excess of crop uptake. The application rate can be based on P needs. In fact, when the application rates of manure are calculated on the N crop requirement, the amount of P added often exceeds the plant P requirement, resulting in soil P accumulation, *e.g.*, high P content in PMC and poultry manure (Yadvinder-Singh et al., 2008, 2009b) and bagasse ash (Thind et al., 2017).

**INM and Nutrient Use Efficiency**

At present, it has been assessed that only 33% to 50% of the applied N fertilizers are used by crops (Ladha et al., 2005). INM may help to achieve efficient use of chemical fertilizers (Mahajan et al., 2008) by reducing N losses and increasing the nutrient availability to the crops. INM generally increases crop yields above those of fertilizers alone. This increase in yield potential is due to many components present in the organic manures and their effects on improved soil health, water regime, and partly to synergism. Slow nutrient release from manures and composts provides stable supply of $NH_4$ and thus support maximal yields. This also suggests that organic manures have considerable potential in increasing the use efficiency of chemical fertilizers by crops. Zhang et al. (2012) reported that INM treatment had significantly higher N use efficiency and reduced apparent N loss compared with chemical fertilizer alone. Compared to chemical fertilizers, apparent N losses were reduced by 73% and 43% in wheat and maize, respectively. Analyzing data from long-term fertilizer experiments, Singh and Wanjari (2018) showed that application of FYM along with 100% NPK increased N use efficiency compared to 100% NPK in rice, maize and wheat. At Ludhiana, the N use efficiency for 100% + FYM in maize and wheat was 40.2% and 67.8% compared to 36.4% and 63.1% for 100% NPK, respectively. At Pantnagar, N use efficiency in maize increased from 44.4% in 100% NPK to 61.7% in 100% NPK + FYM, but no such effect was observed in wheat. Similar increases in P and K use efficiency were reported with the application of FYM along with 100% NPK over 100% NPK alone. The INM had synergistic effects which led to improvement in the crop grain yield and NUE.

Manure N use efficiency for crop production could be increased significantly if the availability of N in these three fractions was better understood. If mineralization-immobilization rate is slow, a crop may not derive any benefit from the immobilized N during a normal growing season. This probably underlines the importance of time of incorporation of manure before seeding/planting of crop. Mineralization of organic N fraction in organic manures during cropping season may range from 40 to as high as 100% depending on the type source of organic manure and soil and climatic conditions during the crop-growing season. Results from the laboratory incubation study showed that a significant portion of N from pressmud cake (PMC) mineralizes during 20 to 30 days after application, which can meet a part of crop N demand during the early period (Yadvinder-Singh et al., 2008). The second phase of N release appearing between 45-60 days will provide sufficient N to rice and may eliminate the need to apply fertilizer N at this crop stage. In PMC-amended fields, supplemental application of fertilizer N may be more critical during the first 3 weeks of rice growth. Wheat is grown in winter season so that mineralization of organic sources of nutrients is slow as compared to in the summer when rice and maize are grown in South Asia. Therefore, INM in wheat is less popular than in rice or maize. Substantial residual effect of organic materials applied to preceding summer season crops of rice, maize or soybean has been observed in wheat by several researchers.

Time, method and rate of manure application are very important for efficient utilization of manure-borne nutrients and for minimizing environmental risk. In the IGP of India, wheat is grown in the winter season; hence, mineralization of organic sources of nutrients is slow as compared to summer when rice and maize are grown. Therefore, the use of organic nutrient sources along with mineral fertilizers in wheat is less popular than in rice or maize. The timing of animal waste additions to the fields affects the risk for N losses. Mineralized N from organic manures added to soil during the non-growing season is at immediate risk for loss because of surface runoff or leaching. However, the timing of incorporation of organic manures, green manures, and crop residues into soil affects the N release pattern of organically bound N, because of the effects of variations in soil temperature and moisture on decomposition. Delaying tillage until shortly before seeding may increase the risk of N deficiency to the subsequent crop as net N release may be too late for its optimal utilization by the crop. In the case of green manure crops, early incorporation may lead to fast release of N, with low availability at later growth stages or losses in rice.

Management practices for organic sources have two fundamental goals: to optimize plant nutrient (particularly N and P) recovery and to minimize pollution from N and P and other constituents. Organic manures mineralize in soil at variable rates and have a greater residual effect on soil fertility than chemical fertilizers, because of slow release character of N and P components. Management strategy for organic sources is to optimize plant nutrient recovery and to minimize pollution from N and P and other constituents.

Improved synchronization between N net mineralization from organic materials and plant N demand has been advocated as a means of improving N use efficiency, especially in tropical cropping systems. It is essential that adequate amounts of N be present during periods of plant N uptake, whereas minimal amounts of N should be present during periods of no N uptake and when there is a high risk of leaching. Nitrogen release that is not in synchrony with plant nutrient demand can lead to an increased risk for N losses to the environment compared with N from mineral sources, even when excessive nutrient applications are avoided. Thus, any N that may accumulate from mineral sources in the soil is prone to leaching during the wet season; therefore, organic manures and amendments frequently have lower use efficiency for N than the mineral N fertilizers do. Another method of improving the synchrony between plant demand and N release is adoption of crop sequences with extended N uptake periods.

Site-specific nutrient management (SSNM), a plant need-based approach for precision nutrient management, considers nutrient differences which exist within and between fields by adjusting the nutrient application through chemical fertilizers and organic sources to match the site, soil, or season differences. Use of leaf colour chart, chlorophyll meter and optical sensor GreenSeeker for N management are the leading examples of need-based fertilizer management for reducing use of N by 12 to 50% in India without any yield loss (Jat et al., 2016). The SSNM approach should be combined with INM and other best fertilizer and crop management practices for increasing NUE in different crops and cropping systems.

Application of organic manures to soil increases P availability through several mechanisms. The efficiency of P from manure may depend on the kind of manure, P status of the soil or the kind of crops etc. Yadvinder-Singh et al. (2008) observed a sharp increase in P availability in PMC-amended plots and maintained high P levels over long periods. The application of PMC proved to be beneficial in meeting 50% of P requirement of rice-wheat rotation. Phosphocompost can serve as a P source for crops in acid as well as alkali soils, when Mussorrie rock phosphate is otherwise ineffective. Trace elements availability is also affected by organic manures mainly through chelation. Crop yields and zinc uptake were increased when organic manures were added along with Zn fertilizer (Nayyar et al, 1990).

**INM and Soil Health**

Soil health is an important factor in improving crop productivity and nutrient use efficiency. Soil health depends on a large number of chemical, physical and biological properties, and its characterization requires the selection of the properties most sensitive to change in management practices. It can be managed through integrated nutrient management. Continuous use of chemical fertilizers in intensive cropping systems has been leading to imbalance of nutrients in soil, which has an adverse effect on soil health and also on crop yields. But, use of organics alone does not result in spectacular increase in crop yields, due to their low nutrient status. Supplementing the chemical fertilizers with organic manures can arrest deterioration in soil health. Thus, ideal way to sustain soil health and crop productivity is to develop INM strategies for different cropping systems all over the country. Bhattacharyya et al. (2008) reported that higher soybean and wheat yields obtained with the FYM + fertilizer treatment than with the fertilizer-alone treatment were not only due to nutrient supply by FYM, but also other benefits of increased SOM content such as improved microbial activities, supply of macro and micro nutrients, smaller losses of nutrients from the soil and improved soil physical properties etc. The use of organic manures for managing soil quality/health has been well recognized (Kundu et al., 2007: Bijay-Singh and Ali, 2020). Soil microbial population and biodiversity play a key role in enhancing nutrient availability and soil health. Build-up of soil organic matter (SOM) due to application of organic nutrient sources leads to improved soil physical properties such as soil structure and water-holding capacity. Data from several long-term experiments on different cropping systems in different agro-climatic zones in India showed that the recommended NPK + FYM resulted in the build-up of SOM more than in the fertilizer-only treatment (Singh and Wanjari, 2018). After three years of rice-wheat system with poultry manure application, soil organic C increased by 17%, Olsen-P by 73%, and $NH_4OAc$-extractable-K by 24%. Similarly, several other researchers from India have reported that the application of organic manures along with mineral fertilizers increased SOM more effectively than the application of fertilizers alone (Bijay-Singh and Ali, 2020 and the references therein; Sharma et al., 2019 and the references therein; Ghosh et al., 2012; Sarkar et al., 2018; Yadvinder-Singh et al., 2004a; Singh et al., 2007; Brar et al., 2015). Sharma et al. (2019) conducted met-analysis of the data from Indian sub-continent on the effect of INM on soil health in rice-wheat system. They noted that soil organic carbon in INM increased by 23.2% and 16.2% in INM compared to chemical fertilizer alone for rice and wheat, respectively. They reported that increase of SOM under INM practices will help in improvement in soil fertility, total soil nutrient content and crop productivity.

Organic manures are helpful in improving soil physical properties (aggregation, bulk density, infiltration rate, water holding capacity) and improve soil carbon status, chemical properties (pH, cation exchange capacity) (Singh et al., 2007; Brar et al., 2015). Ultimately, it can provide a way to improve soil health and crop productivity (Singh and Kumar, 2008). The INM increased the soil health and wheat productivity in a sustainable manner (Bijay-Singh and Ali., 2020; Kumar et al., 2012; Walia et al., 2010). Brar et al. (2015) showed significant increase in SOC and improvement in soil physical properties such as CEC, pH, aggregate MWD, infiltration rate and cumulative infiltration. Integrated use of inorganic fertilizer along with organic fertilizer (100% NPK + FYM) resulted in maximum infiltration rate, and aggregate MWD. Improved soil physical conditions and increase in SOC might have resulted in higher maize and wheat yields.

Improvement in SOC and consequently, SOM also improved the uptake of N, P and K significantly in all the treatments compared to non-treated control. In a rice–wheat cropping system, the INM treatment increased water-use efficiency and water-holding capacity of the soil (Sharma et al., 2001). Das et al. (2014) recorded improvement in soil aggregation and structural stability leading to higher C content in macro aggregates in rice–wheat cropping systems.

Soil chemical and biological properties are also enhanced through the supply of manure or crop residues coupled with chemical fertilizers. Chemically, SOM enrichment increases the capacity of soil to buffer changes in the pH, increases the CEC, reduces P fixation and serves as a reservoir of nutrients, including micronutrients. Biologically, SOM favours growth of soil fauna and microorganisms, which are the primary agents that facilitate decomposition of organic material and release of mineral nutrients in the soil for plant uptake. Organic manures play an important role in improving the soil organic carbon, total NPK status and soil biological activity, which leads to increment in agricultural production in a sustainable manner (Walia et al., 2010; Saikia et al., 2020). The application of NPK fertilizers alone into the soil decreased the soil organic carbon status of the soil while the integration of chemical fertilizers with organic inputs such as FYM, green manure, vermicompost, and crop residue built up the soil organic matter and increased the soil fertility. Soil MBC and MBN are very sensitive to changes in total SOM and could be utilized as indicators of soil health. More recently, a greater range of labile soil organic matter attributes such as light fraction of organic matter, particulate organic matter (POM) showed the benefits of INM technology. Long-term use of urea alone reduced the soil pH but the effect of fertilizer was far more serious in Alfisols because of their poor buffering capacity (Singh and Wanjari, 2018). Sharma et al. (2019) concluded that for all the compared treatments (INM *vs.* chemical fertilizers), the total N, available P and K, and soil MBC showed significant positive effects on rice and wheat crops, indicating that INM treatment improved these soil properties over inorganic fertilizers. Yadvinder-Singh et al. (2009b) reported that application of PMC for 4 years caused significant increase in organic carbon and available P content of the soil over recommended fertilizers alone. The sharp increase in P availability in PMC-amended plots and maintaining high levels over long periods proved to be beneficial in meeting crop P requirements.

Soil health–related microbial indicators such as soil microbial biomass, soil bacterial community diversity and soil enzyme activities are also significantly improved under INM rather than application of chemical fertilisers alone (Nath et al., 2011; Sarkar et al., 2018; Saikia et al., 2020). Application of 100% NPK + FYM increased the microbial biomass carbon (MBC) and dehydrogenase (DHA), acid and alkaline phosphatases, cellulase and protease activities in the soil compared to 100% NPK, irrespective of soil type (Biswas, 2018). In a maize-chickpea system, Meena et al. (2019) observed a significant increase in the various soil health indicators (physical, chemical and biological) under balanced and integrated use of organic and chemical fertilizers. Farmyard manure, poultry manure and urban compost improved the physical properties of soil like mean weight diameter, water stable aggregates, bulk density and porosity. Application of higher level of FYM (20 t $ha^{1}$) significantly increased the SOC (6.30 g $kg^{-1}$), SOC stock (11.8 t $ha^{1}$), Olsen-P (23.8 mg $kg^{-1}$) and $NH_4OAc$-K (274 mg $kg^{-1}$) concentration in surface soil as compared to application of recommended fertilizers. Activities of soil enzymes such as DHA, alkaline phosphates and fluorescein diacetate were enhanced significantly under 75% recommended NPK+FYM (5 t $ha^{1}$) compared to recommended fertilizers alone.

**Soil Carbon Sequestration**

In recent years, global concern over increased atmospheric $CO_2$ and methane ($CH_4$) emissions has raised interest about the potential role of soils as a source of or sink for C and in studying organic matter dynamics and related C sequestration capacity. When organic materials, such as composted wastes, are added to soil, at least a share of their organic C is decomposed producing $CO_2$, while another part is sequestered in the soil. Carbon sequestration implies transfer of atmospheric $CO_2$ into the soil C pool mainly through humification of crop residues and other wastes added to the soil and formation of organo-mineral complexes which encapsulate C and protect it against microbial activities. Brar et al. (2015) reported that 26 yrs after the start of experiment FYM application increased the organic carbon stock build-up @ 0.26 t organic carbon $ha^{-1}$ $yr^{-1}$. The C sequestration rate depends on type of organic source, method of application, climate and soil type. Eghball (2002) reported that after 4 years of application composted manure resulted in higher (36%) build up in SOC compared to uncomposted manure (25%). Soil organic carbon data from long-term studies revealed that continuous balanced nutrients application maintained SOC whereas incorporation of FYM resulted in build-up in SOC in Alfisols of Palampur and Inceptisol of Ludhiana (3.6 g $kg^{-1}$ *vs* 5.2 g $kg^{-1}$). At Ranchi, only NPK+FYM could maintain SOC whereas in all other treatments decline in SOC was recorded

(Biswas, 2018). Other long-term trials (≥10 yrs) revealed that the organic carbon sequestration rate increased more due to FYM compared with mineral fertilizers or other organic materials (Kukal et al., 2009). Sapkota et al. (2017) reported that after seven years, crop residue recycling along with zero tillage increased SOC at 0–0.6 m depth by 4.7 t C $ha^{-1}$, compared to conventional rice-wheat system in the Eastern IGP. Yadvinder-Singh et al. (2010b) observed that the total quantity of soil C sequestered from crop residue C inputs was 20% in rice-wheat system and suggested that crop residues need to be recycled to achieve sizable gains in SOC, particularly under zero till (ZT). It has been estimated that an increase of SOC stock by 1 t C $ha^{-1}$ in the root zone can raise the crop yields by 15-33 kg $ha^{-1}$ for wheat (Benbi and Chand, 2007), 160 kg $ha^{-1}$ for rice, and 145 kg $ha^{-1}$ for soybean (Srinivasarao et al., 2013). Any attempt to enrich the organic carbon reservoir through sequestration of atmospheric C will help to manage global warming.

**INM and Global Warming Potential**

The global climate change is manifested with the increase in the concentration of the three key greenhouse gases (GHGs) namely, $CO_2$, $CH_4$ and $N_2O$ in the atmosphere. From the point of global warming potential (GWP), $CH_4$ and $N_2O$ are more potent than $CO_2$. To regulate GHG emission from agriculture, it is important to understand the microbial processes governing the flux and feedback of GHGs. $CH_4$ and $N_2O$ are important GHGs that are emitted from agricultural soil through the processes of methanogenesis, and nitrification-denitrification, respectively. Both $N_2O$ and $CH_4$ emissions are greatly influenced by the cropping systems and management of soil and irrigation water (Das and Adhya, 2014; Nyamadzawo et al., 2014; Yuan et al., 2017).The GHG fluxes are computed in $CO_2$ equivalents, incorporating as many emission sources and sinks as possible across the entire soil-plant system. Among the two types of measures namely, mitigation and adaptation to tackle the climate change, former is an anthropogenic intervention to reduce the sources of or enhance the sinks for GHGs. Application of N fertilizers more than the plant needs may actually result in decreased N use efficiency and also contribute to nitrate pollution and the GHG emissions (Hoben et al., 2011). The key mitigation strategy is to make better use of existing organic sources of nutrients for INM. The use of biofertilizers in INM can be considered to be a potential climate smart nutrient management strategy. According to Lenka et al. (2017), INM may lead to reduced $N_2O$ emission, reduced $CH_4$ emission and increased soil C storage, as well as reducing mineral fertilizer requirements and the GHG emissions associated with their manufacture. Using organic sources may also reduce soil $N_2O$ emissions. Wu and Ma (2015) reported that the reactive N losses and GHG emissions are reduced substantially by using improved INM practices. Lower inputs of chemical fertilizer and, therefore, lower human and environmental costs are achieved under advanced INM practices without compromising on crop yields. Potential denitrification after application of pretreated manure may be expected to decrease, compared with that after application of untreated manure because easily available C is one of the limiting factors for denitrification. Application of organic manures may increase $CH_4$ emission from paddy fields due to increased availability of carbon source for methanogenic bacteria. As production of fertilizers for agriculture is itself an energy-intensive process, requiring large amounts of fossil fuel burning, using the INM approach, the demand for chemical fertilizer will decrease. As discussed earlier, INM enhances soil carbon sequestration (carbon sinks) and therefore, plays a vital role in imparting mitigation and adaptation value of GHG emission. However, enhanced soil carbon through addition of organic materials to soil does not always mean contribution to climate change mitigation. Conditions where carbon is stabilized or physically protected through aggregation actually add to the climate mitigation and adaptation benefits (Tesfai et al., 2016). There are contradictory reports on the effects (either an increase or a reduction) of manure application on $N_2O$ emissions due to the enhancement of crop yield. Partial substitution of inorganic N (22 to 50%) with manure in basal fertilizer significantly reduced $N_2O$ emission by 24.0% but had no significant effects on wheat and maize yields (Gao and Bian, 2017). However, under the same N rates of application, manure application could provide additional N and available C for the microbial processes of nitrification and denitrification, and thereby significantly increased the $N_2O$ emission by 44.6%. Although crop yield increased by 51% under INM, yield-scaled $N_2O$ emission showed no significant difference between INM at the same N rate. Graham et al. (2017) concluded that increased supply of easily decomposable organic C in the form of organic amendments may increase microbial activity and induce anaerobic conditions, which may lead to increased losses of $N_2O$ via denitrification. From India, Bhatia et al. (2005) reported that mean $N_2O$ emission in rice under INM-treated plots was 11.6% higher in rice and 16.8% lower in wheat compared to chemical fertilizer plots Thus, INM holds promise for decreasing $N_2O$ emissions compared to mineral fertilizer inputs alone. Reduction in requirement of N from chemical fertilizers due to supplementation from organic manures and biofertilizers is also likely to reduce the $N_2O$ flux from rice ecosystems. From a recent review, Graham et al. (2017) concluded that INM treatments utilizing organic manures (composted manures and FYM) having low carbon to nitrogen (C:N ratio <8) tended to reduce emissions compared to organic amendments alone, while INM treatments utilizing organic manures with higher C:N ratios resulted in either no change in or increased the $N_2O$ emissions. However, another recent global meta-analysis concluded that C:N ratio only partially explained the response of $N_2O$ emissions to organic amendments, particularly for C:N ratios <25 where other environmental and management factors appeared to become increasingly important (Charles et al., 2017). There are conflicting reports on the effect of INM on $N_2O$ emissions. The INM resulted in reduced (Abalos et al., 2013; Nyamadzawo et al., 2014), increased (Garcia-Ruiz and Baggs, 2007; Lenka et al., 2017) or no significant effect (Chen et al., 2013; Yuan et al., 2017) on $N_2O$ emission under both upland crops and lowland rice.

It has also been estimated that burning of 98.4 Mt crop residues emitted 8.57 Mt of CO, 141.15 Mt of $CO_2$, 0.037 Mt of SO*x*, 0.23 Mt of NO*x*, 0.12 Mt of $NH_3$, 1.46 Mt non-methane volatile organic compounds, 0.65 Mt of non-methane hydrocarbons and 1.21 Mt of particulate matter during 2008–09 (Jain et al., 2014). There are reports of no significant effect of crop residue retention on area- and yield-scaled $N_2O$ emission and crop yield (Gao and Bian, 2017). Meng et al. (2005) reported that incorporation of straw with low N application rate could reduce $N_2O$ emission compared to no straw retention. On one hand, straw retention can increase soil temperature and/or moisture, which can stimulate the microbial process of nitrification and denitrification, and thereby raise $N_2O$ emissions (Charles et al., 2017). On the other hand, straw with a high C/N ratio can immobilize soil mineral N and decrease soil N availability (Yadvinder-Singh et al., 2014), consequently leading to a reduction in the substrate N for $N_2O$ production. Other studies reported lower GWP of conservation agriculture-based practices (zero tillage and crop residue retention in rice-wheat system (Sapkota et al. 2015, Triol-Padre et al. 2016). INM also adds adaptation value to the management system primarily through higher soil moisture storage so as to withstand drought conditions, higher infiltration rate and water movement, and better soil thermal regimes

Finally, there are upstream environmental impacts beyond the field boundary related to inorganic and organic N sources that need to be considered. Production of chemical fertilizers requires energy and produces GHG emissions during their manufacture and this is associated with significant embodied $CO_2$ costs. Likewise, organic N amendments derived from manure or compost also have GHG emissions associated with their production (*e.g.*, $CH_4$ emission by cattle) processing and transport (Thangarajan et al., 2013). For example, Sharma et al. (2006) estimated $CH_4$, $N_2O$ and total $CO_2$-equivalent emissions from municipal solid waste of India to be 0.33 to 1.80 Tg $yr^{-1}$, 7 Gg $yr^{-1}$, and 38.2 Tg $yr^{-1}$, respectively. In order to fully determine the net impact of INM practices on GWP, changes in soil C and the related GHG costs associated with inorganic N fertilizer and organic amendments need to be quantified and weighed against any increase or decrease in soil GHG emissions.

**Constraints in the Adoption of INM Technologies**

Despite impressive benefits of INM technology, it has not yet been widely adopted among the farming communities as per expectations. For their wide scale adoption, the INM technologies must be compatible with the local farming system. More attention must be paid to examine the interaction among different components of INM and their management and crops in a particular cropping system. The major constraints in the large-scale adoption of INM technology include timely availability of adequate amounts of organic sources and at costs affordable by the farmers. Other constraints include; variable nutrient contents and lack of precise information on nutrient release patterns. A serious problem of predicting manure nutrient content is the heterogeneity of manures, and, related to that, the difficulty of reliable sampling and chemical analysis. Moreover, chemical analysis is usually time-consuming and expensive. The 'typical' nutrient contents of manures can be used for general INM packages. However, it is important to use local information and, where possible, to estimate the nutrient content of manure on a farm basis. The use of bulky organic manures is often restricted by the high costs of transportation and is therefore limited to neighbors within a distance of a 10-15 km. Adoption of mechanized agriculture in place of animal-based farming, use of cattle dung cake for cooking, and crop residue burning are some of the reasons for the low adoption of INM technology by the farming community. The non-availability of suitable machinery (*e.g.*, Happy Seeder) at affordable price is a big constraint for managing crop residues. Other common constraints encountered by the farmers in adoption of INM technology are, (i) difficulties in growing green manure crops (Yadvinder-Singh et al., 1994), (ii) non-availability of good quality bio-fertilizers, a strain found ideal at one location may be ineffective at another location due to competition of native soil microbes and low self life, (iii) lack of financial support for composting organic materials including crop residues, (iv) availability of chemical fertilizers at subsidized rates, and (v) lack of knowledge and poor advisory services. Increasing cost of mineral fertilizers in the future and changes in the global demand may generate renewed interest in adopting various components of INM.

**Future Strategies**

For India with its ever-increasing population, the sustainable agriculture has to be based on site-specific balanced fertilization, and on INM practices depending on local economic and environmental conditions. For effective promotion of INM practices for utilizing the potentially available sources of organic amendments, the following strategies are suggested:

1. Potential availability of all the organic resources of plant nutrients like crop residues, livestock dung, farmyard manures, composts and agro-industrial wastes should be estimated and documented for each agro-eco region and different farming situations to strengthen the research and development efforts and also bring out their nutrient potentials and limitations for use.

2. A large fraction of manure N is lost from the soil-plant system during production, storage and field application. Therefore, proper storage, composting, application techniques of manures is needed to avoid nutrient losses and conserve maximum nutrients. Nutrient losses from organic manures should be quantified to devise methods to increase the efficiency of their use. More research is needed to hasten the process of composting using suitable microbial inoculations to improve the nutrient status of composts. Role of earthworms in digesting organic wastes needs more research.

3. We need to advise the farmers to recycle crop residues on-farm either through incorporation into the soil or to retain on surface as such (*e.g.*, conservation agriculture) to the extent possible. Suitable machinery needs to be developed and made available for *in-situ* crop residue management (*e.g.* Happy Seeder; chopper) to the farmers at affordable price to poor farmers.

4. Future research should focus on developing models (equations) for predicting nutrient contents in organic manures from data collected on their chemical and physical composition to develop proper INM fertilization plans for different crops and cropping systems, and regions. Research efforts should focus on predicting with higher accuracy nutrient (N) release from the materials, thereby improving NUE and decreasing negative environmental effects.

5. Nutrient balance sheet at a farm level including nutrient additions and release from organic sources needs to be studied to develop SSNM based INM practices for establishing the beneficial role of INM in improving nutrient cycling, soil health and crop productivity in different production systems.

6. For understanding the enhanced role of organic manures in increasing NUE due to their favourable effect on soil health and sustainable crop production, long-term trials are the best indicators of both utilizing organic materials in INM and sustainability. In fact, many effects, *e.g.* release of nutrients, carbon sequestration and possible build-up of toxic elements in the soil, evolve slowly, thus needing time to be tested.

7. It still remains unclear whether GHG emissions from the soil increase or decrease under INM as compared to chemical fertilisers. Future work is needed under field conditions to determine whether INM practices with different organic sources and biofertilizers increase or decrease the GHG emissions by monitoring potential changes in $N_2O$ and $CH_4$ fluxes.

8. Adoption of proper guidelines for MSW management and application to crop fields should be encouraged. Subsidizing the high-quality compost (*e.g.*, MSW) to farmers who bring waste to the composting plant is one option, though this would require support from the municipal authority.

9. Krishi Vigyan Kendras, fertilizer industry and NGOs should be motivated to propagate the usefulness of INM through a participatory approach. Based on current understanding and experience, a number of information sheets/pamphlets, on 'best practices' of manure management should be prepared for use by extension workers and farmers.

10. There is a need for strong government support for adoption of INM practices. Legislation should be put in place to prevent residue burning and discharge of organic manures to surface waters (irrigation and drainage channels, rivers, ponds and lakes).

**Summary and Conclusions**

Regular application of chemical fertilizers alone has been perceived to be facilitating soil degradation and disturbing the ecological balance. Alternative organic amendments available in the country need to be explored for their use and nutrient potentials and sustenance of soil health through carbon sequestration. A variety of products obtained from the recycling of crop, animal, human and industrial wastes can serve as sources of plant nutrients. Also significant amount of N is made available through BNF by a number of micro-organisms in soils either independently or in symbiosis with certain plants. Studies have also revealed that application of organic amendments alone cannot meet the nutrient requirements of the highly productive cereal-based cropping systems. For example, Timsina (2018) demonstrated that considering the currently available organic sources of nutrients in the developing countries, organic nutrients alone are not enough to increase crop yields to meet global food demand and that the nutrients from inorganic and organic sources should preferably be applied at 75: 25 ratio.

There is still a long way to go to realize the aims of the INM namely, increasing crop yield and NUE while simultaneously improving soil productivity and environmental quality. Achieving these goals will require continued and expanded efforts nationwide to develop new technologies by inter-disciplinary team of researchers to extend these technologies to small-holder farmers.

INM plays a positive role in climate change mitigation by soil carbon sequestration, which in turn can reverse the process of soil degradation. What the country needs today is the INM technology for meeting nutrient needs of crops and sustainable productivity. Fortunately, the Indian Government is aware of the importance of INM in the sustainable development of agriculture in the country. It has been proved that INM will not only reduce the use of chemical fertilizers but also improve soil health and ensure food security and environmental sustainability. Many INM guidelines have already been considered but not adopted on a large scale. Although sufficient evidence is available that INM exerts a positive effect on soil health when compared with fertilizers alone, research efforts are still inadequate in developing INM strategies which also take into account changes in soil productivity. Thus, in the future, the INM strategies should focus on both soil health and crop performance. Further, to achieve increase in adoption of INM practices, it should be site-specific and must be tailored to local circumstances, as there is no 'one-size-fits-all' solution to the complex problems of smallholder farmers in diverse agricultural systems thus making it a flexible technological package. Calculation of fertilizer equivalents of different organic sources for different soils and agro-ecological regions will be useful in developing INM packages for different cropping systems. Last and not the least, INM technology must be developed in the farmers' participatory research mode using cluster approach giving due consideration to the farmers' resource availability and conditions, farm innovations and indigenous technology knowhow.

## References

Abalos, D., Sanz-Cobena, A., Garcia-Torres, L., van Groenigen, J. W. and Vallejo, A.2013. Role of maize stover incorporation on nitrogen oxide emissions in a non-irrigated Mediterranean barley field. *Plant and Soil* **364**, 357–71.

Anonymous. 1994. *Status Report of AICRP on Renewable Energy Resources (1983-1989)*. IARI, New Delhi.

Behera U.K., Sharma, A.R. and Pandey, H.N. 2007. Sustaining productivity of wheat-soybean cropping system through integrated nutrient management practices on the Vertisols of Central India. *Plant and Soil* **297,** 185–199.

Benbi, D.K. and Chand, M. 2007. Quantifying the effect of soil organic matter on indigenous soil N supply and wheat productivity in semiarid sub-tropical India. *Nutrient Cycling in Agroecosystems* **79**, 103-112.

Bhandari, A.L., Ladha, J.K., Pathak, H., Padre, A.P., Dawe, D. and Gupta, R.K. 2002. Yield and soil nutrient changes in a long term rice–wheat rotation in India. *Soil Sci. Society of America Journal* **66**, 162–170.

Bhatia, A., Pathak, H., Jain, N., Singh, P.K. and Singh, A K. 2005. Global warming potential of manure amended soils under rice–wheat system in the Indo-Gangetic plains. *Atmospheric Environment* **39**, 6976–6984.

Bhattacharyya, R.,Kundu, S., Prakash, V. and Gupta, H. 2008. Sustainability under combined application of mineral and organic fertilizers in a rainfed soybean-wheat system of the Indian Himalayas. *European Journal of Agronomy* **28**, 33–46.

Bhattacharyya, R., Pandey, S.C., Chandra, S., Kundu, S., Saha, S., Mina, B.L., Srivastava, A. K. and Gupta, H.S. 2010. Fertilization effects on yield sustainability and soil properties under irrigated wheat–soybean rotation of an Indian Himalayan upper valley. *Nutrient Cycling in Agroecosystems* **86**, 255–268.

Bijay-Singh and Ali, M. 2020. Advances in integrated plant nutrient management. In *Achieving Sustainable Crop Nutrition* (Z. Rengel, Ed.), Burleigh Dodds Science Publishing, Cambridge, UK. DOI: 10.19103/AS.2019.0062.25

Bijay-Singh, Yadvinder-Singh, Maskina M.S. and Meelu O.P. 1997. The value of poultry manure for wetland rice grown in rotation with wheat. *Nutrient Cycling in Agroecosystems* **47**, 243-250.

Biswas, A.K. 2018. Integrated plant nutrient supply system – a conceptual framework. In*SAARC Training Manual on Integrated Nutrient Management for Improving*

*Soil Health and Crop Productivity* (Pradip Dey, Sanjay Srivastava, N.K. Lenka, K.C.Shinogi, A.K. Vishwakarma and Ashok K. Patra, Eds.), pp. 40-44. ICAR-Indian Institute of Soil Science, Bhopal.

Bitzer, C.C. and Sims, J.T. 1988. Estimating the availability of nitrogen in poultry manure through laboratory and field studies.*Journal of Environmental Quality* **17**, 47-54.

Bouwman, A.F., Beusen, A.H.W. and Billen, G. 2010. Human alteration of the global nitrogen and phosphorus soil balances for the period 1970-2050. *Global Biogeochemical Cycles* **23**, 1–16.

Brar, B.S., Singh, J., Singh, G. and Kaur, G. 2015. Effects of long-term application of inorganic and organic fertilizers on soil organic carbon and physical properties in maize–wheat rotation. *Agronomy* **5**, 220-238.

Charles, A., Rochette, P., Whalen, J.K., Angers, D.A., Chantigny, M.H. and Bertrand, N. 2017. Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: a meta-analysis. *Agriculture, Ecosystems and Environment* **236**, 88–98.

Chen, H., Li, X., Hu, F. and Shi, W. 2013. Soil nitrous oxide emissions following crop residue addition: a meta-analysis. *Global Change Biology* **19**, 2956–64.

Das, A., Sharma, R.P., Chattopadhyaya, N. and Rakshit, R. 2014a.Yield trends and nutrient budgeting under a long-term (28 years) nutrient management in rice-wheat cropping system under subtropical climatic condition. *Plant Soil and Environment* **60**, 351–357.

Das, S. and Adhya, T. K. 2014. Effect of combine application of organic manure and inorganic fertilizer on methane and nitrous oxide emissions from a tropical flooded soil planted to rice. *Geoderma* **213**, 185–92.

Das T.K., Bhattacharyya R., Sudhishri, S., Sharma, A.R., Saharawat, Y.S., Bandyopadhyay, K.K., Sepat, S., Bana, R.S., Aggarwal, P., Sharma, R.K. and Bhatia, A. 2014b. Conservation agriculture in an irrigated cotton–wheat system of the western Indo-Gangetic Plains: crop and water productivity and economic profitability. *Field Crops Research* **158**, 24-33.

Eghball, B. 2002. Soil properties as influenced by phosphorus- and nitrogen-based manure and compost applications. *Agronomy Journal* **94**, 128–135.

FAI. 2019. *Fertiliser Statistics 2018-19*. **64th Edition**. The FAI, New Delhi.

Garcia-Ruiz, R. and Baggs, E.M. 2007. $N_2O$ emission from soil following combined application of fertilizer-N and ground weed residues. *Plant and Soil* 2**99**, 263–274.

Gao, W. and Bian, X. 2017. Evaluation of the agronomic impacts on yield-scaled $N_2O$ emission from wheat and maize fields in China. *Sustainability* **9**, 1201; doi:10.3390/su9071201.

Ghosh, S., Wilson, B., Ghoshal, S., Senapati, N. and Mandal, B. 2012. Organic amendments influence soil quality and carbon sequestration in the Indo-Gangetic plains of India. *Agriculture. Ecosystems and Environment* **156**, 134–141.

Graham, R.F., Wortman, S.E. and Pittelkow, C.M. 2017. Comparison of organic and integrated nutrient management strategies for reducing soil $N_2O$ emissions. *Sustainability* **9,** 510. doi:10.3390/su9040510.

Hoben, J.P., Gehl, R.J., Millar, N., Grace, P.R. and Robertson, G.P. 2011. Nonlinear nitrous oxide ($N_2O$) response to nitrogen fertilizer in on-farm corn crops of the US Midwest. *Global Change Biology* **17**, 1140–1152.

Indoria, A.K., Sharma, K.L., Sammi Reddy, K., Srinivasarao, Ch., Srinivas, K., Balloli, S.S., Osman, M., Pratibha, G. and Raju, N.S. 2018. Alternative sources of soil organic amendments for sustaining soil health and crop productivity in India – impacts, potential availability, constraints and future strategies. *Current Science* **115**, 2052-2062.

Jain., N., Bhatia, A. and Pathak, H. 2014. Emission of air pollutants from crop residue burning in India. *Aerosol Air Quality Research* **14**, 422–430.

Jat, H.S., Datta, A., Sharma, P.C., Kumar, V., Yadav, A.K., Choudhary, M., Choudhary, V., Gathala, M.K., Sharma, D.K., Jat, M.L. and Yaduvanshi, N.P. 2018. Assessing soil properties and nutrient availability under conservation agriculture practices in a reclaimed sodic soil in cereal-based systems of North-West India. *Archives in Agronomy and Soil Science* **64**, 531-545.

Jat, H.S., Jat, R.K.,Yadvinder-Singh, Parihar, C.M., Jat, S.L., Tetarwal, J.P., Sidhu, H.S. and Jat, M.L. 2016. Nitrogen management under conservation agriculture in cereal-based systems. *Indian Journal of Fertilisers* **12(4)**, 76-91.

Joshi, E., Nepalia, V., Verma, A. and Singh, D. 2013. Effect of integrated nutrient management on growth, productivity and economics of maize (*Zea mays* L.). *Indian Journal of Agronomy* **58**, 434-436.

Kukal, S.S., Rasool, R. and Benbi, D.K. 2009. Soil organic carbon sequestration in relation to organic and inorganic fertilization in rice-wheat and maize-wheat systems. *Soil and Tillage Research* **102**, 87–92.

Kumar, A. and Yadav, D.S. 1995. Use of organic manure and fertilizer in rice (*Oryza sativa*) –wheat (*Triticum aestivum*) cropping system for sustainability. *Indian Journal of Agricultural Sciences* **65**, 703–707.

Kumar, M., Kumar, S. and Bohra, S.S. 2020. Cumulative effect of organic and inorganic sources of nutrients on yield, nutrients uptake and economics by rice–wheat cropping system in Indo-Gangetic Plains of India. *Communications in Soil Science and Plant Analysis* DOI: 10.1080/00103624.2020.1729788.

Kumar, V., Rai, P.K. and Mohan, U. 2012. Long-term effect of integrated nutrient management on soil organic carbon and its fractions and sustainability of rice–wheat system in Indo-Gangetic Plains of India. *Field Crops Research* **127**, 129–139.

Kumar, V. and Shivay, Y.S. 2010. Integrated nutrient management: an ideal approach for enhancing agricultural production and productivity. *Indian Journal of Fertilisers* **6(5)**, 41–53.

Kundu, S. 2018. Integrated plant nutrient supply system for improving soil quality. In *SAARC Training Manual on Integrated Nutrient Management for Improving Soil Health and Crop Productivity* (P. Dey, S. Srivastava, N.K. Lenka, K.C. Shinogi, A.K. Vishwakarma and A.K. Patra, Eds.), pp 45-49. ICAR-Indian Institute of Soil Science, Bhopal.

Kundu, S., Bhattacharyya, R., Prakash, V., Ghosh, B.N. and Gupta, H.S. 2007. Carbon sequestration and relationship between carbon addition and storage under rainfed soybean–wheat rotation in a sandy loam soil of the Indian Himalayas. *Soil and Tillage Research* **92**, 87–95.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, P., Kundu, A.L. et al. 2003. How extensive are yield declines in long-term rice-wheat experiments in Asia? *Field Crops Research* **81**, 159–180.

Ladha, J.K., Pathak, H., Krupnik, T.J., Six, J. and van Kessel, C. 2005. Efficiency of fertilizer nitrogen in cereal production: retrospect and prospect. *Advances in Agronomy* **87,** 85–156.

Lenka, S., Lenka, N.K., Singh, A.B., Singh, B. and Raghuwanshi, J. 2017. Global warming potential and greenhouse gas emission under different soil nutrient management practices in soybean-wheat system of Central India. *Environmental Science Pollution Research* **24**, 4603–4612.

Mahajan, A., Bhagat, R.M. and Gupta, R.D. 2008. Integrated nutrient management in sustainable rice-wheat cropping system for food security in India. *SAARC Journal of Agriculture* **6**, 1–13.

Maskina, M.S., Bijay-Singh, Yadvinder-Singh, Baddesha, H.S. and Meelu, O.P. 1988a. Fertilizer requirement of rice-wheat and maize-wheat rotations on coarse textured soils amended with farmyard manure. *Fertilizer Research* **17**,153-164.

Maskina, M.S., Yadvinder-Singh and Bijay-Singh. 1988b. Response of wetland rice to fertilizer N in soil amended with cattle, poultry and pig manures. *Biological Wastes* **26**,1-8.

Meena, B.P., Biswas, A.K., Singh, M., Chaudhary, R.S., Singh, A.B., Das, H. and Patra, A.K. 2019. Long-term sustaining crop productivity and soil health in maize–chickpea system through integrated nutrient management practices in Vertisols of Central India. *Field Crops Research* **232,** 62-76

Meng, L., Ding, W. and Cai, Z. 2005. Long-term application of organic manure and nitrogen fertilizer on $N_2O$ emissions, soil quality and crop production in a sandy loam soil. *Soil Biology and Biochemistry* **37**, 2037–2045.

Mishra, M.M. 1992. Enrichment of organic manures with fertilizers. In *Non-traditional Sectors for Fertilizer Use* (H.L.S. Tandon, Ed.), pp. 48-60. FDCO, New Delhi.

Mondal, S., Mallikarjun, M., Ghosh, M., Ghosh, D.C. and Timsina, J. 2016. Influence of nutrient management (INM) on nutrient use efficiency, soil fertility and productivity of hybrid rice. *Archives in Agronomy and Soil Science* **62**,1521–1529.

NAAS. 2008. Sustainable energy for rural India. *NAAS Policy Paper* **41**. National Academy of Agricultural Sciences, New Delhi.

NAAS. 2017. Innovative viable solution to rice residue burning in rice-wheat cropping system through concurrent use of super straw management system-fitted combines and Turbo Happy seeder (Yadvinder-Singh, M.L. Jat, H.S. Sidhu, Punjab Singh and A. Varma, Eds.). *Policy Brief No.* **2,** pp. 1-16. National Academy of Agricultural Sciences, New Delhi.

Nath, D.J., Ozah, B., Baruah, R., Barooah, R.C. and Borah, D.K. 2011. Effect of integrated nutrient management on soil enzymes, microbial biomass carbon and bacterial populations under rice (*Oryza sativa*)–wheat ( *Triticum aestivum* ) sequence. *Indian Journal of Agricultural Sciences* **81**, 1143–1148.

Nayyar, V.K., Takkar, P.N., Bansal, R.L., Singh, S.P., Kaur, N.P. and Sadana, U.S. 1990. *Micronutrients in Soils and Crops of Punjab*. **Research Bulletin.** *Department of Soils*,PAU Ludhiana., Punjab.

Nyamadzawo, G., Wuta, M., Nyamangara, J., Smith, J. L. and Rees, R. M. 2014. Nitrousoxide and methane emissions from cultivated seasonal wetland (dambo) soils with inorganic, organic and integrated nutrient management. *Nutrient Cycling in Agroecosystems* 1**00**, 161–175.

Padmavathiamma, K.P., Li, Y.L. and Kumar, U.R. 2008. An experimental study of vermin-biowaste composting for agricultural soil improvement. *Bioresource Technology* **31**, 31–23.

Rao, D.L.N. 2018. Promoting biofertilizers in IPNS with improved technology and extension in India. In *SAARC Training Manual on Integrated Nutrient Management for Improving Soil Health and Crop Productivity* (P. Dey, S. Srivastava, N.K. Lenka, K.C. Shinogi, A.K. Vishwakarma and A. K. Patra, Eds.), pp. 71-76. ICAR-Indian Institute of Soil Science, Bhopal.

Rawat, A.K., Khatik, S.K., Rao, D.L.N. and Saxena, A K. 2008. Soybean rhizobial inoculants survey in Madhya Pradesh. *All India Network Project on Biofertilizers* **Bulletin**, pp. 1-33. JNKVV, Jabalpur.

Saikia, R., Sharma, S, Thind, H.S. and Yadvinder-Singh. 2010. Tillage and residue management practices affect soil biological indicators in a rice–wheat cropping system in North-Western India. *Soil Use and Management* **36**, 157-172.

Sapkota, T.B., Jat, R.K., Singh, R.G., Jat, M.L., Jat, M.K., Buarnya, D., Kumar, M., Yadvinder-Singh, Saharawat, Y.S. and Gupta, R.K. 2017. Soil organic carbon changes after seven years of conservation agriculture in a rice–wheat system of the Eastern Indo-Gangetic Plains. *Soil Use and Management*. doi: 10.1111/sum.12331.

Sapkota, T.B., Jat, M.L., Aryal, J.P., Jat, R.K. and Chhetri, R. 2015. Climate change adaptation, greenhouse gas mitigation and economic profitability of conservation agriculture: some examples from cereal systems of Indo-Gangetic Plains. *Journal of Integrative Agriculture* **14**, 1524–1533.

Sarkar, D., Baishya, L.K., Meitei, C.B., Naorem, G.C., Thokchom, R.C., Singh, J.,Bhuvaneswari, S., Batabyal, K., Das, R., Padhan, D., et al. 2018. Can sustainability of maize-mustard cropping system be achieved through balanced nutrient management? *Field Crops Research* **225**, 9–21.

Sharma, B., Sarkar, A., Singh, P. and Singh, R.P. 2017. Agricultural utilization of biosolids: a review on potential effects on soil and plant growth. *Waste Management* **64**, 117–132.

Sharma, M.P., Bali, S.V. and Gupta, D.K. 2001. Soil fertility and productivity of rice (*Oryza sativa*)–wheat (*Triticum aestivum*) cropping system in an Inceptisol as influenced by integrated nutrient management. *Indian Journal of Agriculture Sciences* **71**, 82–86.

Sharma, S., Padbhushan, R. and Kumar, U. 2019. Integrated nutrient management in rice–wheat cropping system: an evidence on sustainability in the Indian subcontinent through meta-analysis. *Agronomy***9**, 71; doi:10.3390/agronomy9020071

Sharma, S., Bhattacharya, S. and Garg, A. 2006. Greenhouse gas emission from India: a prospective. *Current Science* **90**, 326–332.

Sidhu, H.S., Singh, M., Yadvinder-Singh, Blackwell, J., Lohan, S.K., Humphreys, E., Jat, M.L., Singh, V. and Singh, S. 2015. Development and evaluation of the Turbo Happy Seeder for sowing wheat into heavy rice residues in NW India. *Field Crops Research* **184**, 201-212.

Singh, G., Jalota, S.K. and Yadvinder-Singh. 2007. Manuring and residue management effects on soil physical properties of a soil under the rice–wheat system in Punjab, India. *Soil and Tillage Research* **94,** 229-238.

Singh, F. and Kumar, R. 2008. Integrated nutrient management in rice-wheat cropping system for sustainable productivity. *Journal of the Indian Society of Soil Science* **56**, 205-208.

Singh, M. and Wanjari, R.H. 2018. Long-term effect of balanced and integrated plant nutrient supply modules on crop productivity and soil health. In *SAARC Training Manual on Integrated Nutrient Management for Improving Soil Health and Crop Productivity* (P. Dey, S. Srivastava, N.K. Lenka, K.C. Shinogi, A.K. Vishwakarma and A. K. Patra, Eds.), pp. 50-59. ICAR-Indian Institute of Soil Science, Bhopal.

Singh, S.K., Kumar, M., Singh, R.P., Bohra, J.S., Srivastava, J.P., Singh, S.P. and Singh, Y.V. 2018. Conjoint application of organic and inorganic sources of nutrients on yield, nutrient uptake and soil fertility under rice (*Oryza sativa*)–wheat (*Triticum aestivum* ) system. *Journal of the Indian Society of Soil Science* **66**, 287-294.

Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A.K. and Kundu, S. 2013. Sustainable management of soils of dryland ecosystems of India for enhancing agronomic productivity and sequestering carbon. *Advances in Agronomy* **121**, 253-329.

Swarup, A. 2002. Lessons from long-term fertilizer experiments in improving fertilizer use efficiency and crop yields. *Fertiliser News* **47(12)**, 59–73.

Tandon, H.L.S. 1997. Organic resources an assessment of potential supplies, their contribution in agricultural productivity, and policy issues for Indian Agricultural from 2000–2025. In *Plant Nutrient Needs, Supply Efficiency and Policy Issues: 2000–2025* (J.S. Kanwar and J.C. Katyal, Eds.), pp. 15–28. National Academy of Agricultural Sciences, New Delhi.

Tesfai, M., Moed, I., Greipsland, I., Huber, T. and van Duivenbooden, N. 2016. Integrated soil and nutrient management practices: adaptation and mitigation to climate change impacts. In *Climate Change and Agricultural Development: Improving Resilience through Climate Smart Agriculture, Agroecology and Conservation* (U.S. Nagothu, ed), pp. 161-184. Routledge Publisher.

Tewatia, R.K. and Chanda, T.K. 2017.Trends in fertilizer nitrogen production and consumption in India. In *The Indian Nitrogen Assessment: Sources of Reactive Nitrogen, Environmental and Climate Effects, Management Options, and Policies*. (Y.P. Abrol, T.K. Adhya, P.A. Aneja, et al., Eds), pp. 45-56. Elsevier, Dordrecht.

Thangarajan, R., Bolan, N.S., Tian, G., Naidu, R. and Kunhikrishnan, A. 2013. Role of organic amendment application on greenhouse gas emission from soil. *Science of Total Environment* **465**, 72–96.

Thind, H.S., Yadvinder-Singh, Bijay-Singh, Varinderpal-Singh, Sharma, S., Vashistha, M. and Singh, G. 2012. Land application of rice husk ash, bagasse ash and coal fly ash: effects on crop productivity and nutrient uptake in rice–wheat system on an alkaline loamy sand. *Field Crops Research* **135**, 137-144.

Thind, H.S., Yadvinder-Singh, Sharma, S., Varinderpal-Singh, Sran, H.S. and Bijay-Singh. 2017. Phosphorus fertilizer potential of bagasse ash and rice husk ash in wheat-rice system on alkaline loamy sand soil. *Journal of Agricultural Science Cambridge* **155**, 245-254.

Thind, H.S, Sharma, S., Yadvinder-Singh and Sidhu, H.S. 2019. Rice-wheat productivity and profitability with residue, tillage and green manure management. *Nutrient Cycling in Agroecosystems.* DOI: org/10.1007/s 10705-018-09967-8

Timsina, J. 2018. Can organic sources of nutrients increase crop yields to meet global food demand? *Agronomy* **8**, 214.

Tirol-Padre, A., Rai, M., Kumar, V., Gathala, M., Sharma, P.C., Sharma, S., Nagar, R.K., Deshwal, S., Singh, L.K., Jat, H.S. and Sharma, D.K. 2016. Quantifying changes to the global warming potential of rice wheat systems with the adoption of conservation agriculture in northwestern India. *Agriculture, Ecosystems and Environment* **219**, 125–137.

Walia, M.K., Walia, S.S. and Dhaliwal, S.S. 2010. The long-term effect of integrated nutrient management soil properties of Typic Ustochrept after 23 cycles of an irrigated rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) system. *Journal of Sustainable Agriculture* **34**, 724-743.

Wu, W. and Ma, B. 2015. Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: a review. *Science of Total Environment* **512–513**, 415–427.

Yadav, R.L., Dwivedi, B.S., Prasad, K., Tomar, O.K., Shurpali, N.J. and Panday, P.S. 2000. Yield trends and changes in soil organic-C and available NPK in a long-term rice-wheat system under integrated use of manures and fertilizers. *Field Crops Research* **68**, 219–246.

Yadvinder-Singh, Gupta, R.K., Singh, G., Singh, J., Sidhu, H.S. and Bijay-Singh. 2009a. Nitrogen and residue management effects on agronomic productivity and nitrogen use efficiency in rice–wheat system in Indian Punjab. *Nutrient Cycling in Agroecosystems* **84**, 141-154.

Yadvinder-Singh, Gupta, R.K. Thind, H.S., Bijay-Singh, Varinderpal-Singh, Singh, G., Singh, J. and Ladha, J.K. 2009b.Poultry litter as a nitrogen and phosphorus source for a rice-wheat system. *Biology and Fertility of Soils* **45**, 701-710.

Yadvinder-Singh, Bijay-Singh, Nayyar, V.K. and Singh, J. 2003a. Integrated plant nutrient supply systems for sustainable rice-wheat rotation.In *Nutrient Management for Sustainable Rice-Wheat Cropping System* (Yadvinder-Singh, Bijay-Singh, V.K. Nayyar and J. Singh, Eds.), pp. 237-252. National Agricultural Technology Project, Indian Council of Agricultural Research, New Delhi and Punjab Agricultural University, Ludhiana.

Yadvinder-Singh, Bijay-Singh and Gupta, R.K. 2003b. Management of organic manures in rice- wheat cropping system. In *Nutrient Management for Sustainable Rice-Wheat Cropping System* (Yadvinder-Singh, Bijay-Singh, V.K. Nayyar and J. Singh, Eds.). pp. 253-271. National Agricultural Technology Project, Indian Council of Agricultural Research, New Delhi and Punjab Agricultural University, Ludhiana.

Yadvinder-Singh, Bijay-Singh, Gupta, R.K., Ladha, J.K.,Bains, J.S. and Singh, J. 2008. Evaluation of press mud cake as a source of nitrogen and phosphorus for rice-wheat cropping system in the Indo-Gangetic Plains of India. *Biology and Fertility of Soils* **44**, 755-762.

Yadvinder-Singh, Bijay-Singh, Ladha, J.K., Khind, C.S., Gupta, R.K., Meelu, O.P. and Pasuquin, E. 2004a. Long-term effects of organic inputs on yield and soil fertility in the rice–wheat rotation. *Soil Science Society of America Journal* **68**, 845-853.

Yadvinder-Singh, Bijay-Singh, Ladha, J.K., Khind, C.S., Khera, T.S., and Bueno, C.S. 2004b. Effects of residue decomposition on productivity and soil fertility in rice–wheat rotation. *Soil Science Society of America Journal* **68**, 854-864.

Yadvinder-Singh, Bijay-Singh, Maskina, M.S. and Meelu, O.P. 1988. Effect of organic manures, crop residues and green manure (*Sesbania aculeata*) on nitrogen and phosphorus transformations in a sandy loam at field capacity and waterlogged conditions. *Biology and Fertility of Soils* **6**, 183-187.

Yadvinder-Singh, Bijay-Singh, Maskina, M.S. and Meelu, O.P. 1995. Response of wetland rice to nitrogen from cattle manure and urea in a rice-wheat rotation. *Tropical Agriculture* (*Trinidad*) **72**, 91-96.

Yadvinder-Singh, Bijay-Singh and Thind, H.S. (Editors). 2010a. *Green Manure Approaches to Crop Production and Sustainable Agriculture,* pp. 1-130. Angkor Publishers Pvt. Ltd, Noida.

Yadvinder-Singh, Bijay-Singh and Timsina, J. 2005. Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. *Advances in Agronomy* **85**, 269-407.

Yadvinder-Singh, Khind, C.S. and Bijay-Singh. 1991. Efficient management of leguminous green manures in wetland rice. *Advances in Agronomy* **45**, 135-189.

Yadvinder-Singh, Ladha, J.K., Bijay-Singh and Khind, C.S. 1994. Management of nutrient yields in green manure systems. In *Green Manure Production Systems for Asian Rice Fields* (J.K. Ladha and D.P. Garrity, Eds.), pp. 125-154. IRRI, Manila, Philippines.

Yadvinder-Singh, Gupta, R.K. Singh, J., Singh, G., Gobinder-Singh and Ladha, J.K. 2010b. Placement effects on rice residue decomposition and nutrient dynamics on two soil types during wheat cropping in rice–wheat system in North-Western India. *Nutrient Cycling in Agroecosystems* **88**, 471-480.

Yadvinder-Singh and Sidhu, H.S. 2014. Management of cereal crop residues for sustainable rice-wheat production system in the Indo Gangetic Plains of India. *Proceedings of the Indian National Science Academy* **80**, 95-114.

Yadvinder-Singh, Sidhu, H.S., Jat, M.L. and Gupta, N. 2017. Can recycling of potassium from crops and other organic residues be integrated into potassium rate recommendations? *Indian Journal of Fertilisers* **13(11)**, 60-66.

Yadvinder-Singh, Thind, H.S. and Sidhu, H.S. 2014. Management options for rice residues for sustainable productivity of rice-wheat cropping system *Journal of Research Punjab agricultural University* **51**, 239-245.

Yuan, J., Sha, Z., Hassani, D., Zhao, Z. and Cao, L. 2017. Assessing environmental impacts of organic and inorganic fertilizer on daily and seasonal greenhouse gases effluxes in rice field. *Atmospheric Environment* **155**, 119–128.

Zhang, F., Cui, Z., Chen, X., Ju, X., Shen, J., Chen, Q., Liu, X., Zhang, W., Mi, G., Fan, M. and Jiang, R. 2012. Integrated nutrient management for food security and environmental quality in China. *Advances in Agronomy* **116**,1–40. ■

# Integrated Nutrient Management Strategies for Rainfed Agro-ecosystems of India

Ch. Srinivasa Rao[1], C. Subha Lakshmi[1], Sumanta Kundu[2], G. Ranjith Kumar[1], R. Manasa[1] and S. Rakesh[1]

[1] ICAR – National Academy of Agricultural Research Management, Rajendranagar, Hyderabad
[2] ICAR-Central Research Institute for Dryland Agriculture, Hyderabad, Telangana

Received : 04/03/2020 Accepted : 11/03/2020

## Abstract

Nutrient management is a major factor governing soil health status and crop productivity as most of the Indian soils are multi-nutrient deficient. The intensity of nutrient deficiencies in Indian soils under diverse ecosystems is increasing. Benefits accruing from the efficient nutrient management systems include reduced cost of cultivation, and improved factor productivity of nutrients and environmental sustainability. Rainfed agro-ecosystems hold pivotal importance as they contribute a major share to the food basket of the nation. These agro-ecosystems need to be developed with efficient management practices as they hold the potential to meet the increasing demands of burgeoning population. Crop production in these regions is constrained by various factors *viz*., erratic rainfall, poor soil conditions, resource poor and marginal farmers, poor infrastructure and market linkages, etc. Integrated nutrient management (INM) system has been promoted in rainfed ecosystems as it takes the advantage of locally available organic resources along with fertilizer nutrients towards sustainability of rainfed systems in India. The subject of INM will continue to draw an attention of all agriculture scientists working on natural resource management, KVKs, line departments, policy makers in India as it has multi-dimensional advantages.

**Key words**: Fertilizers, integrated nutrient management, rainfed agro-ecosystems, organic sources, soil health enhancement, cost of cultivation, crop productivity.

## Introduction

Rainfed agro-ecosystem occupies prominent place in Indian agriculture covering nearly 66% of the net cultivated area supporting 40% of the country's population and contributing 44% to the national food basket. It supports cultivation of 91% coarse cereals, 90% pulses, 85% oilseeds, 65% cotton and 55% rice and two thirds of India's livestock population (Srinivasarao et al., 2014b, 2014c, 2015). Geographically, rainfed ecosystems of India include the north-western desert regions of Rajasthan, the plateau region of Central India; the alluvial plains of Ganga Yamuna river basin; the central highlands of Gujarat, Maharashtra and Madhya Pradesh; the rain shadow region of Deccan Maharashtra; the Deccan Plateau of Andhra Pradesh and the Tamil Nadu highlands (**Figure 1)**. Farming systems are quite complex with varied variety of crops and cropping systems, agroforestry and livestock production. The dominant soil orders in rainfed production system of India are Inceptisols followed by Entisols, Alfisols, Vertisols, mixed soils, Aridisols, Mollisols and Oxisols. Major soil groups and their moisture storage capacities in rain dependent regions are presented in **Table 1**. Monocropping system comprising a long fallow period (October to June) is a rule rather than an exception. In semi-arid regions, major portions of Vertisols are left

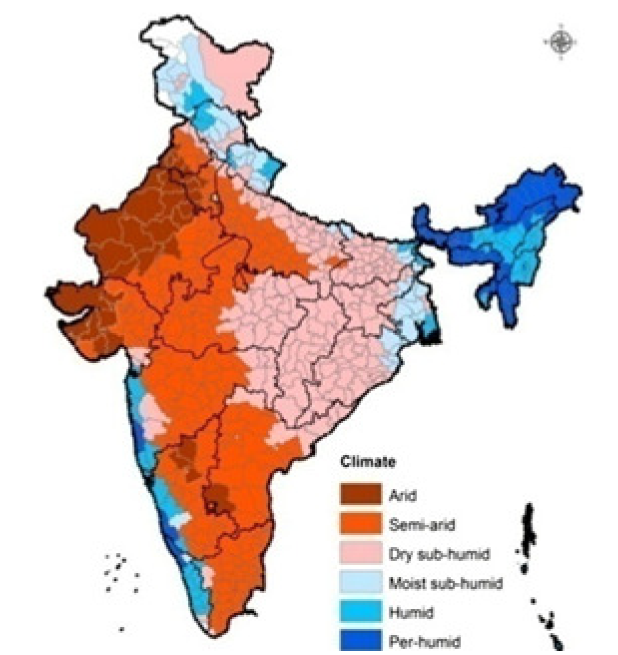



**Figure 1. Predominant rainfed dryland regions in India (Arid, Semi-Arid, Dry sub-humid) (Source: Srinivasarao et al., 2015)**

fallow which could be attributed to water logging and drainage problems. Cultivation of crops is taken up prior to rainy season depending on the moisture stored in the soil profile. Sorghum, chickpea and

chsrao_director@naarm.org.in ; cherukumalli2011@gmail.com

**Table 1. Major soil groups and their moisture storage capacities in rain-dependent areas of India (Srinivasarao et al., 2017a)**

| Broad soil group | Subgroup (based on soil depth) | Moisture storage capacity (mm) |
|---|---|---|
| Vertisols and related soils | Shallow to medium (up to 45 cm)<br>Medium to deep (45-90 cm)<br>Deep (>90 cm) | 135-145/45 cm<br>145 - 270/90 cm<br>300/m |
| Alfisols and related soils | Shallow to medium (up to 45 cm)<br>Deep (>90 cm) | 40 - 70/45 cm (sandy loam)<br>70-100/45 cm (loam)<br>180-200/90 cm |
| Aridisols | Medium to deep (up to 90 cm) | 80 - 90/90 cm |
| Inceptisols | Deep | 90 - 100/m (loamy sand)<br>110 - 140/m (sandy loam)<br>140 - 180/m (sandy loam) |
| Entisols | Deep | 110 - 140/m (sandy loam)<br>140 -180/m (loam) |

safflower are majorly grown either solely or as intercrop in Central India. In the north central plains mostly, wheat is cultivated as a monocrop but is sometimes intercropped with chickpea. The cultivation of cotton is taken up in most portions of Vertisols. In Alfisols, rainy season cropping is common; in the events of receiving good rainfall double cropping is also practiced.

**Production Constraints of Rainfed Agro-ecosystems**

Rainfed agro-ecosystems encounter several constraints which limit productivity enhancement in these regions. The farmers in rainfed drylands are majorly small holders. Smallholder farming systems are perceived to share certain characteristics which distinguish them from large-scale, profit-driven enterprises which include limited access to land, financial capital and inputs, high levels of climate vulnerability, and low market participation. Rainfall is a major factor determining crop production and variability in rainfall in the last two decades has been a serious challenge for sustainability of rainfed systems in India which could be attributed to increased frequency of drought events (Early-season, mid-season and terminal droughts) (Srinivasarao et al., 2020b). Therefore, agriculture investments at farm level are risky in terms of enhanced nutrient application critically required for higher crop yields. Drought not only affects the food production at farm level, but also affects the overall food security and the national economy (Srinivasarao et al., 2017e). High rate of oxidation and accelerated erosion are major factors responsible for degradation and low soil organic matter in tropical soils. In the tropics, stabilizing or enhancing soil organic matter is crucial to curtailing risks of soil degradation and ensuring sustainability of agriculture. Organic matter plays major role in preserving soil's physical, chemical and biological integrity apart from supplementing nutrients. Large area under dryland agriculture is in various stages of physical, chemical and biological degradation which could be majorly attributed to poor soil management practices. Hence combating land degradation and enhancing productivity of rainfed drylands is a major challenge which needs to be addressed in order to conserve the overall food production of the country. Fertilizer consumption in predominant rainfed states (2017-18; 2018-19) is presented in **Figure 2**. It shows that fertilizer application even in rainfed ecosystems in the recent past has been at higher levels contrary to the general opinion that rainfed crops receive lesser fertilizers. Along with this level of fertilizer inputs, adapting all locally available organic resources is the most important strategy for reducing yield gaps, improving nutrient use efficiency and lesser greenhouse gas (GHG) emissions per each tonne (t) of food produced in rainfed systems (Srinivasarao et al., 2020a).

**Strategies for Improved Soil Health in Rainfed Ecosystems**

Rainfed ecosystems are highly prone to vagaries of climate and among the prominent impacts encountered, soil health decline assumes major concern. The soil organic matter plays significant role in maintaining soil health through its effects on microbial community, soil physical structure, nutrient cycling and soil water storage. Soil organic matter maintenance in an agro-ecosystem majorly depends on the balance between biomass C inputs, their quality and C loss from decomposition, leaching and erosion. Soil health enhancement holds the potential to elevate productivity levels which would eventually contribute to higher profits and livelihood security of small and marginal farmers. Hence, development and adoption of strategies towards improving soil health is of paramount importance. Site-specific nutrient management (SSNM) is an approach which optimizes the supply of soil nutrients

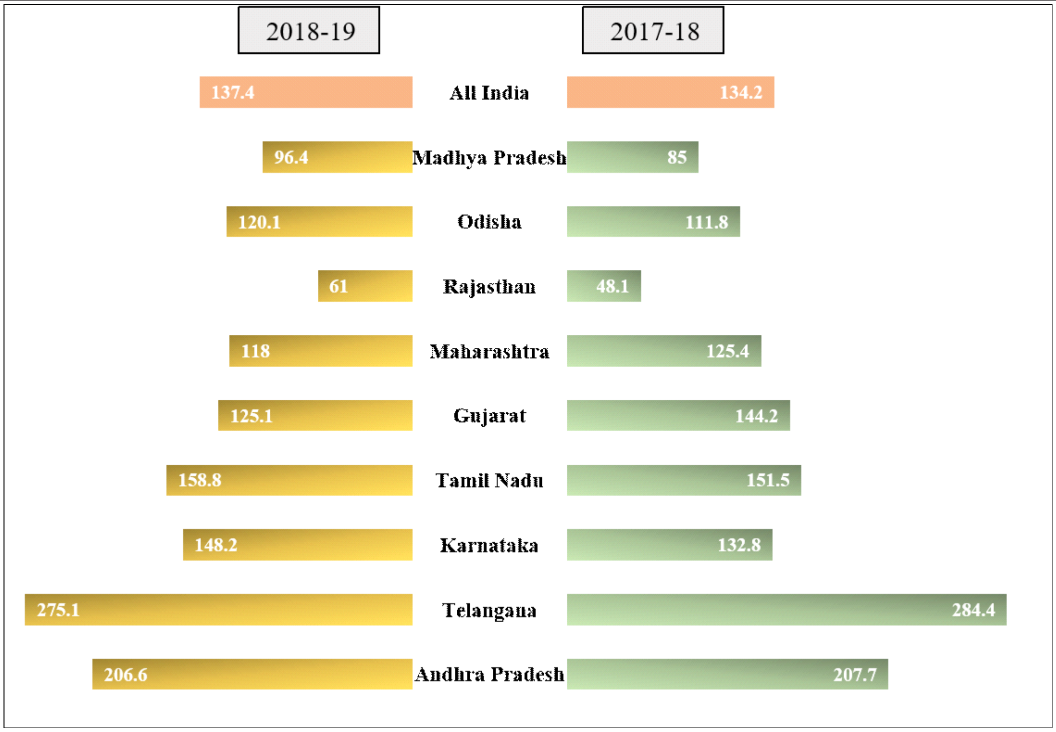



**Figure 2. Fertilizer consumption by predominant rainfed states of India during 2017-18 and 2018-19 (Source: FAI, 2019)**

over space and time to match crop requirements which aids in enhancing crop productivity, fertilizer use efficiency and climate change mitigation. Balanced fertilization which envisages the application of plant nutrients in the right proportion through appropriate methods at the time suited for a specific crop and agro-climatic situation is another strategy which would lead to soil health building and enhancing nutrient use efficiency (Srinivasarao et al., 2008). The indiscriminate application of fertilizers leads to soil sickness and reduced food grain production. The integrated nutrient management (INM)/integrated plant nutrient system (IPNS) envisaging maintenance or adjustment of soil fertility and of plant nutrient supply to an optimum level for sustaining the desired crop productivity through optimization of benefits from all possible resources of plant nutrient in an integrated manner could prove to be the most effectual and viable option towards enhancing soil health in rainfed regions (Srinivasarao et al., 2017a).

## Integrated Nutrient Management Strategies

### *Soil Fertility Assessment and Crop Nutrient Recommendations*

The assessment of soil fertility helps in getting precise information about the nutrient supplying capacity of the soil and the amount of fertilizers to be applied to meet the requirement of a crop. Fertilizer recommendations based on qualitative/semi-qualitative approaches or methods do not give expected yield responses. The targeted yield approach of Soil Test Crop Response (STCR) Project of ICAR is to develop relationship between crop yield on one hand and soil test estimates and fertilizer inputs on the other has been utilized in STCR studies. The Soil Health Card (SHC) Scheme was initiated by Government of India in 2015 to provide soil test-based fertilizer recommendations to all the farmers in the country. As per the scheme, the soil health card will be provided to farmers by analyzing the farmer's soil sample in authenticated soil laboratory. Based on the soil test results, the soil health card will give information to farmers on nutrient status of the soil. It will also give the recommendation on appropriate dosage and kind of nutrients to be applied to improve the soil fertility. For every 2 years, the soil will be analyzed and soil health card will be issued to all the farmers in the country so that nutrient deficiencies are identified and amendments applied. This soil health card scheme will promote balanced and integrated use of plant nutrients; consequently, soil health will be improved for sustainable soil productivity. A good progress has been achieved by SHC Scheme in India by distributing 10.48 crores of SHCs by December 2018 (Srinivasarao et al., 2019).

### *Development of Location/Site Specific Nutrient Management Strategies*

Soil testing procedure to check the nutrient requirement is rarely adopted by farmers. The requirement of N, P and K varies from crop to crop and from one type of soil to another type, and the norm for N, P and K ratio is bound to be different for different regions representing different cropping patterns, soil types, and their nutrient status at a given point of time. Though fertilizers contribute to enhance productivity levels, their indiscriminate use contributes to soil health deterioration and environmental concerns. Development and adoption of SSNM strategies would help in reducing the cost of inputs, increasing productivity, improving nutrient use efficiency and minimizing the depletion of soil fertility. SSNM implementation in eight clusters of Andhra Pradesh under National Agriculture Innovation Project (NAIP) by testing individual fields for nutrient deficiencies and correcting them by applying that particular nutrient depending upon crop requirements and found to give 25% higher yield in major rainfed crops compared to farmers' practices (Srinivasarao et al., 2010, 2011a). Farmer field specific fertilizer recommendations for green gram in multi-nutrient deficient soil in Dupahad cluster of Nalgonda district are presented in **Table 2**. With balanced nutrient application based on soil test values, the productivity enhancement in rainfed chickpea in black soil regions in Sitagondi cluster in Adilabad district ranged from 5 to 25% (**Figure 3**). This was amply reflected in field trials where balanced nutrient application showed significant yield increase in rainfed cotton-pigeonpea intercropping (**Figure 4**).

**Table 2. Farmer field specific fertilizer recommendations for green gram based on soil test value for Dupahad cluster of Nalgonda district, Telangana**

| Farmer No. | Village | Fertilizer requirement (kg ha$^{-1}$) | | | | |
|---|---|---|---|---|---|---|
| | | Urea | DAP | MOP | Gypsum | $ZnSO_4$ |
| 1 | Jalmakunta Tanda | 50 | | 90 | | |
| 2 | New Banjarahills | 50 | | 65 | 150 | 50 |
| 3 | Jalmakunta Tanda | 50 | | | | 25 |
| 4 | Jalmakunta Tanda | | 125 | 90 | 150 | 50 |
| 5 | Jalmakunta Tanda | 50 | | | | 50 |
| 6 | New Banjarahills | | 125 | 65 | 150 | 50 |
| 7 | Peddagarakunta Tanda | 50 | | 90 | 150 | 50 |
| 8 | Jalmakunta Tanda | | 125 | | | 50 |
| 9 | Jalmakunta Tanda | | 125 | 90 | | 50 |
| 10 | Jalmakunta Tanda | 50 | | 65 | | 50 |
| 11 | Jalmakunta Tanda | | 125 | 90 | 150 | 50 |
| 12 | Jalmakunta Tanda | | 125 | 65 | 150 | 50 |
| 13 | Jalmakunta Tanda | | 125 | 65 | 150 | 50 |
| 14 | Jalmakunta Tanda | | 125 | 65 | | 25 |
| 15 | Jalmakunta Tanda | 50 | | 65 | | 50 |
| 16 | Jalmakunta Tanda | 50 | | 90 | | 50 |
| 17 | Peddagarakunta Tanda | 50 | | 65 | | 25 |

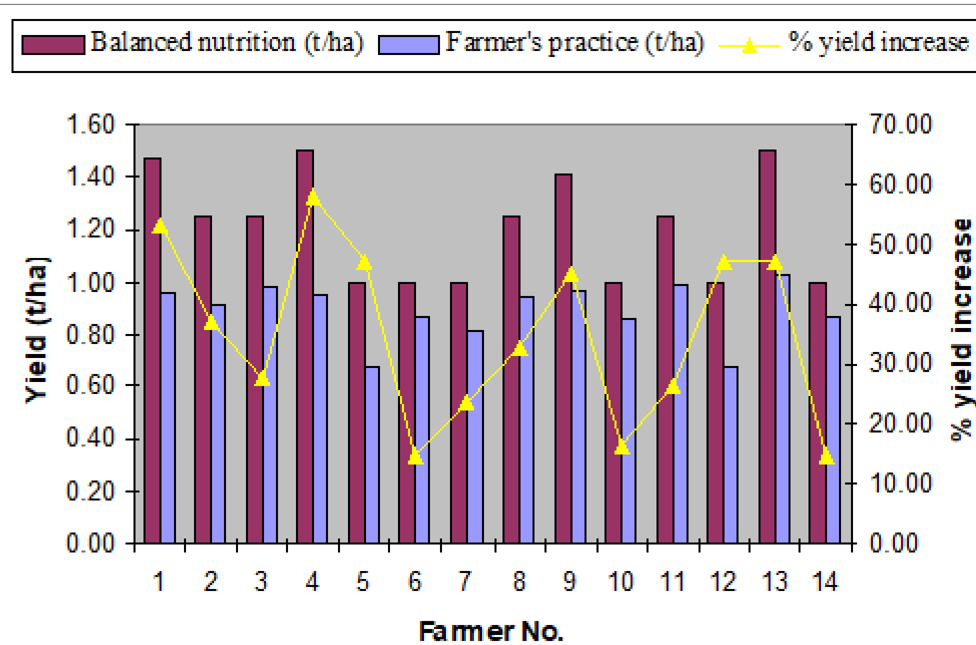



**Figure 3. Impact of balanced fertilization in chickpea (var. JG-11) yield in some selected farmer's field of Seethagondi cluster of Adilabad district, Telangana**


**Figure 4. Impact of balanced nutrient application in rainfed cotton-pigeon pea intercropping on black soils of Southern India**

### *Assessing Organic Resource Availability*

As soils of Dupahad cluster in Nalgonda district of Telangana are deficient in N, P, K and Zn, the recommendations given in **Table 2** have been developed based on soil testing (Srinivasarao et al., 2010). The question is to what extent these nutrient recommendations are substituted by available organic resources in the farm or household or village level which needs to be assessed. Various sources of soil organic amendments are available to farmers as on-farm materials *viz*., crop residue, weed biomass, green manuring, compost, animal bedding material, seri waste, etc. and also off-farm waste, municipal biosolid, poultry manure, coir pith, biochar, tank silt, etc. (**Figure 5**). Assessing the annual potential of organic resources in the country available for use would serve as a reckoner for evaluating the requirement of fertilizers to meet the food grain requirements. Studies reported that 300 million tonnes (Mt) of alternative sources of soil organic amendments are available in the country. Potential availability of different organic sources in India is presented in **Table 3**. Implementing INM by adding both fertilizers and organic manures, recorded substantial yield improvements in *rabi* green gram under farmers' fields (**Figure 6**).

### *Recycling Crop Residues*

In areas, where mechanical harvesting is practiced, a large quantity of crop residues is left in the field, which can be recycled for nutrient supply. Crop residues are good sources of plant nutrients and are important components for the stability of agricultural ecosystems. About 500 Mt of crop residues are produced in India alone (MNRE, 2009). Huge crop residue is field- burned in rainfed drylands including rice, cotton, pigeon pea, castor, chillies, turmeric and other crops besides huge amounts of vegetable and fruit biomass is not being recycled towards nutrient supply systems. Any amount of organic manure addition to fields adds considerable amounts of plant nutrients besides enriching soil carbon stocks. About 25% of nitrogen (N) and phosphorus (P), 50% of sulphur (S), and 75% of potassium (K) uptake by cereal crops are retained in crop residues, making them valuable nutrient sources (Srinivasarao et al., 2017b). Crop residue contributes to soil organic matter and increases nutrient, water retention, microbial and macro-invertebrate activity. Crop residues of rainfed crops such as cotton, castor, pigeon pea, maize, etc., were chopped and left on the surface of soil to act as a mulch-cum-manure. Soil organic carbon (SOC) improvement in farmer's fields registered with

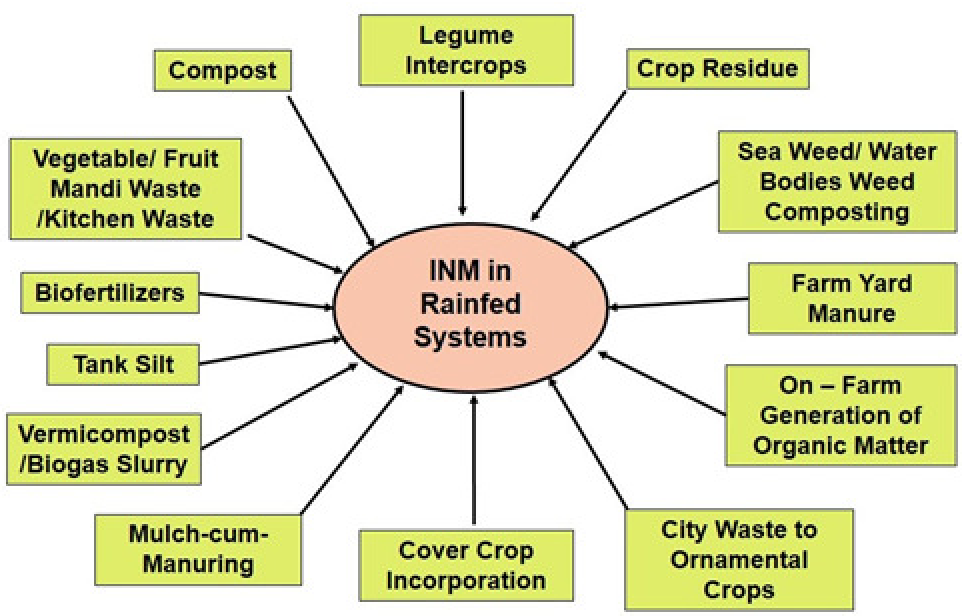



**Figure 5. Potential sources of organics along with fertilizers in rainfed INM strategies in India**

**Table 3 Potential availability of different organic sources**

| Organic sources | Total availability $yr^{-1}$ | Reference |
|---|---|---|
| Crop residues | 500 – 550 Mt | NAAS (2012) |
| Municipal biosolid | 48 Mt | Pappu et al. (2007) |
| Rice husk | 20 Mt | Sengupta (2002) |
| Sugarcane bagasse | 90 Mt | Sengupta (2002) |
| Groundnut shell | 11 Mt | Sengupta (2002) |
| Sugarcane pressmud | 9.0 Mt | Chanakya et al. (2006) |
| Poultry manure | 6.25 -8 Mt | THE HINDU (2009) |
| Coir pith | 7.5 Mt | Vijaya et al. (2008) |
| Food/fruit processing industries | 4.5 Mt | Chanakya et al. (2006) |
| Seri waste | 5,000 t | Gunathilagaraj and Ravignanam (1996) |
| Willow dust | 30,000 t | Chanakya et al. (2006) |
| Green manuring crop area | About 7 Mha | FAO (2005) |

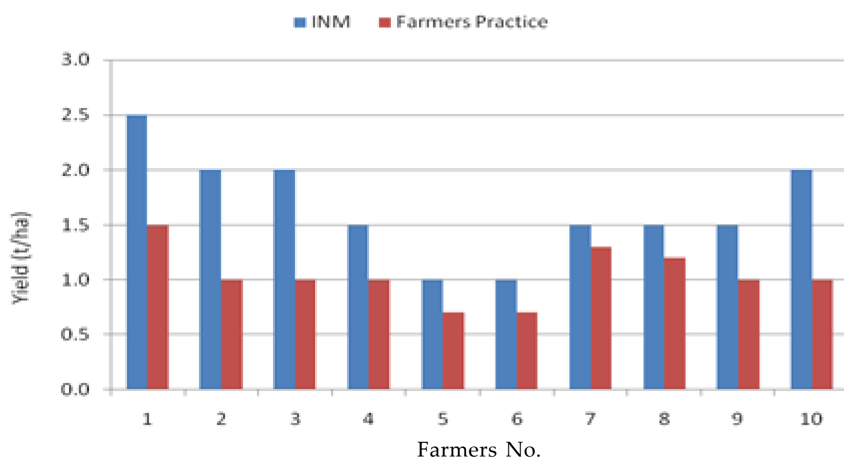



**Figure 6. Impact of INM in *rabi* green gram yield in some selected farmers' fields**

continuous carbon management practices, resulted in increased available soil moisture retention by 2-3% in the soil. Thus, improved SOC mediated in higher water retention (Srinivasarao et al., 2013e). The surface spreading of weed residues also helps in improving SOC and yield in rainfed agroecology (Thiyageshwari et al., 2018). Biomass of weeds viz. *Parthenium hysterophorus*, *Eichhornia crassipes*, *Trianthema portulacastrum*, *Ipomoea* sp., *Calotropis gigantea*, and *Cassia fistula* can also be used as a source of C and nutrients for enhancing different soil properties as well as the overall soil health and important soil functions.

The conversion of crop residues into biochar through the process of pyrolysis that are burnt otherwise could be regarded as a feasible option to enhance carbon sequestration, soil nutrient status and crop productivity (Srinivasarao et al., 2013a; Venkatesh et al., 2018). Highest grain yield (1685 kg $ha^{-1}$) of pigeon pea was recorded with alternate year application of cotton stalk biochar @ 3 t $ha^{-1}$ supplemented with NPK. Converting farm residue into biochar instead of surface burning and addition of biochar along with fertilizer nutrients showed yield improvements of several rainfed crops besides mitigation of mid-season droughts with enhanced water retention by biochar added to the soil (**Figure** 7). Recycling of legume residues as mulch-cum-

**Figure 7. Crop residue recycling in rainfed systems as part of INM is essential for enhanced productivity**

**Figure 8. Recycling legume biomass as mulch cum manure improves crop productivity and soil fertility**

manure contributes to improve crop productivity and soil fertility (**Figure 8**).

*Vegetable Wastes and Market Wastes*

Vegetable crops generate a large amount of crop residues after harvesting of economic part. These potentially nutritious residues are soft, succulent and easily decomposable and instead of disposing or dumping in landfills, these can be used as source of organic residues for utilizing the embedded nutrients through compost production. In developing countries, large quantities of market wastes are produced which poses serious disposal problems, environmental pollution and possible health risks. Composting could be regarded as a good strategy through which solid wastes could be converted into useful product aiding in improvement of soil properties (Pratibha et al., 2011).

*On-farm Generation of Organic Matter*

In rainfed agro-ecosystems, there lies an option of on-farm generation of organic matter. On farm generation of organic matter could help in meeting a part of the nutrient requirement of crop and also meet the demands towards enhancing soil quality. As these components aiding in soil organic matter enhancement are available on farm, the cost incurred on fertilizers could be reduced which ultimately would enhance net profits of farmers. The various on-farm components which would contribute to generation of organic matter are presented in **Figure 9**. Introduction of food legumes as intercrops is common practice in rainfed ecosystems in India which contributes to soil fertility and risk reduction during monsoon-deficient years (**Figure 10**)

Adoption of integrated farming systems involving different components *viz*. crop, livestock, poultry, fisheries, etc., could be regarded as a powerful tool and holds the key for ensuring income, employment, livelihood and nutritional security for small and marginal farmers residing in rain-dependent regions. Farmyard manure (FYM), poultry manure (PM), etc., produced on-farm could serve as source of nutrients to augment crop growth and yield as well as contribute to soil health enrichment (Srinivasarao et al., 2014a, 2016, 2018). Green manuring/green leaf manuring is one of the important strategies that improves soil organic carbon, adds soil nutrients, improves soil biological health, and enhances soil moisture storage as a consequence of which the crops

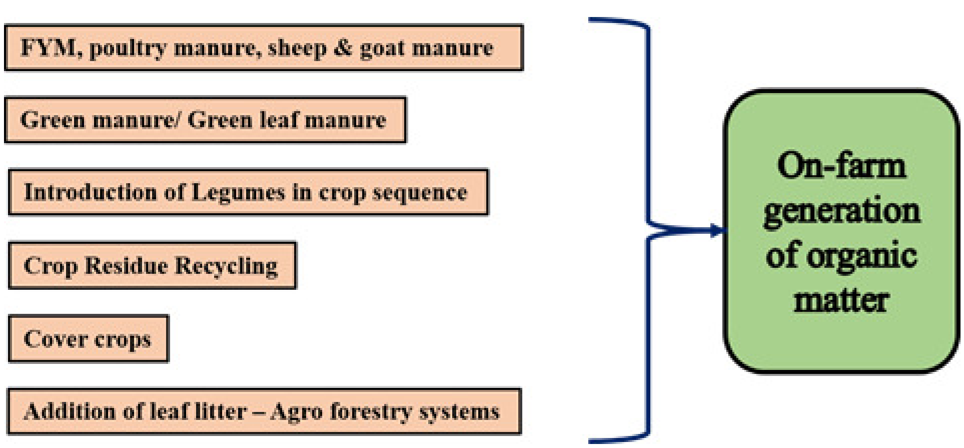
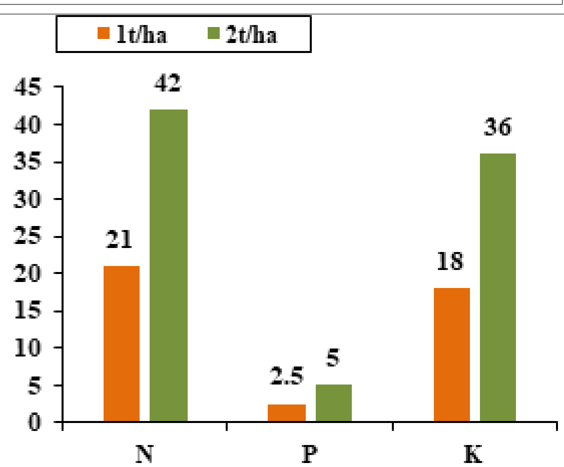



**Figure 9. Strategies contributing towards on-farm generation of organic manures (Srinivasarao et al., 2011b; 2013c)**

**Figure 10. Cotton–green gram and soybean-pigeon pea intercropping system in rainfed Vertisol regions of Central and Western India (Srinivasarao et al. 2012a; Srinivasarao and Gopinath, 2016)**

**Figure 11. On-farm generation of gliricidia green leaf manure on farm bunds**

can cope with intermittent droughts. Green leaf manuring with gliricidia aided in supplementing both macro and micronutrients **(Figures 11 and 12)**. Growing short duration legume crops as cover crops and their incorporation into soil at flowering stage would add organic matter to soil, contribute to nutrient cycling and protect the soil (**Figure 13**). Horse gram incorporation in rainfed sorghum-sunflower and sunflower-sorghum rotations during rainy season demonstrated the restoration of degraded soils and improved crop yields in Rangareddy district indicating that off-season rainfall in semi-arid regions, where a single rainy season crop is grown, can be used to produce up to 3.75 t ha$^{-1}$ of legume biomass



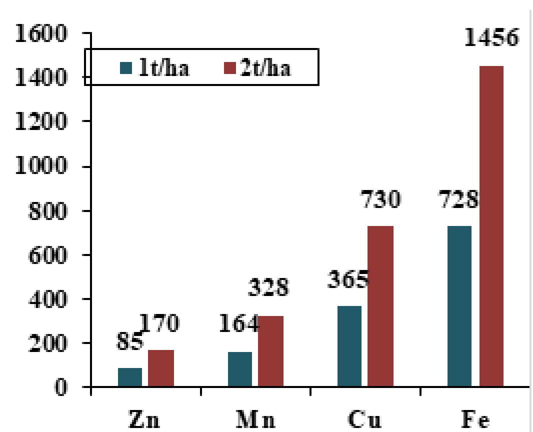




**Figure 12. Macro and micronutrient addition through gliricidia green leaf manuring at different levels of manuring (Srinivasarao et al., 2011a, b)**

**Figure 13. Legume cover crop biomass incorporation with off-season rainfall and green manure incorporation generated on-farm in rainfed systems (Srinivasarao et al., 2017c, d)**


**Figure 14. Legume relay cropping improves soil quality and reduces the fertilizer application rates in rainfed rice system (Srinivasarao et al. 2003)**

(fresh weight) annually without competing with the main crop (Venkateshwarlu et al., 2007).

Introduction of legumes into crop sequences contributes multiple benefits. They fix the atmospheric nitrogen, release in the soil high-quality organic matter and facilitate soil nutrients' circulation and water retention minimizing the amount of fertilizer applications (**Figure 14**). In rainfed landscapes, adoption of agroforestry could be regarded as a potential strategy to restore soil organic matter and enhance carbon sequestration. The tree component contributes to improve soil quality through nutrient cycling by mining of deeper layers, litter fall and root turnover (Ramesh et al., 2019; Srinivasarao and Gopinath, 2016).

Following conservation agriculture (CA) practices and balanced fertilization in *kharif* crop (maize) and utilizing residual moisture and offseason rainfall (around 70 mm during November-December), it is possible to harvest 720 kg of horse gram in *rabi* season in light textured degraded Alfisols of Southern India. Thus, monocropped areas of rainfed Alfisols can be converted into double cropping with CA practices, particularly when terminal rains are good in the *kharif* season. The advantages of this technology include improvement in cropping intensity, longer period of soil cover in a year, reduced soil erosion and enhanced soil fertility (**Figure 15**) under rainfed dryland regions of Southern India (Srinivasarao et al. 2015; Pratibha et al., 2015, 2016; Prasad et al., 2016; Kundu et al., 2013; Kumar et al., 2011; Indoria et al., 2017, 2018).

### *Composting*

Composting is a method by which organic waste is transformed to stable humic substances through biological processes. Organic matter in the compost aids in improving soil structure and water holding capacity contributing to enhanced nutrient holding capacity. Composting of farm level available organic resources needs to be encouraged particularly in the regions where crop residue of different rainfed crops is being field-burned such as cotton, pigeon pea, rainfed rice, vegetable waste, flower waste to substitute fertilizer requirements in rainfed ecosystems of India (Sharma et al. 2018; Satisha et al. 2016; Ramachandrappa et al. 2016, 2017; Srinivasarao et al. 2011b) (**Figure 16**). Mean nutrient content of organic sources is presented in **Table 4**.

### *Vermicomposting*

Vermicomposting is an effective process for effectual and quick recycling of organic waste to the soil; it is an eco-friendly process of converting organic waste into nutrient-rich product. The easy availability of raw materials for the preparation of vermicompost *viz*. crop residue, weeds, tree leaves biomass, cow dung, fruit and vegetable waste, etc., in different regions of India makes it a feasible option

**Figure 15. Horse gram crop on residual moisture in maize-horsegram system in rainfed dryland conditions of Southern India (Srinivasarao et al. 2015)**

**Table 4. Mean nutrient content of composted organic sources**

| Organic sources | Organic carbon (%) | Total N (%) | Total P (%) | Total K (%) | C : N ratio |
|---|---|---|---|---|---|
| Paddy straw – based poultry waste compost | 23.05 | 1.89 | 1.83 | 1.34 | 12.2 |
| Coir pith (in deep litter system) | 30.03 | 2.13 | 2.40 | 2.03 | 14.1 |
| Paper mill compost | 25.46 | 1.34 | 0.58 | 1.12 | 19.0 |
| Press mud compost | 33.17 | 3.10 | 1.95 | 3.50 | 10.7 |
| Sugarcane trash compost | 28.6 | 0.50 | 0.20 | 1.10 | 56.2 |
| Castor cake compost | 23.0 | 3.48 | 1.24 | 0.84 | 10.8 |
| Biocompost | 16.0 | 1.10 | 0.70 | 0.64 | 17.4 |
| Vermicompost | 23.1 | 1.59 | 1.63 | 1.07 | 15.7 |
| Poultry waste compost using coir pith | 30.0 | 2.13 | 2.40 | 2.03 | 14:1 |
| Wheat straw compost | 35.33 | 0.92 | 0.60 | 1.11 | 38.4 |
| Mustard straw compost | 33.59 | 1.04 | 0.54 | 1.35 | 33.6 |

**Figure 16. Preparation of composting at field level in rainfed conditions**

(Srinivasarao et al., 2013d, f) (**Figure 17**). Composition-wise, vermicompost contains a high level of plant growth hormones, enzymes and supplies; it holds the nutrients for longer periods and improves soil microbial population and other soil properties. The application of rice straw, sugarcane trash and water hyacinth vermicompost enhanced the yield of rice by 17.17, 30.29 and 47.31%, respectively in comparison to 100% RDF (Sudhakar, 2000).

### *Recycling of Eroded Soil*

Intermittent occurrences of rainfall with high intensity during the monsoons and the consequent heavy surface run-off cause erosion of valuable nutrient rich top soil from the surrounding agricultural lands. The soil is carried along with the running water and is deposited as silt in the tanks. Accumulation of silt in the tank bed adversely affects

**Figure 17. Community-based vermicomposting units in Andhra Pradesh and Telangana**

**Figure 18. Impact of tank silt (recycling of eroded soil) on soil colour and castor productivity under rainfed conditions**

its storage capacity and also the percolation potential by forming silt pan. Periodic desilting is traditionally practiced and recommended. Being a rich source of nutrients, application of tank silt to soils aids in enhancing crop productivity (**Figure 18**) and reduces the amount of synthetic fertilizer application. Tank silt application coupled with ridge and furrow method of *in-situ* moisture conservation resulted in additional yield of 500 kg $ha^{-1}$ in *rabi* sorghum in scarcity zone of Maharashtra (Srinivasarao et al., 2015). Under Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), ample opportunity provided to recycle fertile silt-clay to the soil will boost the soil organic carbon, fertility and crop productivity in rainfed systems.

### *Biofertilizers*

Biofertilizers contain living microorganisms which, when applied to seeds, plant surfaces, or soil, colonize the rhizosphere or the interior of the plant and promote growth by increasing the supply or availability of primary nutrients to the host plant. Most of food legumes (pulses) such as chickpea, pigeon pea, mung bean, *urdbean*, lentil, etc., are grown in rainfed drylands. In such lands, residual effects of fixed nitrogen are obtained. However, for improving efficiency of biofertilizers, addition of organic manures is essential. The efficient use of biofertilizer in rainfed agroecology could be a viable approach to increase crop yield and improve soil health. The effect of added biofertilizers could be enhanced when used in conjunction with chemical fertilizers and different organic sources. Based on INM trials conducted in mulberry in rainfed agroecology it was found that the conjunctive use of poultry manure with *Azotobacter* helped in reducing the doses of inorganic fertilizers, which in-turn had a significant effect on plant growth and the quality of mulberry plants (Chakraborty and Kundu, 2015). Integrated application of 50% N through gliricidia + 50 % N through inorganics + biofertilizers + 100% P + 25 kg K $ha^{-1}$ resulted in improvement of soil fertility, nutrient uptake and yield of cotton grown in Vertisols under rainfed conditions (Khambalkar et al., 2017). The Network Project on Soil Biodiversity – Biofertilizers has developed effective strains of biofertilizers utilizing various strains of bacteria, algae and fungi as microbial inoculants to fix nitrogen specific to different crops and soil types. Liquid biofertilizer with higher shelf life has also been developed in recent past (Srinivasarao and Manjunath, 2017).

## Why INM is a Must in Rainfed Agroecosystems?

In fact, the virtues of INM are not limited to rainfed systems, these are for entire agriculture ecosystems. However, rainfed dryland soils are impoverished due to poor soil organic carbon, limited biomass recycled naturally in the form of roots or leaf litter (as biomass production is low), and soil fertility decline is rapid not only in terms of major nutrients but also secondary and micronutrients. Based on rainfed long-term experiments, the Mg and other secondary nutrient balance was found to be negative (Srinivasarao et al., 2013b, e; Nataraj et al., 2016; Jawahar et al., 2016; Ali et al., 2002). Therefore, addition of organics along with major nutrient sources of fertilizers is essential for maintaining soil health and sustainability of the systems. Thus, INM strategy provides a holistic nutrient supply management in agriculture. The critical contributions of INM in particularly rainfed ecologies are in the form of a) soil health, b) crop productivity, c) input cost reduction, d) environmental sustainability, and e) improved crop or food quality (**Figure 19**).

### *Soil Health Maintenance*

Rainfed regions are highly prone to land degradation which could be attributed to poor soil health conditions. Soil health is the capacity of a soil to function within ecosystem boundaries to sustain

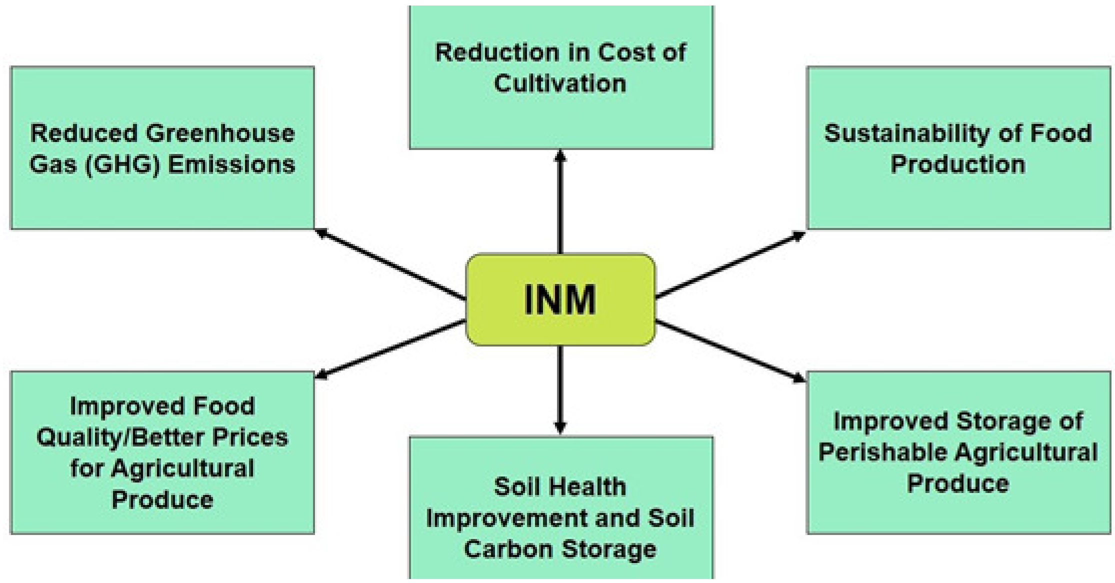



**Figure. 19. Benefits of INM implementation at farm and ecosystem level**

biological productivity and maintain environmental quality. Enhancing and sustaining soil health in these regions assumes prominence because if these lands are left without adopting suitable management practices would lead to further degradation making them unfit for cultivation. INM encompassing the conjunctive use of chemical fertilizers and organic sources would prove beneficial in augmenting soil health. Organic manures, a major component of INM package, provide multiple benefits towards soil health maintenance and enhancement. Organic manures increase soil organic carbon which ultimately improves the biological activity in the soil, helps retain soil moisture longer, and reduces the leaching of plant nutrients besides imparting drought tolerance during dry spells (Srinivasarao et al. 2013b, e).

### *Agricultural Sustainability*

Agricultural growth can be sustained by promoting conservation and sustainable use of available natural resources through appropriate location-specific measures. If a technology works to improve productivity and livelihood security of farmers and does not cause undue harm to the environment, then it contributes towards attaining sustainability. The adoption of INM practice provides multiple benefits *viz*. reduced reliance on fertilizers, maintaining and enhancing productivity without affecting soil health, conserving locally available resources and their judicious utilization, minimizing the gap between nutrient applied and nutrient uptake by the crop by augmenting nutrient use efficiency, etc. These multiple benefits accrue towards attaining agricultural sustainability. National Mission for Sustainable Agriculture (NMSA) has been formulated for enhancing agricultural productivity especially in rainfed areas focusing on integrated farming, water use efficiency, soil health management, and synergizing resource conservation. Results from several rainfed long-term experimental showed that the productivity benefits derived from INM are from improved soil organic carbon, which provides stability of agricultural production during moisture stressed years. For example, increase of each tonne of soil organic carbon yield benefits in the range of 0.02 to 0.16 t $ha^{-1}$ among several rainfed crops (**Figure 20**) (Srinivasarao et al. 2009, 2014a; Singh et al. 2008).

### *Input Cost Reduction and Improved Livelihood*

Majority of small holder farmers in rainfed regions, being resource poor with low investment capacity, face difficulty in spending high amounts on fertilizers and crop management practices due to uncertainties. Under this situation, substituting a part of the nutrient requirement of the crop through amalgamation of organic sources into the nutrient management schedule will contribute towards saving a proportion of their income. Also, the practice of INM would enhance nutrient use efficiency which ultimately would curtail the amount of fertilizer application aiding in input cost reduction and improved livelihood. Whatever limited organic resources available at farm or household level need to be recycled as much as possible so that cost of cultivation can be considerably reduced, particularly of high input needed crops like cotton, chillies and other cash crops (Srinivasarao et al., 2011a).

### *Environmental Services*

Integrated nutrient management holds potential in reducing carbon foot print in food production systems

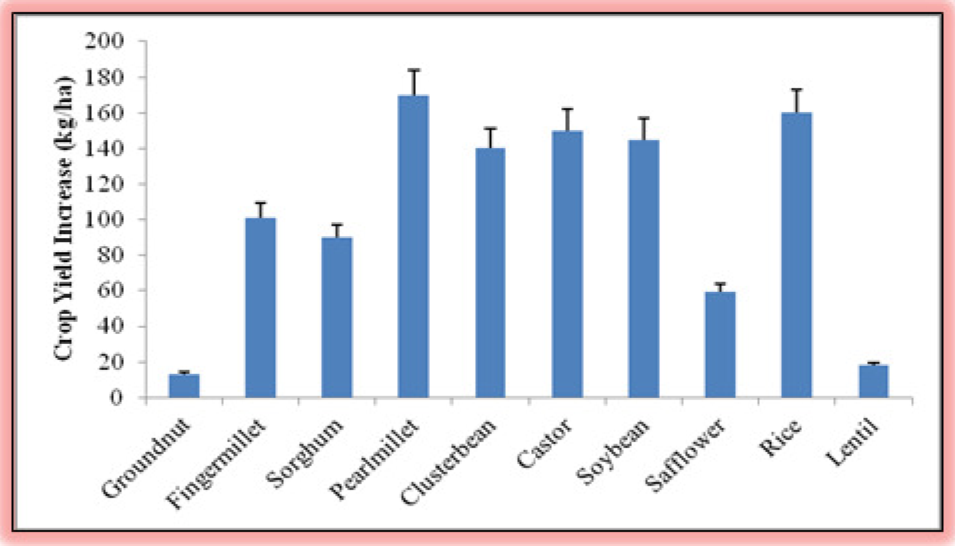



**Figure 20. Increase in crop yield (kg ha$^{-1}$) for every t ha$^{-1}$ increase in SOC stock in the root zone under various INM practices in different rainfed production systems (Srinivasarao et al. 2014a)**

and plays a prominent role towards adapting to and mitigating the climate change. The major principles by which integrated plant nutrient system (IPNS) contributes to the mitigation aspect in soil management systems include reduced $N_2O$ emission, reduced $CH_4$ emission, and increased soil C storage. IPNS also contributes to climate resilience through higher soil moisture storage which would aid in combating drought conditions, better soil structure for favourable infiltration and water movement, enhanced biological activity to supply plant nutrients through altered rates of soil processes and finally through a higher biological productivity even under stress conditions (Lenka, 2018; Srinivasarao et al. 2019).

The production of fertilizers is an energy intensive process, requiring large amounts of fossil fuel burning. Supplementing a part of the fertilizer requirement of the crop through organic amendments would curtail the amount of fertilizer usage eventually reducing greenhouse gas emissions. As per estimates methane emission ranges from 0.33 to 1.80 Tg yr$^{-1}$, nitrous oxide 7 Gg yr$^{-1}$, and total carbon dioxide equivalent 38.2 Tg yr$^{-1}$ from municipal solid waste of India (Sharma et al., 2006). According to another study, 1 tonne of rice straw on burning releases about 3 kg particulate matter, 60 kg CO, 1460 kg $CO_2$, 199 kg ash and 2 kg $SO_2$ (Gadi et al., 2003). Conversion of solid wastes and crop residues into composts could aid in minimizing the application of chemical fertilizers. In addition, greenhouse gas emissions could be reduced by substitution of fossil fuels for energy production by agricultural feed stocks (*e.g.*, crop residues, dung and dedicated energy crops). Crop residues, legumes, green manure, off-farm organic waste and improved soil and crop management practices help in C-sequestration. It has been advocated that conversion of organic residues into biochar could be a viable technology for long-term deposition of C and climate change mitigation strategy in different regions of India, because the average soil residence time for biochar can be up to thousands of years (Venkatesh et al., 2018) (**Figure 21**) Thus, practice of INM through inclusion of organic amendments coupled with appropriate management practices could be regarded as a viable strategy towards mitigating climate change and augmenting soil carbon stocks (Srinivasarao et. al., 2020a, 2011a) **(Figure 22)**.

### *Quality of Produce*

Initially the mandate of researchers was to maximize yield for which methods and procedures have been already established and are still in vogue. In recent past, along with quantity, quality of produce also is assuming significance. Organically cultivated and nutritive products have acquired high consumer

**Figure 21. Addition of biochar along with fertilizer nutrients enhanced maize yield and soil carbon storage in rainfed Alfisols**

**Figure 22. Continuous addition of FYM in cotton fields contributed to mid-season drought adaptation in rainfed cotton in Southern India**

acceptability in developing countries owing to enhanced economic status and lifestyle changes besides improving the storage of perishable agriculture commodities like vegetables and fruits grown with limited water supply. As organic resources are not available to substitute nutrient requirements of fruit crops, INM is considered as the best nutrient management strategy. Wide spaced fruit orchards provide ample opportunity to generate organic matter on farm between rows and addition of such biomass at fruit tree basin acts as mulch-cum-manure. The efficient utilization of available organic sources as nutrient supplement in rainfed ecosystem would open arenas for cultivators to enhance their net profits and pave way towards enhancing livelihood security (Srinivasarao et al. 2011a).

## Conclusions

Rainfed agro-ecosystems, which hold the potential to meet a major share of the food, fuel and fibre requirement of the country's ever-increasing population, need to be made much more productive by adopting suitable soil and crop management practices. Adopting strategies which would cater to both sustaining and elevating soil health status and enhancing crop productivity levels in these regions assumes high priority. INM is a holistic approach which would enable in meeting the needs of replenishing soil, augmenting productivity levels and also enhancing livelihood security of peasants inhabiting rainfed lands. In the current situation of escalating cost of fertilizers coupled with their role as a component augmenting emission of greenhouse gases, curtailing their use through amalgamation of all other nutrient supplying sources through integrated nutrient management would serve as a viable solution to enhancing productivity, restoring soil health, increasing net profits of farmers along minimizing GHG emissions and environmental pollution. INM technologies need to be promoted with a combination of strategies such as awareness creation, demonstration, training, communication in regional languages, and social media besides creating knowledge among school students (**Figure 23**). Role of several key players such as scientists, extension experts, innovative or lead farmers, state and central governments, policy bodies, etc., is critical for successful implementation of INM technologies at farm, village or land scape level in rainfed ecosystems of India (**Figure 24**).

## Way forward

- Continue the focussed research on efficient utilization of both on-farm and off-farm organic sources having nutrient supplying potential as components of INM which would aid in minimizing excessive use of chemical fertilizers.
- Promoting awareness among farming community about the benefits accrued

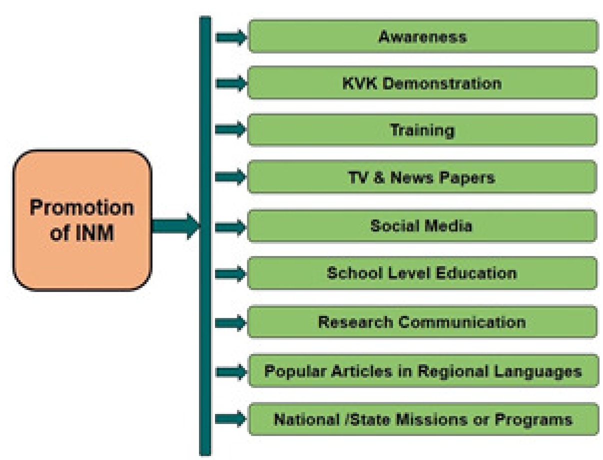



**Figure 23. Promotion of INM implementation to village adoption level**

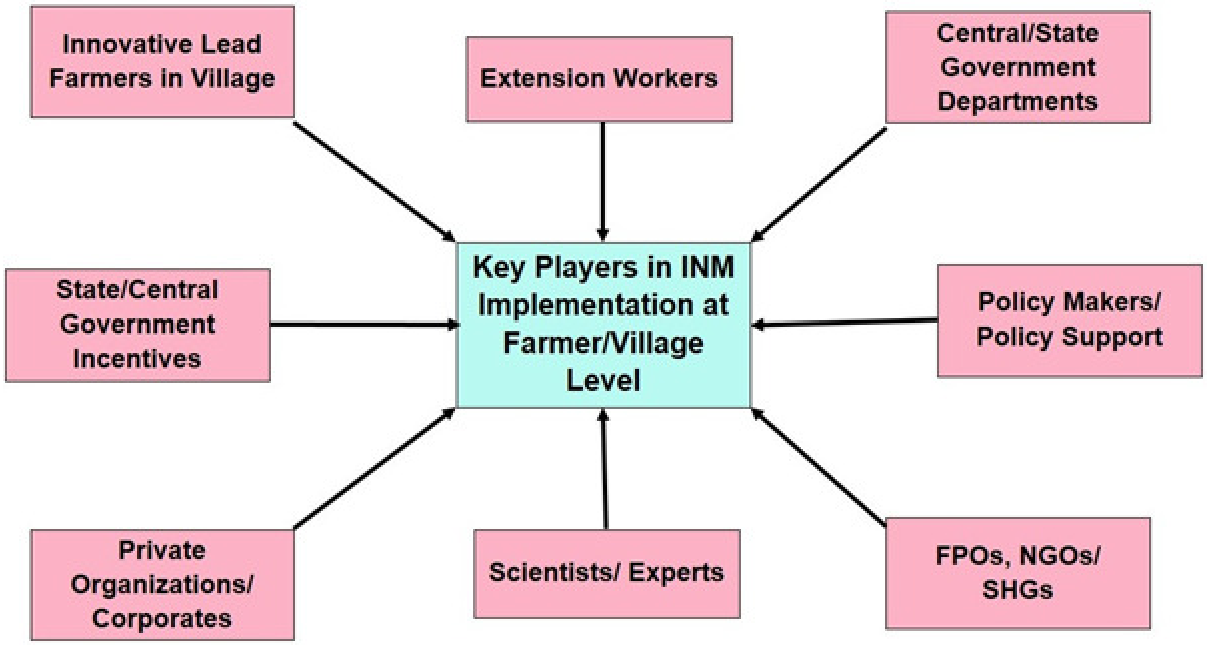



**Figure 24. Key players in implementation of INM strategies at farm or village level**

through adoption of INM practice *viz.*, enhanced soil health, crop productivity and higher net profits through large scale demonstrations.

- Exploring innovative technologies which would prove beneficial in enhancing the nutrient supplying capacity of available nutrient supplying sources.
- Bring in the Vyavasaya Panchangam (Package of Practices by respective Agriculture Universities) INM strategies developed in different rainfed agroecosystems and release the technologies with appropriate incentives considering environmental services derived by the implementation of these technologies.
- Upscaling of INM/IPNS technology by involving researchers, extension workers and creating linkage with line departments and in convergence central and state government programmes with multi-ministerial participation.
- Documentation and periodic evaluation of various INM technology implementation in terms of country's food security, nutrition, soil health (physical, chemical and biological) and maintenance of soil carbon stocks need to be popularized among all the stakeholders including policy makers.
- Policy development towards efficient and judicious utilization of available organic sources taking into consideration other significant factors *viz.*, soil type, climate and crop.
- Multi-ministerial platform needs to be created at district level headed by the district collector for no crop residue burning with accountability for implementation. Technical expert's inputs for appropriate technologies need to be part of this platform.

## References

Ali, M., Ganeshamurthy, A.N. and Srinivasarao, Ch. 2002. Role of pulses in soil health and sustainable crop production. *Journal of Food Legumes* (*Indian Journal of Pulses Research*) **15(2)**, 1-14.

Chakraborty, B. and Kundu, M. 2015. Effect of biofertilizer in combination with organic manures on growth and foliar constituents of mulberry under rainfed lateritic soil condition. *International Journal of Engineering Science* **4**, 16–20.

Chanakya, H.N., Ramachandra, T.V. and Vijayachamundeeswari, M. 2006. Anaerobic digestion and reuse of digested products of selected components of urban solid waste. In *Technical Report No*. **114,** pp. 1-109. Centre for Ecological Sciences and Centre for Sustainable Technologies, Indian Institute of Science, Bengaluru.

FAI. 2019. *Fertiliser Statistics 2018-19*. 64th Edition. The Fertilizer Association of India, New Delhi.

FAO. 2005. *Fertilizer Use by Crops in India*, pp. 1-45. Land and Plant Nutrition Management Service, Land and Water Development Division, FAO, Rome.

Gadi, R., Kulshrestha, U.C., Sarkar, A.K., Garg, S.C. and Parashar, D.C. 2003. Emissions of $SO_2$ and $NO_x$ from bio-fuels in India. *Tellus* **55**, 787–795.

Gunathilagaraj, K. and Ravignanam, T. 1996. Vermicomposting of sericultural wastes. *Madras Agricultural Journal* **83**, 455–457.

Indoria, A.K., Sharma, K.L., Sammi Reddy, K, Srinivasarao, Ch., Srinivas, K., Balloli, S.S., Osman, M., Pratibha, G. and Raju, N.S. 2018. Alternative sources of soil organic amendments for sustaining soil health and crop productivity in India – impacts, potential availability, constraints and future strategies. *Current Science* **115**, 2052-2062.

Indoria, A.K., Srinivasarao, Ch., Sharma, K.L. and Sammi Reddy, K. 2017. Conservation agriculture – a panacea to improve soil physical health. *Current Science* **112**, 52-61.

Jawahar, D., Rajeswari, M., Elmathi, S., Sanjivkumar, V., Joseph, M., Thangapandian, R., Anandaraj, N., Sundersingh Rajapandian, J., Solaimalai, A., Ravindra Chary, G. and Srinivasarao, Ch. 2016. *Four Decades of Dryland Agricultural Research in Southern Zone of Tamil Nadu (1971-2011)*, pp. 1-246. All India Coordinated Research Project on Dryland Agriculture, TNAU, Agricultural Research Station, Kovilpatti.

Khambalkar, S.M., Gabhane, V.V. and Khambalkar, V.S. 2017. Studies on effect of integrated nutrient management on productivity of cotton in rainfed condition. *International Journal of Current Microbiology and Applied Sciences* **6**, 3639-3641.

Kumar, S., Sharma, K.L., Kareemulla, K., Ravindra Chary, G., Ramarao, C.A., Srinivasarao, Ch. and Venkateswarlu, B. 2011. Techno-ecomomic feasibility of conservation agriculture in rainfed regions of India. *Current Science* **101**, 1-11.

Kundu, S., Srinivasarao, Ch., Mallick, R.B., Satyanarayana, T., Prakash Naik, R., Johnston, A. and Venkateswarlu, B. 2013. Conservation agriculture in maize (*Zea mays* L.) - horsegram (*Macrotyloma uniflorum L.*) system in rainfed Alfisols for carbon sequestration and climate change mitigation. *Journal of Agrometeorology* **15**, 144-149.

Lenka, N.K. 2018. Role of integrated plant nutrient management in mitigation and adaptations to climate change. *SAARC Regional Training Programme on Integrated Nutrient Management for Improving Soil Health and Crop Productivity*, pp. 60-64.

MNRE. 2009. Ministry of New and Renewable Energy Resources, Govt. of India, New Delhi. www.mnre.gov.in/biomassrsources.

NAAS. 2012. Management of crop residues in the context of conservation agriculture. *Policy Paper No.* **58**, pp. 1–12. NAAS, New Delhi.

Nataraj, K.C., Vijaysankar Babu, M., Narayanaswamy, G., Bhargavi, K., Sahadeva Reddy, B. and Srinivasarao, Ch. 2016. Nutrient management strategies in groundnut-based crop production systems in dryland regions of Southern Andhra Pradesh. *Indian Journal of Fertilisers* **12(10)**, 58-75.

Pappu, A., Saxena, M. and Asolekar, S.R. 2007. Solid wastes generation in India and their recycling potential in building materials. *Building and Environment* **42**, 2311–2320.

Prasada, J.V.N.S., Srinivasarao, Ch., Srinivasa, K., Naga Jyothia, Ch., Venkateswarlu, B., Ramachandrappa, B.K., Dhanapal, G.N., Ravichandra, K. and Mishra. P.K. 2016. Effect of ten years of reduced tillage and recycling of organic matter on crop yields, soil organic carbon and its fractions in Alfisols of semi-arid tropics of Southern India. *Soil and Tillage Research* **156**, 131–139.

Pratibha, G., Korwar, G.R., Srinivasarao, Ch., Venkateswarlu, B. and Srinivas, D. 2011. Nutrient management strategies in medicinal, aromatic and dye yielding crops in rainfed regions. *Indian Journal of Fertilisers* **7(4)**, 118-135.

Pratibha, G., Srinivas, I., Rao, K.V., Shanker, A.K., Raju, B.M.K., Deepak K. Choudhary, Srinivas Rao, K., Srinivasarao, Ch. and Maheswari, M. 2016. Net global warming potential and greenhouse gas intensity of conventional and conservation agriculture system in rainfed semi-arid tropics of India. *Atmospheric Environment* **145**, 239-250.

Pratibha, G., Srinivas, I., Rao, K.V., Raju, B.M.K., Thyagaraj, C.R., Korwar, G.R., Venkateswarlu, B., Shanker., Arun K, Choudhary, Deepak K., Srinivas Rao, K. and Srinivasarao, Ch. 2015. Impact of conservation agriculture practices on energy use efficiency and global warming potential in rainfed pigeonpea- castor systems. *European Journal of Agronomy* **66**, 30-40.

Ramachandrappa, B.K., Maruthi Sankar, G.R., Sathish, A., Dhanapal, G.N., Shankar, M.A., Raju, B.M.K., Sharma, K.L., Osman, M., Ravindra Chary, G., Srinivasarao, Ch. and Nagarjuna Kumar, R. 2016. Statistical assessment of sustainability of finger millet yield through rainfall and soil fertility variables using regression and principal component models in rainfed semi-arid Alfisol. *Communications in Soil Science and Plant Analysis* **47**, 1476-1492.

Ramachandrappa, B.K., Krishna Murthy, R., Thimmegowda, M.N., Savitha, M.S., Srikanth Babu, P.N, Manjunatha, B.N., Bhavitha, N.C., Ravindra Chary, G., Gopinath, K.A. and Srinivasarao, Ch. 2017. *Long-term Integrated Nutrient Management – Soil and Crop*, pp. 1-117. All India Coordinated Project for Dryland Agriculture (AICRPDA). Directorate of Research, UAS, Bengaluru, Karnataka.

Ramesh, T., Bolan, N.S., Kirkham, M.B., Wijesekara, H., Manjaiah, K.M., Srinivasarao, Ch., Sandeep, S., Rinklebe, J., Ok, Y.S., Choudhury, B.U., Want, H., Tang, C., Song, Z. and Freeman II, O.W. 2019. Soil organic carbon dynamics: impact of land use changes and management practices: a review. *Advances in Agronomy* **156**, 1-125.

Satisha, A., Ramachandrappa, B.K., Shankar, M.A., Srikanth Babu, P.N., Srinivasarao, Ch. and Sharma, K.L. 2016. Long-term effects of organic manure and manufactured fertilizer additions on soil quality and sustainable productivity of finger millet under a finger millet – groundnut cropping system in Southern India. *Soil Use and Management* **32**, 311–321.

Sengupta, J. 2002. Recycling of agro-industrial wastes for manufacturing of building materials and components in India. An overview *Civil Engineering and Construction Review* **15**, 23–33.

Sharma, S., Bhattacharya, S. and Garg, A. 2006. Greenhouse gas emission from India: prospective. *Current Science* **90**, 326–332.

Sharma, K.L., Srinivasarao, Ch., Chandrika, S.D., Lal, M., Indoria, A.K., Sammi Reddy, K., Ravindrachary, G., Amrutsagar, V., Kathmale, D.K., More, N.B., Srinivas, K., Gopinath, K.A. and Srinivas, K.D. 2018. Effect of predominant integrated nutrient management practices on soil quality indicators and soil quality indices under post-monsoon (*rabi*) sorghum (*Sorghum bicolor*) in rainfed black soils (Vertisols) of Western India. *Communications in Soil Science and Plant Analysis* **49**, 1629-1637.

Singh, K.K., Srinivasarao, Ch. and Ali, M. 2008. Phosphorus and mungbean residue incorporation improve soil fertility and crop productivity in sorghum and mungbean-lentil cropping system. *Journal of Plant Nutrition* **31**, 459-471.

Srinivasarao, Ch., Ganeshamurthy, A.N. and Massod Ali. 2003. *Bulletin on Nutritional Constraints in Pulse Production*, pp. 1-34. Indian Institute of Pulses Research, Kanpur.

Srinivasarao, Ch., Wani, S.P., Sahrawat, K.L., Rego, T.J. and Pardhasaradhi, G. 2008. Zinc, boron and sulphur deficiencies are holding back the potential of rainfed crops in semi-arid India: experiences from participatory watershed management. *International Journal of Plant Production* **2**, 89-99.

Srinivasarao, Ch., Vittal, K.P.R., Venkateswarlu, B., Wani, S.P., Sahrawat, K.L., Marimuthu, S. and Kundu, S. 2009. Carbon stocks in different soils under diverse rainfed production systems in tropical India. *Communications in Soil Science and Plant Analysis* **40**, 2338-2356.

Srinivasarao, Ch., Venkateswarlu, B., Dixit, S., Wani, S.P., Sahrawat, K.L., Kundu, S., Gayatri Devi, K., Rajesh, C. and Pardasaradhi, G. 2010. Productivity enhancement and improved livelihoods through participatory soil fertility management in tribal districts of Andhra Pradesh. *Indian Journal of Dryland Agriculture Research Development* **25(2)**, 23–32.

Srinivasarao, Ch., Venkateswarlu, B., Dixit, S., Kundu, S. and Gayatri Devi, K. 2011a. *Livelihood Impacts of Soil Health Improvement in Backward and Tribal Districts of Andhra Pradesh*, pp. 1-119. CRIDA, Hyderabad.

Srinivasarao, Ch., Venkateswarlu, B., Dinesh Babu, M., Wani, S.P., Dixit, S., Sahrawat, K.L. and Kundu. S. 2011b. *Soil Health Improvement with Gliricidia Green Leaf Manuring in Rainfed Agriculture*, pp. 1-23. CRIDA, Hyderabad.

Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A.K., Vittal, K.P.R., Kundu, S., Singh, S.R. and Singh, S.P. 2012a. Long-term effects of soil fertility management on carbon sequestration in a rice-lentil cropping system of the Indo-Gangetic plains. *Soil Science Society of America Journal* **76**, 168-178.

Srinivasarao, Ch., Gopinath, K.A., Venkatesh, G., Dubey, A.K., Wakudkar, H., Purakayastha, T.J., Pathak, H., Jha, P., Lakaria, B.L., Rajkhowa, D.J., Mandal, S., Jeyaraman, S., Venkateswarlu, B. and Sikka, A.K. 2013a. *Use of Biochar for Soil Health Management and Greenhouse Gas Mitigation in India: Potential and Constraints*, pp. 1-51. CRIDA, Hyderabad.

Srinivasarao, Ch., Jakkula, V.S., Kundu, S., Kasbe, S.S., Veeraiah, R., Rammohan, S., Dixit, S., Dinesh Babu, M. and Venkanna. K. 2013b. Management of intermittent droughts through on-farm generation of organic matter: participatory experiences from rainfed tribal districts of Andhra Pradesh. *Journal of Agrometeorology* **15**, 140-145.

Srinivasarao, Ch., Kundu, S. and Venkateswarlu, B. 2013c. Long-term effects of fertilization and manuring on groundnut yield and nutrient balance of Alfisols under rainfed farming in India. *Nutrient Cycling in Agroecosystems* **96,** 29–46.

Srinivasarao, Ch., Venkateswarlu, B., Hegde, M.B., Rao, Venkateswara and Kundu, S. 2013d. Use of organic fertilizers alone or in combination with inorganic ones: effects on water- and nutrient use efficiency in Indian farming systems. In *Improving Nutrient and Water Use Efficiency in Food Production Systems* (Zed Rengel, Ed.), pp 235-262. Wiley-Blackwell, USA.

Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A.K. and Kundu, S. 2013e. Sustainable management of soils of dryland ecosystems of India for enhancing agronomic productivity and sequestering carbon. *Advances in Agronomy* **121**, 253-329.

Srinivasarao, Ch., Venkateswarlu, B., Veeraiah, R., Ramamohan, S., Jakkula, V.S., Dixit, S., Ramamohan, R.V. and Shivarudrappa, B. 2013f. *Vermicomposting for Efficient Crop Residue Recycling, Soil Health Improvement and Imparting Climate Resilience: Experiences from Rainfed Tribal Regions*, pp. 1-40. CRIDA, Hyderabad.

Srinivasarao, Ch., Lal, R., Kundu, S., Prasad Babu, M.B.B., Venkateswarlu, B. and Singh, A.K. 2014a. Soil carbon sequestration in rainfed production systems in the semiarid tropics of India. *Science of the Total Environment* **487**, 587-603.

Srinivasarao, Ch., Venkateswarlu, B., Sudha Rani, Y., Singh, A.K. and Dixit, S. 2014b. Soil carbon sequestration with improved soil management in three tribal villages in India. In *Soil Carbon* (A.E. Hartemink and K. McSweeney, Eds.), pp 239-248. Springer International Publishing, Switzerland.

Srinivasarao, Ch., Ravindra Chary, G., Mishra, P.K., Subba Reddy, G., Sankar, G.R.M., Venkateswarlu, B. and Sikka, A.K. 2014c. *Rainfed Farming-A Compendium of Doable Technologies*, pp. 1-194. All India Coordinated Research Project for Dryland Agriculture, CRIDA, Hyderabad.

Srinivasarao, Ch., Lal, R., Prasad, J.V.N.S., Gopinath, K.A., Rajbir Singh, Jakkula, V.S., Sahrawat, K.L., Venkateswarlu, B., Sikka, A.K. and Virmani. S.M. 2015. Potential and challenges of rainfed farming in India. *Advances in Agronomy* **133**, 113-181.

Srinivasarao, Ch. and Gopinath, K.A. 2016. Resilient rainfed technologies for drought mitigation and sustainable agriculture. *Mausam* **67(1)**, 169-182.

Srinivasarao, Ch, Sammi Reddy, K. and Venkateswarlu, B. 2016. Soil quality assessment under restorative soil management practices in soybean (*Glycine Max*) after 6 years in semi-arid tropical black lands of Central India. *Communications in Soil Science and Plant Analysis* **47**, 1465-1475.

Srinivasarao, Ch. and Manjunath, M. 2017. Potential of beneficial bacteria as eco-friendly options for chemical-free alternative agriculture. In *Plant-Microbe Interactions in Agro-Ecological Perspectives* (D. Singh, H. Singh and R. Prabha, Eds.), pp. 473-493. Springer, Singapore.

Srinivasarao, Ch., Gopinath, K.A., Ramarao, C.A. and Raju, B.M.K. 2017a. Dryland agriculture in South Asia: experiences, challenges and opportunities. In *Innovations in Dryland Agriculture.* Springer.

Srinivasarao, Ch., Indoria, A.K. and Sharma, K.L. 2017b. Effective management practices for improving soil organic matter for increasing crop productivity in rainfed agroecology of India. *Current Science* **112**, 1497-1504.

Srinivasarao, Ch., Kundu, S. and Karlapudi. S. 2017c. Carbon sequestration: semiarid regions of India. In *Encyclopedia of Soil Science*. Third Edition, pp. 299-305. Taylor & Francis.

Srinivasarao, Ch., Prasad, J.V.N.S., Osman, M., Prabhakar, M., Kumara, B.H. and Singh, A.K. 2017d. *Farm Innovations in Climate Resilient Agriculture*, pp. 1-123. CRIDA, Hyderabad.

Srinivasarao, Ch., Shanker, A.K. and Gopinath, K.A. 2017e. Developments in management of abiotic stresses in dryland agriculture. In *Abiotic Stress Management for Resilient Agriculture* (P.S. Minhas, J. Rane and R.K. Pasala, Eds.), pp. 121-151. Springer Nature Singapore publishing.

Srinivasarao, Ch., Kundu, S., Grover, M., Manjunath, M., Sudhanshu, K.S., Patel, J.J., Singh, R.S., Singh, P.R., Patel, M.M., Arunachalam, A. and Soam. S.K. 2018. Effect of long-term application of organic and inorganic fertilizers on soil microbial activities in semi-arid and sub-humid rainfed agricultural systems. *Tropical Ecology* **59(1)**, 99–108.

Srinivasarao, Ch., Subha Lakshmi, C. and Kundu, S. 2019. Critical role of nutrient management in climate adaptive dryland farming systems in India. *Indian Journal of Fertilizers* **15(11)**, 12-26.

Srinivasarao, Ch., Sharma, K.L. and Kundu, S. 2020a. Potential soil carbon sequestration in different land use management systems in peninsular India. In *Carbon Management in Tropical and Sub-Tropical Terrestrial Systems* (P.K. Ghosh, S.K. Mahanta, B. Mandal and S. Ramakrishnan, Eds.), pp. 3-21. Springer Nature Pte Ltd. https://doi.org/10.1007/978-981-13-9628 1

Srinivasarao, Ch., Rao, K.V., Gopinath, K.A., Prasad, Y.G., Arunachalam, A., Ramana, D.B.V., Ravindra Chary, G., Gangaiah, B., Venkateswarlu, B. and Mohapatra T. 2020b. Agriculture contingency plans for managing weather aberrations and extreme climatic events: development, implementation and impacts in India. *Advances in Agronomy* **159**. https://doi.org/10.1016/bs.agron.2019.08.002

Sudhakar, G. 2000. Investigation to identify crop wastes/ low land weeds as alternative sources to organic to sustain the productivity of rice based system. *Ph.D. Thesis*, Tamil Nadu Agricultural University, Coimbatore.

The HINDU. 2009. Benefits from poultry manure – no chicken feed. *The Hindu*, Chennai Edition of 22 October 2009.

Thiyageshwari, S., Gayathri, P., Krishnamoorthy, R., Anandham, R. and Paul, D. 2018. Exploration of rice husk compost as an alternate organic manure to enhance the productivity of black gram in Typic Haplustalf and Typic Rhodustalf. *International Journal of Environment Research* 15 (358).

Venkatesh, G., Gopinath, K.A., Sammi Reddy, K., Sanjeeva Reddy, B., Prasad, J.V.N.S., Rajeshwar Rao, G., Pratibha, G., Srinivasarao, Ch., Ravindra Chary, G., Prabhakar, M., Visha Kumari, V., Shankar, A.K. and Venkateswarlu, B. 2018. Biochar Production and its Use in Rainfed Agriculutre: Experiences from CRIDA. *CRIDA-NICRA Research Bulletin* **02/2018**, 1-50. ICAR - CRIDA, Hyderabad.

Venkateswarlu, B., Srinivasarao, Ch., Ramesh, G., Venkateswarlu, S. and Katyal. J.C. 2007. Effects of long-term legume cover crop incorporation on soil organic carbon, microbial biomass, and nutrient build up and grain yields of sorghum/sunflower under rainfed conditions. *Soil Use and Management* **23**, 100-107.

Vijaya, D., Padmadevi, S.N., Vasandha, S., Meerabhai, R.S. and Chellapandi, P. 2008. Effect of vermicomposted coir pith on the growth of *Andrographis paniculata*. *Journal of Organic System* **3**, 51-56. ■

Indian Journal of Fertilisers **16** (4) : 368-375, April 2020

# Comparative Performance of Different Production Systems with Respect to Yield, Income and Sustainability

**N. Ravisankar, Raghuveer Singh, A.S. Panwar, M. Shamim and A.K. Prusty**
ICAR-Indian Institute of Farming Systems Research, Modipuram, Meerut, Uttar Pradesh

Received : 12/03/2020 Accepted : 13/03/2020

## Abstract

Every development has its own shadow in which sustainability issues are hidden or mostly ignored at initial step in consideration of profit. But after a certain period, its prerequisite is realized and addressed as otherwise maintaining growth in long path becomes difficult. Half a century of agriculture depended on intensive cultivation with high input use (synthetic inputs such as fertilizers, pesticides apart from seeds from market) to maximize crop production. However, the ill-effects soon became visible in the form of reducing factor productivity. Alternative production systems such as Organic Farming (OF), Conservation Agriculture (CA), Integrated Farming Systems (IFS), Natural Farming (NF), Integrated Nutrient Management (INM), Bio-dynamic Farming (BF), etc., are being currently discussed, tested and popularized among the farmers to reverse the factor productivity issue and improve the sustainability of agriculture. No doubt that ideologically they have similar objective to grow healthy food without disturbing our natural habitat and many a times, it is felt that these production systems have similar/synonymous intent, but in reality there are principal differences which make them distinguishable from each other. Emphasis in this paper is on comparing the performance of different production systems in terms of productivity, profitability and sustainability besides other related issues.

**Keywords:** Production systems, organic farming, conservation agriculture, integrated farming systems, natural farming, integrated crop management, bio-dynamic farming

## Introduction

One of the major problems with conventional agriculture is that it lays major emphasis on maximizing production at any cost, without due consideration to soil, water and environmental quality. At the time of Green Revolution, the priority was to get higher production to feed burgeoning population of the country and technologies were developed to meet this national objective. In the last few decades, varieties with higher genetic potential fitting into intensive cultivation system and responsive to high input use (irrigation and fertilizer) were developed and popularized. Definitely these technologies benefitted in terms of grain yield; year after year new records are being achieved in terms of food grain production. As per Fourth Advance Estimates for 2018-19, total food grain production in the country is estimated at 284.95 million tonnes (Mt) which is 30.7 Mt higher than the previous decade (2008-09 to 2017-18) average (Anonymous, 2019). Other commodities such as sugarcane have also shown similar trends. Due to mono-cropping and intensive cultivation, many issues such as decline in ground water table, multinutrient deficiencies, declining factor productivity, residue burning - a threat to environment, ground water pollution, etc., have cropped up and are becoming alarmingly menacing. In the absence of the diversification, higher use of synthetic compounds to combat the disease, insect, pest and weed attacks are being resorted to. For example, weed in wheat (*Phalaris minor)* emerged as a big issue due to continuous mono-cropping on large scale in Indo-Gangetic plains. Farmers are using herbicides and their combination to control it, but all the four alternate herbicides namely, clodinafop, sulfosulfuron, pinoxaden and mesosulfuron + iodosulfuron (RM) are facing development of resistance against them and farmers need to apply higher dose of these herbicides to get the same results (Singh et al., 2019).

One of the major concerns with conventional agriculture is injudicious exploitation of ground water mainly due to target of getting higher yields without taking into consideration the other factors. The ground water level data for pre-monsoon 2017 released by Central Ground Water Board (CGWB) indicates that out of the total 15078 wells analyzed, 4%, 24%, 43%, 23%, 5% and 2% showed water level less than 2 m, 2-5 m, 5-10 m, 10-20 m, 20-40 m and more than 40 m below ground level, respectively (Anonymous, 2017).

Without following the principles of crop diversification and implementing the intensive cropping system model of growing high input-responsive *i.e* including high yielding varieties continually and excessively mined the soil of its nutrients and the result was the accelerated appearances of multi-nutrient deficiencies. Over the years, farmers increased the fertilizer dose to fulfill the crop demand and get optimum yield. Farmers developed tendency to apply primary nutrients namely NPK, and with passage of time, soils became

ifsofr@gmail.com

deficit in secondary and micro nutrients. Researcher-designed farmer managed trials were conducted during 2013-14 through farmer participatory research covering the major food production systems in India. A total of 144 trials in rice - rice, 156 in rice - wheat, 48 in rice - green gram and 60 in maize - wheat systems were conducted with seven treatments. Across the various National Agricultural Research Project (NARP) zones and cropping systems, farmers applied 29%, 25%, 71% and 100% lower level of N, $P_2O_5$, $K_2O$ and micronutrients, respectively (Singh et al., 2019). Micronutrient deficiencies are now frequently observed in intensively grown cereals, oilseeds, pulses and vegetable crops. Based on analysis of GPS-guided more than 200, 000 soil samples, deficiencies of sulphur (S), zinc (Zn), iron (Fe), manganese (Mn), copper (Cu) and boron (B) in the country were assessed at 40.5, 36.5, 12.8, 7.1, 4.2 and 23.2%, respectively (Shukla and Behera, 2019); however, extent of Zn deficiency showed a decline to 36.5% in 2017 against 48.8% in 1999.

India is a developing country and its input demand is increasing with each passing day. Although consumption rate of input is low in India as compared to other developed countries, yet major issue with Indian agriculture is that input consumption pattern is highly imbalanced across the states or agricultural regions of few states/union territories like Andhra Pradesh, Telangana, Tamil Nadu, Puducherry, Punjab and Haryana applying higher doses of NPK ranging from 221.4 to 284.7 kg $ha^{-1}$. On the other side of spectrum, Rajasthan, Odisha, Jharkhand and north eastern states excluding Assam are consuming very low NPK. Overall, in India during 2018-19, per hectare fertilizer consumption (N+P+K) was 137.4 kg (FAI, 2019). Application of higher doses of nitrogen in place of balanced dose of NPK also adds to the issue of lesser use efficiency of applied nitrogen. Wider NPK ratio also further complicates the issue of sustainability, especially the one related to soil health.

Therefore, depending solely on conventional production system having more per cent share of synthetic and market inputs, unsustainability issue has assumed a central stage and moving towards eco-friendly farming practices which integrate the modern science based inputs with tradition and innovations in agriculture are attracting the attention. The alternative production systems being currently examined either largely exclude or avoid the synthetics in farming, especially those related to nutrient, weed, insect and disease management.

## Materials and Methods

ICAR-Indian Institute of Farming Systems Research, Modipuram evaluated the different production systems under All India Coordinated Research Project on Integrated Farming Systems (AICRP on IFS) and All India Network Programme on Organic Farming (AI-NPOF) over the years including the natural farming in vogue since *rabi* 2017-18. Brief description on the various alternate production systems evaluated compared to conventional farming are given below.

### *Organic Farming*

Organic farming is a system which avoids or largely excludes the use of synthetic inputs (such as fertilizers, pesticides, hormones, feed additives etc.) and to the maximum extent feasible rely upon crop rotations, crop residues, animal manures, on-farm organic waste, mineral grade rock additives, and biological system of nutrient mobilization and plant protection.

### *Conservation Agriculture*

Conservation agriculture is a system of raising crop with minimum disturbance of soil through reduced tillage or no-till or minimum tillage along with maintaining soil covered either by growing cover crops or maintain crop residue as mulch or maintain stubble of previous crops as protective cover and efficient crop rotation followed by including pulses and legumes in cropping system to maintain soil bio-physical property and protect from water and air erosion. Many researchers use CA and resource conservation technologies (RCTs) synonymously but in reality, RCTs are broader in the context that these include every agriculture technology which saves natural resources and time, are efficient in water and nutrient application, and reduce monetary investment to crop production like site-specific nutrient management, direct seeded rice and furrow irrigated raised bed planting. The conservation agriculture practices include only those RCTs having three interlinked principles namely, i) minimal mechanical soil disturbance - soil is minimally disturbed to sow seed; ii) permanent organic soil cover - soil cover is maintained to reduce the direct impact of water and wind; and efficient crop rotation - to maintain soil biological health instead of mono-cropping crop rotation followed in such a way that pulses and legumes are grown in rotation.

### *Integrated Farming System*

Integrated farming system is a judicious mix of two or more components using cardinal principles of minimum competition and maximum complementarity with advanced agronomic management tools aiming for sustainable and environment-friendly improvement of farm income, family nutrition and ecosystem services. Preservation of bio-diversity, diversification of cropping/farming system and maximum recycling is the base for success of the farming systems approach (Singh and Ravisankar, 2015).

### *Natural Farming*

Natural farming, also commonly/synonymously known as zero budget natural farming (ZBNF), Subash Palekar Natural Farming, etc., relies mostly on enhancing native supply of soil nutrients through microbial processes. It is a type of farming which emphasizes on the use of local species of microbes, earthworms and enriches the soil or fulfils the soil organic matter demand through mulching and intercropping. Alternate row application of water is resorted during noon time to save the water. The four pillars of natural farming include application of *Ghanjeevamrit*, *Beejamrit/Jeevamrit*, *Acchadana* (mulching: live with intercropping or with crop residues) and *Whapasa* (condition where there are both air molecules and water molecules present in the soil, irrigating in alternate furrows during noon) (FAO, 2016). As per Food and Agriculture Organization, zero budget natural farming means farming with nature without using any credit, purchased inputs and chemicals.

### *Integrated Nutrient Management*

Integrated nutrient management (INM) system envisages the combined use of synthetic/chemical fertilizers in conjunction with organic manures (farmyard manure, compost, poultry manure, city-waste compost, etc.), legumes in cropping systems (as grain/green manure/fodder/vegetable, etc.), bio-fertilizers and other locally available nutrient sources of biological origin (non-edible oil cakes etc.) to improve and sustain the soil health. INM primarily aims at improving and sustaining soil health (physical, chemical as well as biological) in long-term, along with optimization of crop yields in cropping-system perspective, as against the conventional system of crop nutrition – which primarily relies on supplying need-based plant nutrients through synthetic chemical fertilizers for exploiting full potential of a crop. Combined and harmonious use of organic and inorganic nutrient sources not only meets the concurrent needs of food production but also helps in sustaining soil productivity in long-term perspective.

### *Bio-dynamic Farming*

Bio-dynamic farming is a form of alternative agriculture very similar to organic farming, but it includes various esoteric concepts drawn from the ideas of Rudolf Steiner (1861–1925). It considers the cosmos energy before planting and harvesting of crop. They follow crop calendar based on the positioning of moon and stars. Emphasis is on to fulfill the nutrient demand of crops through farm itself as far as possible, minimum 50% animal feed also supplied from farm instead of purchasing from outside and allocate 10% area for the maintenance of field biodiversity.

## Results and Discussion

### *Comparative Performance of Organic, Inorganic and Integrated Production Systems*

Different production systems (organic, inorganic and integrated) were evaluated at different locations through All India Network Programme on Organic Farming (AI-NPOF) scheme from 2004-05. The results clearly established that the yield levels are higher under organic production systems compared to inorganic production system for almost all the field crops in *kharif* and summer but in *rabi* organic system recorded lower yields than the conventional system (**Table 1**). In *rabi*, decomposition rate gets affected due to hampering of microbial activity with low temperature which in turn slows down the mineralization process. Biederbeck and Campbell (1971) observed that during low temperatures, the viable counts of microorganisms, particularly nonspore-forming bacteria, declined sharply. Tuber crops performed well under organic production system with yield improvement of 10 to 20% and the net profit by 20–40% over conventional farming. The tuber quality also improved with higher dry matter, starch, crude protein, potassium (K), calcium (Ca) and magnesium (Mg) contents. The oxalate content was lowered by 21% in elephant foot yam (Girija et al., 2016). In almost all the crops (except non-basmati rice and lentil) across the season, performance of integrated approach recorded higher yield than the conventional system. Therefore, from the long-term data, it can be inferred that organic production system can be promoted during *kharif* and summer seasons while in *rabi,* integrated approach of using organic manures and fertilizers will be more appropriate for keeping the soil quality and also promotion of eco-friendly farming. Further, the selection of alternative production system should also be based on crop and area specificity.

### *Conservation Agriculture*

Based on the three years of investigation, it was concluded that application of paddy straw as mulch @ 5 t $ha^{-1}$ during *rabi* with INM under conventional method of sowing to rice-marigold-french bean can be recommended with maximum REY of 21.0 t $ha^{-1}$ with net returns Rs.2,39,693 $ha^{-1}$ and B:C ratio of 2.1 for Jammu region. Resource conservation technologies such as direct seeded rice-zero till wheat with 110% and 100% RDN (recommended dose of N) + recommended P, K, Zn could sustain productivity and sustainability (SYI of 0.85 and 0.84, respectively) of rice-wheat cropping system in Uttarakhand. Among all the four cropping systems evaluated for Chhattisgarh, rice – maize (sweet corn) system produced the highest total productivity and net returns under conventional tillage in rice and mulching with 125% higher RDF in *rabi* crops (18.49 t $ha^{-1}$ and Rs.1,97,128 $ha^{-1}$, respectively) followed by rice-brinjal (15.84 t $ha^{-1}$ and Rs. 1,60,844 $ha^{-1}$, respectively). Various physico-chemical parameters of soil such as pH, organic carbon, and available major nutrients (N, P and K) content in soil were not affected by different tillage practices, cropping system followed, mulch and fertilizer doses. At Coimbatore, minimum tillage to both cotton and maize and planting on furrow irrigated raised bed was found to be suitable tillage and planting management practice in cotton - maize cropping system. It recorded higher cotton equivalent yield (4.33 t $ha^{-1}$), net return (Rs.

**Table 1. Number of data entries, averages and ranges (%) of relative yields between organic-inorganic, organic-integrated and integrated-inorganic for selected crops (Mean of 6 to 7 years depending on the data availability)**

| Crops | Number of data entries | Organic over inorganic | | Organic over integrated | | Integrated over inorganic | | Locations |
|---|---|---|---|---|---|---|---|---|
| | | Mean | Range | Mean | Range | Mean | Range | |
| | | | | *Kharif* | | | | |
| Basmati rice | 67 | 104 | 88-121 | 95 | 83-109 | 110 | 93-136 | Modipuram, Jabalpur, Ludhiana, Pantnagar, Ranchi |
| Rice | 52 | 100 | 89-122 | 101 | 88-116 | 99 | 92-110 | Umiam, Karjat, Modipuram |
| Maize | 37 | 110 | 62-137 | 93 | 72-111 | 119 | 85-153 | Modipuram, Coimbatore, Dharwad, Karjat, Ludhiana, Bajaura |
| Sorghum | 17 | 114 | 89-132 | 105 | 96-111 | 109 | 94-126 | Modipuram, Jabalpur, Dharwad, Ludhiana |
| Berseem | 23 | 107 | 93-120 | 103 | 92-117 | 104 | 99-115 | Jabalpur, Raipur, Ludhiana |
| Soybean | 54 | 104 | 96-123 | 101 | 95-107 | 103 | 98-114 | Raipur, Bhopal |
| Green gram | 12 | 107 | 96-122 | 99 | 89-106 | 109 | 102-116 | Modipuram, Ludhiana |
| Groundnut | 16 | 103 | 83-116 | 95 | 81-105 | 107 | 103-111 | Dharwad, Karjat, Ludhiana |
| *Okra* | 10 | 118 | 90-142 | 107 | 93-114 | 109 | 97-125 | Modipuram , Jabalpur |
| Chilli | 12 | 109 | 107-112 | 99 | 98-99 | 111 | 108-113 | Coimbatore, Dharwad |
| Tomato | 11 | 106 | 83-130 | 94 | 88-101 | 112 | 95-129 | Bajaura, Umiam |
| | | | | *Rabi* | | | | |
| Wheat | 55 | 93 | 78-113 | 91 | 80-108 | 102 | 90-114 | Modipuram, Jabalpur, Raipur, Dharwad, Ludhiana, Bhopal, Pantnagar, Ranchi |
| Chickpea | 24 | 100 | 65-114 | 95 | 82-103 | 105 | 80-116 | Jabalpur, Raipur, Dharwad, Ludhiana, Bhopal |
| Mustard | 32 | 93 | 67-137 | 88 | 71-122 | 105 | 93-114 | Karjat, Bhopal, Pantnagar, Ranchi, Modipuram |
| Potato | 32 | 95 | 48-162 | 81 | 46-98 | 117 | 98-183 | Modipuram, Jabalpur, Dharwad, Ludhiana, Ranchi, Umiam |
| Lentil | 12 | 92 | 83-101 | 98 | 89-107 | 93 | 93-94 | Pantnagar, Ranchi |
| French bean | 16 | 92 | 69-105 | 86 | 58-109 | 109 | 93-117 | Bajaura, Umiam |
| Pea | 21 | 125 | 94-162 | 106 | 90-125 | 120 | 96-162 | Jabalpur, Bajaura, Pantnagar, Modipuram, Dharwad |
| Onion | 13 | 107 | 87-127 | 93 | 82-104 | 116 | 98-138 | Coimbatore, Raipur, Dharwad, Ludhiana |
| Cauliflower | 12 | 104 | 90-117 | 79 | 66-86 | 135 | 123-143 | Bajaura |
| Ginger | 12 | 120 | 108-129 | 91 | 88-95 | 132 | 118-149 | Calicut |
| Turmeric | 18 | 146 | 93-242 | 105 | 82-141 | 138 | 102-201 | Coimbatore, Calicut, Ludhiana |

1,08,917 $ha^{-1}$) and BCR (2.47) (AICRP-IFS, 2016) (**Table 2**).

*Integrated Farming Systems*

Farmers' income can be sustainably improved besides ensuring soil and environmental quality through integrated farming systems (IFS). Across the locations, it has been found that net return of Rs. 1,67,983 from one hectare, with Rs. 52,510 worth of recycling can be obtained from IFS apart from generating 447 man-days of on-farm employment for the farm family. Net return ranged from Rs. 75,537 in East Coast Plains and Hills to Rs. 2,65,576 Middle Gangetic Plains across various ACZs (**Figure 1**). Resources recycling, efficient utilization of farm labour, and available space is behind the success of IFS (Singh et al., 2011; Swarnam

**Table 2. Influence of conservation practices on yield**

| **Treatments (Cotton and Maize)** | **Cotton equivalent yield (kg ha$^{-1}$), 2014-15** |
|---|---|
| Conventional tillage for all crops + flat surface | 3509 |
| Minimum tillage for all crops + Furrow irrigated raised bed | 4331 |
| Zero tillage+ flat bed | 3210 |

et al., 2014). High start-up costs (Tipraqsa et al., 2007), procuring the improved breeds of livestock, timely availability of fish seed and feed, low cost energy efficient pumping machine, information on government schemes and credit support from financial institutions (Nageswaran et al., 2009) have been identified as major constraints that restrict farmers from switching on to IFS.

***Comparative Performance of Natural Farming with Organic and Integrated Crop Management***

Under All India Network Programme on Organic Farming (AI –NPOF), from *rabi* 2017, the concoctions (Ghanjeevamrit, Beejamrit and Jeevamrit) of natural farming were compared with AI-NPOF developed organic farming package and integrated crop management practice. Yield reduction ranging from 31.8 to 37.7% in basmati rice (2018) and 55.1 to 58.6% in wheat (2017-18 & 2018-19) at Modipuram were observed due to application of only concoctions of natural farming compared to the integrated crop management.

***Integrated Nutrient Management***

A long term experiment on integrated nutrient management in cereal-based cropping systems was conducted from *kharif* 1985 to understand the dynamics of integrated nutrient management practices with substitution approach in six cereal - cereal systems such as rice - wheat (12 locations), rice - rice (6 locations), rice - maize (1 location), pearl millet - wheat (4 locations), maize - wheat (1 location) and sorghum - wheat (3 locations). Experiment was continued for 22 to 28 years with reduced application of nutrients through chemical fertilizers up to 50% and substituting 50% with organic sources like FYM, paddy straw and green manuring during *kharif*. In *rabi* crops, no substitution was done with organic sources. Observations on crop parameters, sustainable yield index, trends in yield, nutrient status of soil, uptake by crops, economics, microbial studies, weed dynamics, and nutrient balance were taken for all the systems and locations. Irrespective of the systems and locations, continuous use of FYM, crop residue and green manuring in partial substitution of chemical source significantly improved the soil properties, plant growth and yield. In all the locations and cropping systems during initial period of 3 years (stabilizing period), yield of crops was higher under 100% recommended NPK to both the crops which was closely followed by substitution of up to 25% through organic sources. However, after stabilizing period and in a long-term (around 22 cycles), the system productivity was higher with substitution up to 50% with organic sources during *kharif* and 100% chemical fertilizers to *rabi* crops. Appreciable buildup of soil P, K and micronutrients such as zinc (Zn), iron (Fe), manganese (Mn) and copper (Cu) was observed under the INM practices. It indicates that there is no need of separate micronutrient application when INM approach is adopted in cereal-cereal cropping systems. The INM approach also improved the soil physical, chemical and biological properties concurrently as it was observed that soil bulk density, porosity and microbes improved significantly in the long term. Frequent application of organic manures (at least once in each crop cycle)

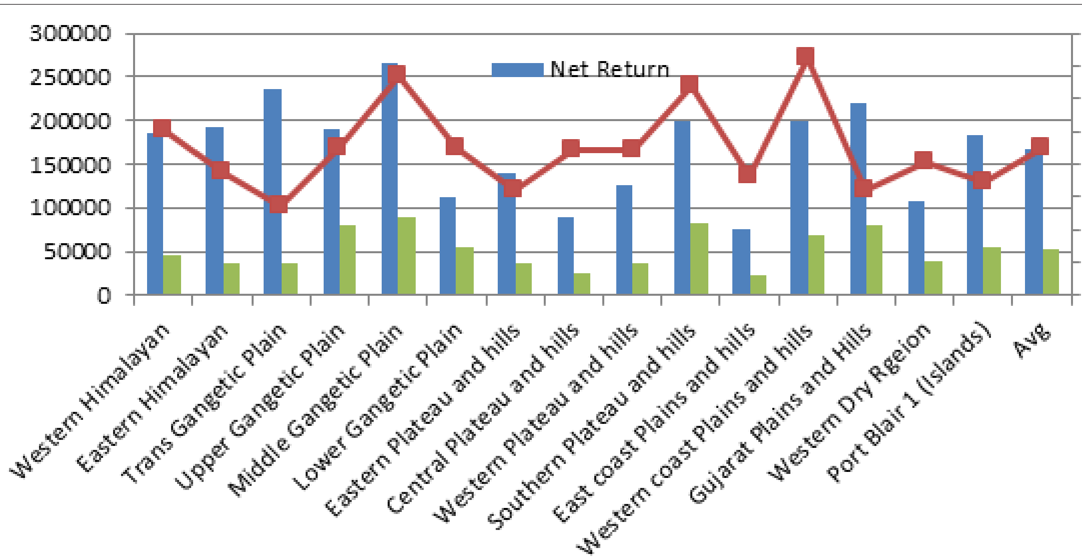



**Figure 1. Net return, value of recycling and man-days generated from one hectare of area by IFS model across different agroclimatic zones (ACZs) of the country**

is a must for realizing the sustainable yield in predominant cereal - cereal food systems like rice - wheat, rice - rice and rice - maize. Leguminous residues such as *moong* straw and green manures were found to be better among different organic sources in the cereal - cereal system. In terms of economics and sustainable yield index also, substitution through organic manures up to 50% was found to be better for most of the systems and locations (Gangwar et al., 2015). The systems and location-specific best performing treatments in the long run in terms of system yield, sustainability, economics and soil fertility are summarized in **Table 3**.

**Table 3. Best performing INM treatments at various locations and cropping systems**

| Location/System | *Kharif* | *Rabi* |
|---|---|---|
| | **Rice - Wheat** | |
| Jammu, Jammu and Kashmir | 50% NPK through fertilizers + 50% NPK through FYM | 100% NPK through fertilizers |
| Palampur, Himachal Pradesh | 50% NPK through fertilizers + 50% N through organic sources such as FYM green manure and wheat straw | 100% NPK through fertilizers |
| Pantnagar, Uttarakhand | 50% N through Urea + 50% N through green gram straw | 100% NPK through fertilizers |
| Ludhiana, Punjab | 50% NPK through fertilizers + 50% N through FYM or green manure or wheat straw | 100% NPK through fertilizers |
| Kanpur, Uttar Pradesh | 75% NPK through fertilizers + 25-50% N through green manure | 100% NPK through fertilizers |
| Faizabad, Uttar Pradesh | 50% NPK through fertilizers + 50% N through FYM or green manure | 100% NPK through fertilizers |
| Varanasi, Uttar Pradesh | 50% NPK through fertilizers + 50%Nthrough FYM | 100% NPK through fertilizers |
| Sabour, (Bihar | 50-75% NPK through fertilizers + 25-50% N through FYM or green manure or wheat straw | 100% NPK through fertilizers |
| Kalyani, West Bengal | 50% NPK through fertilizers + 50% N through FYM/green manure or rice straw | 100% NPK through fertilizers |
| Raipur, Chhattisgarh | 75% NPK through fertilizes + 25% N through FYM/green manure or 100% NPK through fertilizers | 100% NPK through fertilizers |
| Jabalpur, Madhya Pradesh | 50-75% NPK through fertilizers + 25-50% N through green manure | 100% NPK through fertilizers |
| Navsari, Gujarat | 75% NPK through fertilizers + 25% N through FYM or green manure | 100% NPK through fertilizers |
| | **Rice-Rice** | |
| Jorhat, Assam | 75% NPK through fertilizers + 25% N through rice straw | 75% NPK through fertilizers |
| Karamana, Kerala | 50-75% NPK through fertilizers + 25-50% through FYM or crop residue or green manure | 75% NPK through fertilizers |
| Bhubaneswar and Chiplima, Odisha | 50 % NPK through fertilizers + 50 % Nthrough *Sesbania* or *Azolla* or FYM | 100 % NPK through fertilizers |
| Rajendranagar, Telangana | 50% NPK through fertilizers + 50% N through *glyricidia* green leaf manure | 100% NPK through fertilizers |
| Siruguppa, Karnataka | 50-75% NPK through fertilizers + 25-50% N through rice straw or *glyricidia* green leaf manure | 100% NPK through fertilizers |
| Karjat, Maharashtra | 50% NPK through fertilizers + 50% N through *glyricidia* green leaf manuring | 100% NPK through fertilizers |
| | **Rice - Maize** | |
| Kathalgere, Karnataka | 75% NPK through fertilizers + 25% N through FYM or paddy straw or*glyricidia* green leaf manure | 100% NPK through fertilizers |
| | **Pearl Millet – Wheat** | |
| Hisar, Haryana | 50% NPK through fertilizers + 50% N through FYM | 100% NPK through fertilizers |
| S.K. Nagar, Gujarat | 50-75% NPK through fertilizers + 25-50% N through FYM/wheat straw/sunhemp | 75% NPK through fertilizers |
| Bichpuri, Uttar Pradesh | 50-75% NPK through fertilizers + 25-50% through FYM or green manuring | 75% NPK through fertilizers |
| Junagadh, Gujarat | 50% NPK through fertilizers + 50% N through FYM | 100% NPK through fertilizers |
| | **Maize - Wheat** | |
| Ranchi, Jharkhand | 50-75% NPK through fertilizers + 25-50% through FYM | 75 to 100% NPK through fertilizers |
| | **Sorghum - Wheat** | |
| Rahuri, Maharashtra | 50% NPK through fertilizers + 50% N through FYM | 100% NPK through fertilizers |
| Akola, Maharashtra | 50% NPK through fertilizers + 50% N through FYM or wheat straw or *Leucaena* loppings | 100% NPK through fertilizers |
| Parbhani, Maharashtra | 50% NPK through fertilizers + 50% N through FYM | 100% NPK through fertilizers |

**Table 4. Influence of biodynamic practices along with other organic inputs on yield of crops (Anonymous, 2013)**

| Location | Crop | Yield (kg ha$^{-1}$) | | *Other inputs applied with biodynamic practice |
|---|---|---|---|---|
| | | Biodynamic practice alone | Biodynamic practice with other inputs* | |
| Raipur | Rice | 2263 | 4256 | Enriched compost, cow dung manure, non-edible oil cakes and Panchagavya spray |
| | Chickpea | 796 | 1375 | |
| Ludhiana | Wheat | 1900 | 3540 | Farmyard manure and Panchagavya |
| Pantnagar | Basmati rice | 3644 | 4829 | Farmyard manure, vermicompost, *neem* cakes and enriched compost and Panchagavya |
| | Chickpea | 1244 | 2003 | |

### *Biodynamic Farming*

Application of biodynamic practice + enriched compost + cow dung manure + non edible oilcakes @ 1/3$^{rd}$ N each + Panchagavya (PG) recorded higher yield of rice and chickpea compared to biodynamic practice alone at Raipur. At Ludhiana, application of FYM + PG + biodynamic practices recorded higher grain yield of maize (6.14 t ha$^{-1}$), while in wheat FYM + PG alone recorded higher yield (2.52 t ha$^{-1}$). The wheat yield was significantly reduced when grown with only biodynamic practice (**Table 4**).

## Conclusions

Alternative production systems such as organic farming, conservation agriculture, integrated farming systems provide the scope to reduce the synthetics in agriculture and move towards eco-friendly farming. However, the experimental evidences clearly indicate the season-specific performance of alternate production systems and need to promote integrated approach especially during *rabi* crops for realizing the optimum yield and maintaining sustainability. The results of long-term experiment clearly establish that substitution of up to 50% is possible and required for sustaining the yield of cereal-based cropping systems. The results also clearly indicate that once in a cropping cycle, organic manures need to be supplemented. Therefore, appropriate policy needs to be formulated for promoting the alternate production systems including natural farming by taking into consideration of seasonal effects on nutrient mineralization process and native nutrient supplying capacity of the soil. Organic farming combining the tradition (rearing crop and livestock together), innovations (hybrids, biological inputs such as biofertilizers, etc.) and science (meeting the nutrient demand by various means) in niche areas and crops, integrated farming system with proper knowledge-led integration of components and integrated crop management involving conservation and precision farming practices could be the effective alternative systems which can be promoted for sustaining the soil, water and environmental quality.

## Acknowledgement

Contribution of all the centres of AICRP on IFS and AI-NPOF in generating the data in coordinated experiments is thankfully acknowledged.

## References

AICRP-IFS. 2016. *Annual Report 2015-16*, pp. 1-258. ICAR-Indian Institute of Farming Systems Research, Modipuram, Meerut.

Anonymous. 2013. *Annual Report 2012-13*, *Network Project on Organic Farming*. pp. 1-130. Project Directorate for Farming Systems Research (ICAR), Modipuram, Meerut.

Anonymous. 2017. Ground water level scenario in India Pre-Monsoon-2017. http://cgwb.gov.in/GroundWater/GW% 20Monitoring% 20Report_PREMONSOON% 202017.pdf. Accessed on April 20, 2018.

Anonymous, 2019. *4$^{th}$ Advance Estimates of Production of Major Crops for 2018-19*. Press Information Bureau, Ministry of Agriculture & Farmers Welfare, Government of India. http://pibphoto.nic.in/documents/rlink/2019/aug/p201981901.pdf. Accessed on March 3, 2020.

Shukla, A.K. and Behera, S.K. 2019. All India Coordinated Research Project on Micro- and Secondary Nutrients and Pollutant Elements in Soils and Plants: Research achievements and future thrusts. *Indian Journal of Fertilisers* **15(5)**, 522-543.

Biederbeck, V.O., and Campbell, C.A. 1971. Influence of simulated fall and spring conditions on the soil system: I. Effect on soil micro flora. *Soil Science Society of America Proceedings* **35**, 474–479.

FAI. 2019. *Fertiliser Statistics 2017-18*, **64$^{th}$ Edition**. Fertiliser Association of India, New Delhi.

FAO. 2016. *52 Profiles on Agroecology: Zero Budget Natural Farming in India.* http://www.fao.org/3/a-bl990e.pdf.

Gangwar, B, Prasad, K., Ravisankar, N. and Singh, J.P. (Editors) 2015. *Long-term Integrated Nutrient Management in Cereal-Based Cropping Systems*, pp. 1-416. All India Coordinated Research Project on Integrated Farming Systems, ICAR-Indian Institute of Farming Systems Research, Modipuram, Meerut.

Girija, S., Jyothi, A.N. and Byju, G. 2016. Response of varieties of elephant foot yam (*Amorphophallus paeoniifolius*) to organic management. *Indian Journal of Agricultural Sciences* **86**, 1343-1352.

Nageswaran, M., Selvaganapathy, E., Subbiah, V.R. and Nair, S. 2009. Demonstration and replication of integrated farming systems at Chidambaram. *Report of M.S. Swaminathan Research Foundation (MSSRF)*, pp. 16-53, Chennai

Singh, J.P. and Ravisankar, N. 2015. Integrated farming systems for sustainable agricultural growth: strategy and experience from research, *Proceedings of National Seminar on Integrated Farming Systems for Sustainable Agriculture and Enhancement of Rural Livelihoods*, pp. 9-22. Organized by the Retired ICAR Employees Association and ICAR-National Academy of Agricultural Research Management, Hyderabad

Singh, J.P., Gangwar, B., Pandey, D.K. and Kochewad, S.A. 2011. Integrated farming system model for small farm holders of western plain zone of Uttar Pradesh. *PDFSR Bulletin No*. **5,** pp. 1-58., Project Directorate for Farming Systems Research, Modipuram, Meerut.

Singh, R., Yadav, D.B., Ravisankar, N., Yadav, A. and Singh, H. 2019. Crop residue management in rice–wheat cropping system for resource conservation and environmental protection in north-western India. *Environment Development and Sustainability (2019)*. Published on 8 May 2019. https://doi.org/10.1007/s10668-019-00370-z.

Swarnam, T.P., Velmurugan, A., George, Z., Ravisankar, N., Sai, T.P.S., Roy, D. and Srivastava, P. 2014. Integrated farming system for sustainable livelihood in tribal areas of Nicobar Island, India. *Journal of the Andaman Science Association* **19 (1)**, 19-22.

Tipraqsa, P., Craswell, E.T., Noble, A.D. and Schmidt, V.D. 2007. Resource integration for multiple benefits: multifunctionality of integrated farming systems in Northeast Thailand. *Agricultural Systems* **94**, 694-703. ■

Indian Journal of Fertilisers **16** (4) : 382-396, April 2020

# Integrated Nutrient Management for Climate Change Mitigation and Adaptation

**P. Bhattacharyya[1], S.R. Padhy[1], P.P. Padhi[1] and H. Pathak[2]**
[1]ICAR-National Rice Research Institute, Cuttack, Odisha
[2]ICAR-National Institute of Abiotic Stress Management, Baramati, Maharashtra

Received : 11/03/2020 Accepted : 16/03/2020

## Abstract

Integrated nutrient management (INM) can play a vital role on climate change mitigation by reducing emission of greenhouse gases (GHGs), and adaptation by reducing nutrient and moisture stresses with improved soil health. We analysed the potential of GHGs mitigation and carbon sequestration in major cropping systems of India and abroad as impacted by long-term practices of INM. The INM practices included use of farmyard manure (FYM), biofertilizer, biochar and compost along with balanced use of chemical fertilizers (NPK) on crop yield, GHG mitigation and carbon storage at 13 locations and 14 major cropping systems. The GHG emissions could be reduced by 12 to 47% and C-sequestration could be enhanced by 38 to 100%. Climate change adaptation with INM through higher water holding capacity of soil and water saving in climate stress situations were also reviewed. It is concluded that the site-specific INM approach could be considered as a component of 'climate-smart agriculture'. It helps in mitigating GHG emissions, increasing C sequestration, enhancing adaptation, improving soil health, sustaining crop productivity, and thereby developing resilience of the crops and cropping systems to climate change.

**Key words**: GHG mitigation; carbon sequestration; integrated nutrient management; climate change adaptation; cropping system.

### Introduction

Climate is the primary determinant of crop productivity. Therefore, if the climate changes towards adversity, so will the crop productivity be affected adversely. Most crop simulation studies have predicted a net reduction in yield of crops with climate change, if no adaptation is followed. Further, adverse temperature and moisture conditions affect quality of food grains. Climate change is also likely to have significant effect on quality of plantation and cash crops such as cotton, fruits, vegetables, tea, coffee, aromatic and medicinal plants. Agro-biodiversity may be threatened due to rainfall uncertainty, temperature increase, sea level rise, and increased frequency and severity of droughts, cyclones and floods. The impact of climate change resulting in warming, changes in precipitation patterns, increased frequency of extreme events, rise in sea level, etc., would affect water balance and water quality in different parts of the country. Changes in rainfall patterns can cause water shortages in some regions which, combined with thermal stress due to higher mean temperature, can adversely affect the crops. Warmer climate would increase irrigation demands and higher evapo-transpiration, resulting in lowering of groundwater table due to over-exploitation to meet out the irrigation demand. Increase in carbon dioxide concentration is likely to compensate for the negative effect on yields due to increase in temperature, but as temperature increases further, it would result in yield losses. Contrary to all the above negative impacts, predictions have been made for decreased cold waves and frost events in future due to the atmospheric temperature rise, which would lead to a decreased probability of yield loss associated with frost damage in northern India in crops such as mustard and vegetables.

hpathak.iari@gmail.com

Change in precipitation patterns and amounts, and increase in temperature may degrade soil quality, reduce soil moisture content and affect microbial diversity, which in turn will affect the crop growth. Increase in temperature reduces quantity and quality of organic matter content, which is already quite low in the Indian soils. An increase in temperature also leads to increased evapo-transpiration, thereby lowering groundwater table and adversely affecting irrigation potential. At some places, increased surface temperature coupled with reduced rainfall may lead to accumulation of salts in upper soil layers. Similarly, a rise in sea level associated with increased temperature may lead to salt-water ingression in coastal lands, making them unsuitable for conventional agriculture.

As per IPCC (2014), the agriculture, forestry and other land uses (AFOLU) sector account for about 25% (about 10-12 billion-tonnes $CO_2$eq. $yr^{-1}$) of the net anthropogenic GHG emissions. These take place mainly from deforestation, emissions from soil and nutrient application and methane ($CH_4$) emission from livestock sector. Out of the total emission caused by human activities, agricultural sector is responsible for 25% of carbon dioxide ($CO_2$) (largely from deforestation); 50% of $CH_4$ (rice cultivation and enteric fermentation); and about 75% of nitrous oxide ($N_2O$) (mostly from excessive chemical fertilizer use) emissions. Despite of recent declining trend of $CO_2$ flux in the sector largely due to reduction in deforestation rates and increasing afforestation, still a high level of uncertainty exists in this sector. Nevertheless, there is high possibility of the AFOLU sector of becoming a net $CO_2$ sink in future. Specifically, in agriculture the most cost-effective mitigation options are soil nutrient management in crop fields, carbon sequestration, grazing-land management, and restoration of organic/peat soils. However, some mitigation options in the AFOLU sector such as soil carbon sequestration is also vulnerable to climate change and beset with high levels of leakages.

Integrated Nutrient Management (INM) has been associated with agriculture practices for a long time. However, before 'Green Revolution', agriculture was mostly characterized by 'low input-output' system with less dependence on inorganic chemical fertilizers. During and after the 'Green Revolution' the introduction of high yielding varieties and increase in cropping intensity led to widespread nutrient mining from soil and a negative nutrient balance in soils of major cropping systems. This led to promote the INM, as the fertilizer response ratio decreased drastically in the many of South-East Asian countries. The INM is not simply a practice; it is an approach, where the nutrient demands of crops are met from a combination of nutrient sources including chemical fertilizers, organic manures, non-conventional organic sources, crop residues, green manures, biofertilizers, etc. Several researches showed that crop residue, biofertilizer could reduce about 20-25% chemical fertilizer use and site-specific green manure alone could save 20-25% chemical N application (Lenka, 2018). However, the key of INM is that, its components should be properly balanced depending on site and crop specific demand. Local availability of organics also should be considered during planning of INM options.

The INM has a substantial role in reducing carbon foot print in food production systems and plays a vital role in climate change mitigation. The two mitigation components like reduction of GHGs ($N_2O$ and $CH_4$) emission and increased soil carbon (C) sequestration are directly governed/regulated by INM. At the same time, INM could also add adaptation value by enhancing soil moisture storage, reducing drought effect, ensuring better soil structure for favourable infiltration and water movement, and by maintaining biological activities in soil that leads to adequate supply of plant nutrients even under climate-stress conditions. The article deals with the approaches of INM and its role in climate change adaptation and mitigation.

**Concept and Approaches of INM**

The INM is an approach of site-specific application of organic manure, inorganic fertilizer, and biological amendments in combination in order to increase nutrient use efficiency and to sustain crop productivity. At the same time, it also reduces nutrient losses by synchronizing nutrient availability in soil with crop demand (Janssen, 1993; Wu and Ma, 2015). There are three basic principles of INM, namely (i) using all the possible sources of nutrients (organic, inorganic, biofertilizer, etc.) to optimize the input; (ii) matching crop demand to soil nutrient supply both temporally and spatially; and (iii) reducing the nutrient losses and improving crop yield. In context of present day-food security challenges, the INM approaches have been considered as important strategies for boosting crop productivity and improving soil health by several international initiatives (Vanlauwe et al., 2012). Importantly, site-specific INM strategies are broadly applicable and the approach of combining of organics with inorganic nutrient sources could either be integrated into low-input systems for enhancing nutrient supply to soil or to high-input systems for reducing chemical fertilizer requirements and maintaining soil health. The INM approaches are flexible and have higher adaptability as these could be adjusted in different kind of cropping systems and inputs availability (at specific site). Additionally, the organic manures/ amendments provide essential nutrients to the plant and also act as a slow-release-fertilizer throughout the crop growing seasons which has the potential to curtail the nutrient losses and GHGs emissions. As for example, low C:N organic manures/ amendments decompose quickly and contribute less to stable organic matter, while, manures having high C:N ratios decompose very slowly, resulting in relatively low supply of nutrients for crop demand during the initial years of application (Wortman et al., 2012), but potentially those could sequester higher C in the long run. Therefore, organic manure application with higher C:N ratio may sometimes result in lower yields. In contrast, the inorganic fertilizers dissolve easily in the soil-solution that makes immediately available the nutrients for plant uptake and fetches higher yield with immediate application. Therefore, using the contrasting properties of organic manure and inorganic chemical fertilizer; the integrated mixing of both organic manures/amendments with inorganic fertilizers can significantly improve soil quality without sacrificing crop nutrition or yield. However, numerous researches have reported the effects of INM on soil quality, nutrient use efficiency and also crop productivity, but impact of INM on climate change mitigation is still not precisely documented. This review is planned to account for the 'know-how' about the trade-off of GHGs emissions, carbon sequestration, nutrient uptake/loss and yield of crops as impacted by INM approaches. Considering that the reduction

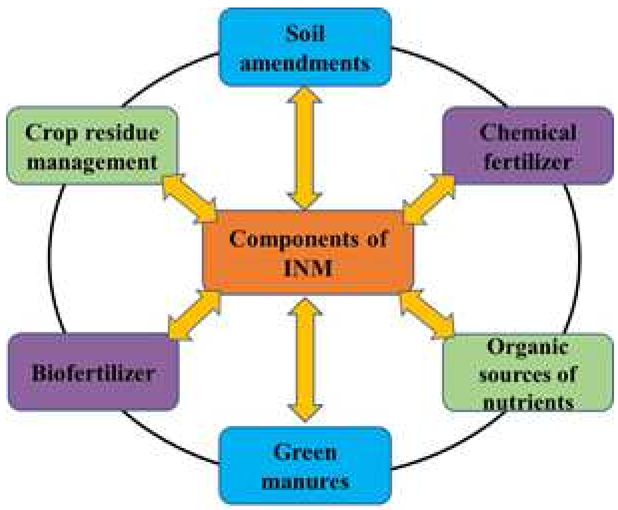



**Figure 1. Components of integrated nutrient management**

of GHGs emissions and C sequestration are the two major pillars of climate change mitigation options from agricultural sector, the objective of this paper is to critically review the long-term impacts of INM on reduction of GHG emissions and to assess the carbon sequestration potential of INM approaches in principal cropping systems in tropics/sub-tropics.

## Components of INM and their Relation to Climate Change Mitigation and Adaptation

The main components of INM include chemical fertilizer, crop residue management, manures, soil amendments, biofertilizers and different sources of organic nutrients (**Figure 1**). Several agricultural practices could potentially mitigate GHGs emissions. The major practices include increasing C input by organics, such as compost, manure and plant residues; minimum or no tillage and cover crops to reduce $CO_2$ emission. Judicious water management like mid-season drainage, improving organic nutrient management, such as composting, crop residues decomposition could mitigate $CH_4$ emissions. Real-time N fertilizer management to match crop demand with supply, introducing nano-fertilizers, slow/ controlled release fertilizers and inhibitors are the effective options to reduce the $N_2O$ emissions.

### *I) Site-specific Nutrient Management*

It is known that need-based fertilizer application refers to nutrients/fertilizers application depending upon the plant demand and soil test value. Use of leaf colour chart, chlorophyll meter, SPAD indexing for N management in rice crop in Asian countries are the leading examples of need based N-fertilizer management. Studies have shown that with these approaches, a reduction in the use of N by 12 to 25% could be achieved in India without any yield loss (Ali et al., 2015).

### *II) Organic Manure*

In agriculture, organic manures such as farmyard manure, vermicompost, green manure, *Azolla*, etc., have been used in INM depending on their availability and farmers' convenience. However, one of the major limitations of these manures is their low nutrient content and thus are required in bulk. For example, most organic manures contain 0.5 to 1.5% N as compared to 25-46% N in mineral fertilizers. Despite low nutrient value, organic manures improve soil quality by increasing the soil C content and enhancing biological activity (**Figure 2**). Manures like farmyard manure (FYM) applied add stability to the C in the soil after a decomposition cycle. Manure addition

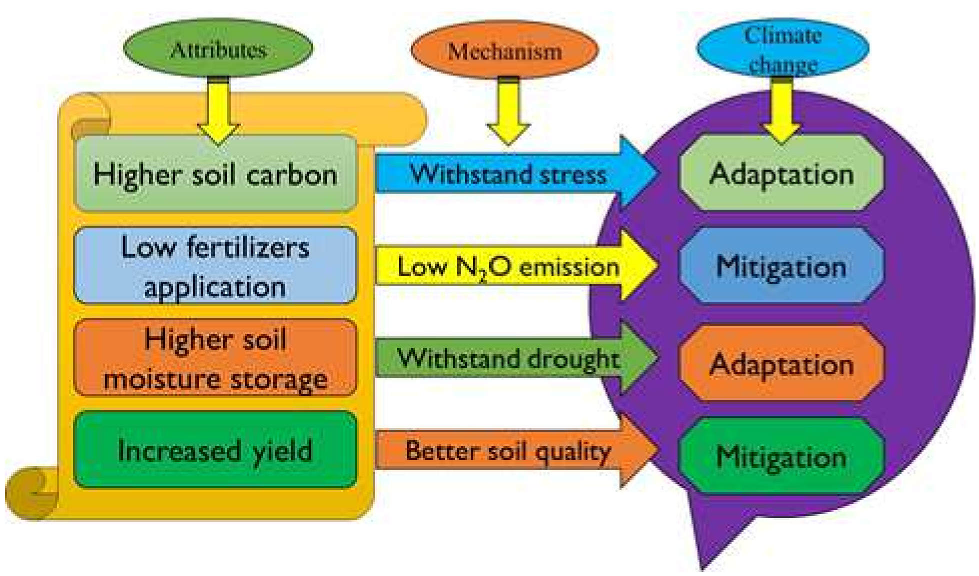



**Figure 2. Effects of organic manure applications to climate change mitigation (Lenka, 2018)**

enhances soil carbon sequestration (carbon sinks) and also enhances physical protection of soil-C through better aggregation. However, enhanced soil C through addition of organic materials to soil does not always mitigate climate change. Conditions where carbon is stabilized or physically protected through aggregation for a long time actually add to the mitigation and also the adaptation value (Tesfai et al., 2016).

### *III) Biofertilizer Application*

Biofertilizers are products or formulations that contain living cells of different types of microorganisms and are used either with seed and/or in soil (application). After being applied, the microbial cells multiply and eventually colonize in the rhizosphere or the interior of the plant and help in solubilizing or increasing the availability of plant nutrients. *Rhizobium* is a symbiotic N-fixer with legumes where as *Azospirillum* and *Azotobacter* are free living N-fixing bacteria. Phosphate solubilizing bacteria like *Bacillus* spp. help in converting P from insoluble forms to soluble forms. Several studies reported the saving in N and P through the use of biofertilizers, though the extent varies depending upon the soil and climate conditions. Tesfai et al. (2016) reported a saving of about 30% of urea due to soil test-based fertilizer application along with biofertilizers. The treatments having Cyanobacteria (blue green algae) application apart from registering higher rice yields, showed lower methane flux as compared to the flooded rice. Low requirement of N from chemical fertilizers due to supplementation of biofertilizers is also likely to reduce the $N_2O$ flux from rice ecosystems. From the point of global warming potential, $CH_4$ and $N_2O$ are more potent than $CO_2$. Thus, the use of biofertilizers can be considered to be a potential climate-smart nutrient management strategy (**Figure 3**).

### *IV) Soil Amendments*

Soil amendments are any organic or inorganic additive added to soil for improving its chemical and/or properties. However, the exact chemical composition and ingredients of soil amendments vary widely among different sources. Soil amendments could be used to rebuild soil-carbon that has been damaged by improper practices to make degraded soils more usable and to sustain the soil health. Several geological and plant-derived materials having some nutritive value could be used as soil-amendments to mitigate GHG emissions in agriculture. The amendments generally used in agriculture include, phosphogypsum, biochar, basic slag, rice-straw, fly ash, etc. Phosphogypsum is reach in sulphate that might reduce the methane formation in soil as well as $CH_4$ emissions (Ali et al., 2012; Hussain et al., 2015; Bhattacharyya et al., 2016). Biochar could be used as climate change mitigation option as it is primarily having more carbon as recalcitrant pool that enhances C-sequestration in the soil in long-run. It also improves the physical properties of soil. Basic slag, a by-product of steel industry having considerable amount of silicate and free iron and manganese oxides that act as electron acceptors (compete with $CO_2$ and acetate) could reduce the $CH_4$ production in soil (Ali et al., 2008, 2013). Apart from this, slag also provides adequate silica that improves rice crop-health, increases the yield potential and develops

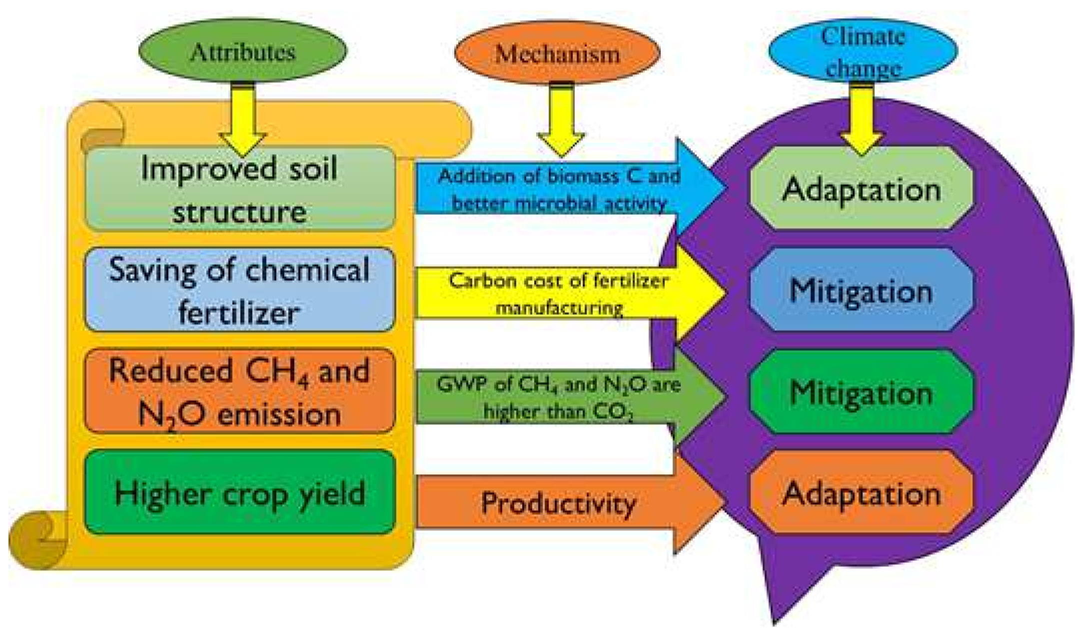



**Figure 3. Contributions of biofertilizer application to climate change mitigation (Lenka, 2018)**

resistance to the pathogens. The combination of urea with rice straw on a 1:1 N-basis could facilitate soil carbon build-up, enhancement of crop yield and also lower $N_2O$ emissions have the potential to mitigate climate change (Bhattacharyya et al., 2012).

**Impact of INM on Carbon Sequestration**

Global warming affects terrestrial C cycle, thereby distorting functions and structure of ecosystems. Soil organic C concentration (SOC), that is already low (<1.0%) in the tropical region, would reduce further in the climatic change scenario (Lal, 2004; Smith et al., 2008; Dash et al., 2019). Soil biological functioning and microbial diversities are changing and are also expected to change under changing climatic conditions in future (Baker, 2004; Bhattacharyya et al., 2016). Mitigation of GHG emissions from agriculture could be very effectively achieved by increasing C sequestration in the soil by any means (Lal, 2004). In this context, precision nutrient management is one of the crucial approaches to SOC sequestration in tropical soils (Bhattacharyya et al., 2007; Mandal et al., 2007; Bhattacharyya et al., 2016). Adequate balanced supply of nutrients through nutrient management INM in soil can enhance biomass production (both above and below ground biomass) and SOC content (van Kessel and Hartley, 2000). Application of compost and organic manure directly enhances the SOC pools more than the application of the same amount of nutrients as inorganic fertilizers alone in a certain period of time up to soil carbon saturation (Gregorich et al., 2001; Bhattacharyya et al., 2016, 2019). Long-term integrated nutrient management increased the SOC pools that not only sequestered $CO_2$, but also enhanced the productivity of soil and reduced the GHG emissions (Gilley and Risse, 2000; Swarup et al., 2000; Manna et al., 2005). The C-sequestration is a challenge in tropical and sub-tropical soils, where climate is harsh and the rate of C-mineralization is higher because of high temperature and low humification capacity of the soil (Ladha et al., 2003; Dash et al., 2019). However, in those regions the long- term INM could enhance the C-sequestration and sustain productivity if implemented properly.

Assessment of changes in SOC fractions under different INM practices is needed for quantifying the C-sequestration (Tian et al., 2015). The photosynthetic $CO_2$ fixation is one of the major sources of C-sequestration (Cai et al., 2014). Estimates showed that sequestration of C within the soil provides a huge sink for atmospheric $CO_2$ (potentially 0.4-0.8 Gt C sequestered globally) (Lal, 2004). Crop-derived C is also one of the major sources of organic C regulating the C cycle in terrestrial ecosystems (Ge et al., 2012). The use of green manures and FYM along with crop residues to the soil would enhance C-sequestration as well as crop production (Singh et al., 2007). Changes in the labile SOC fractions (including water soluble and microbial biomass C) are affected by changes in C inputs (Bharali et al., 2017). Long-term impact of INM on C-pools revealed that irrespective of different INM approaches, there was also an enhancement in the SOC pools in the soil inorganic fertilizer use (NPK) only, that was essential and added beneficial nutrients (macro and micro) to the soil (Biswas and Benbi, 1996; Bharali et al., 2017). In INM, C-rich organic components directly provide nutrients to the soil. At the same time, higher growths of above and below ground biomass (root) under INM additionally provide root exudates C which enrich the SOC continuously and subsequently enhance the C-sequestration in soil (Kukal et al., 2009; Banger et al., 2010; Benbi and Senapati, 2010; Ghosh et al., 2012; Kuzyakov and Gavrichkova, 2010; Saikia et al., 2015).

In this review, we have selected 13 locations in India having rice-wheat cropping system and INM was practiced over long-term (at least for 8 or more years) and tried to compare the C-sequestration status/ potential as an indicator of climate change mitigation among the location and systems (**Table 1**). Further we selected primarily, NPK+FYM approach as the INM and compared it with only NPK treatments (inorganic treatment). The published data in different peer reviewed journals are considered for meta-data analysis. In general, under rice-wheat cropping system, the percentage increase of C-sequestration rate under NPK+FYM was higher over NPK at eight (8) different locations in India; however, in five (5) locations the trend was reversed (**Table 1**). Overall, in most of the locations under long-term rice-wheat cropping system the yield was higher under NPK+FYM than that under NPK. Improvement in the physico-chemical properties and addition of balanced nutrition to soil with addition of organic matter as FYM, resulted in higher water and nutrient use efficiency and also fetched higher yields (Ladha et al., 2003; Hati et al., 2007). In the long-term rice-wheat systems, higher yield with the addition of FYM was also due to correction of unrecognized-nutrient-deficiencies. Additionally, indirect beneficial effects were obtained by nutrient enrichment (potassium on resistance to lodging) (Swarup et al., 2000; Duxbury, 2001; Manna et al., 2005) and prevention/control of soil-borne pathogens (Regmi et al., 2002). However, in 5 locations, mostly in the Indo-Gangetic plain (IGP), where intensive rice-wheat cropping system has been practiced, the yield and carbon sequestration rate in INM was lower than NPK system. Such reverse trend might be due to differences in climate, soil, quality of organic manure used and agronomic management practices followed. Quality of FYM used might be the possible reason for negative C-sequestration in those regions. Further, studies should be carried out to

**Table 1. Location, crop, treatment, duration, fertilizer, yield and carbon sequestration (C-seq) increase over control in various experiments used for assessing carbon status**

| S. No. | Location | Cropping period | Crop | Treatment | Fertilizer dose | Yield (t ha$^{-1}$) | C-seq increase (%) | References |
|---|---|---|---|---|---|---|---|---|
| 1 | Umiam, Meghalaya | 2000–08 (8)* | R** | NPK | 120-26-25 | 3.0 | | |
| | | | | NPK+FYM | NPK + 10 t ha$^{-1}$ | 4.7 | | |
| | | | W | NPK | 90-16-0 | 2.3 | 54.5 | Ghosh et al., 2009 |
| | | | | NPK+FYM | NPK + 10 t ha$^{-1}$ | 3.5 | | |
| 2 | Barrackpore, West Bengal | 1972–01 (28) | R | NPK | 120-26-50 | 3.8 | | |
| | | | | NPK+FYM | NPK + 10 t ha$^{-1}$ | 3.9 | | |
| | | | W | NPK | 120-26-50 | 2.3 | -28.6 | Manna et al., 2005 |
| | | | | NPK+FYM | NPK + 10 t ha$^{-1}$ | 2.3 | | |
| 3 | Mohanpur, West Bengal | 1986–99 (20) | R | NPK | 120-26-33 | 2.0 | | |
| | | | | NPK+FYM | NPK + 7.5 t ha$^{-1}$ | 2.5 | | |
| | | | W | NPK | 120-26-33 | 2.5 | -66.7 | Mandal et al., 2007 |
| | | | | NPK+FYM | NPK + 7.5 t ha$^{-1}$ | 2.8 | | |
| 4 | Varanasi Uttar Pradesh | 1985–97 (12) | R | NPK | 120-26-33 | 4.6 | | |
| | | | | NPK+FYM | NPK + 5 t ha$^{-1}$ | 4.3 | | |
| | | | W | NPK | 60-13-16.5 | 4.0 | 57.1 | Yadav et al., 2000 |
| | | | | NPK+FYM | NPK + 5 t ha$^{-1}$ | 4.2 | | |
| 5 | Faizabad Uttar Pradesh | 1984–85 (14) | R | NPK | 120-26-33 | 4.5 | | |
| | | | | NPK+FYM | NPK + 7 t ha$^{-1}$ | 3.4 | | |
| | | | W | NPK | 60-13-16.5 | 3.5 | -67.6 | Yadav et al., 2000 |
| | | | | NPK+FYM | NPK + 7 t ha$^{-1}$ | 3.6 | | |
| 6 | Samastipur, Bihar | 1988-96 (8) | R | NPK | 120-26-33 | 3.1 | | |
| | | | | NPK + FYM | NPK + 16 t ha$^{-1}$ | 3.7 | 38.5 | Prasad and Sinha, (2000) |
| | | | W | NPK | 120-26-33 | 3.6 | | |
| | | | | NPK + FYM | NPK + 16 t ha$^{-1}$ | 4.0 | | |
| 7 | Kanpur Uttar Pradesh | 1984–97 (14) | R | NPK | 120-26-33 | 3.3 | | |
| | | | | NPK + FYM | NPK + 7.3 t ha$^{-1}$ | 3.0 | -70.6 | Yadav et al., 2000 |
| | | | W | NPK | 120-26-33 | 4.8 | | |
| | | | | NPK + FYM | NPK + 7.3 t ha$^{-1}$ | 4.8 | | |
| 8 | Pantnagar Uttarakhand | 1983–97 (14) | R | NPK | 120-26-33 | 4.2 | | |
| | | | | NPK + FYM | NPK + 6.3 t ha$^{-1}$ | 4.0 | -70.0 | Yadav et al., 2000 |
| | | | W | NPK | 120-26-33 | 4.7 | | |
| | | | | NPK + FYM | NPK + 6.3 t ha$^{-1}$ | 4.4 | | |
| 9 | Ludhiana, Punjab | 1983–97 (15) | R | NPK | 120-26-33 | 6.1 | | |
| | | | | NPK + FYM | NPK + 5 t ha$^{-1}$ | 4.8 | 50.0 | Yadav et al., 2000 |
| | | | W | NPK | 120-26-33 | 4.0 | | |
| | | | | NPK + FYM | NPK + 5 t ha$^{-1}$ | 3.9 | | |
| 10 | Karnal, Haryana | 1994–04 (10) | R | NPK | 120-26-42 | 4.8 | | |
| | | | | NPK + FYM | NPK + 10 t ha$^{-1}$ | 5.3 | 75.0 | Yaduvanshi and Swarup, (2005) |
| | | | W | NPK | 120-26-42 | 3.7 | | |
| | | | | NPK + FYM | NPK + 10 t ha$^{-1}$ | 4.1 | | |
| 11 | Kanpur, Uttar Pradesh | 1984-2009 (25) | R | NPK | 120-60-60 | - | | |
| | | | | NPK + FYM | 60-60-60 + 7.3 t ha$^{-1}$ | - | 42.9 | Nayak et al., 2012 |
| | | | W | NPK | 80-30-00 | - | | |
| | | | | NPK + FYM | NPK + 7.3 t ha$^{-1}$ | - | | |
| 12 | Sabour, Bihar | 1984-2009 (25) | R | NPK | 80-40-20 | 4.2 | | |
| | | | | NPK + FYM | 40-40-20 + 7.3 t ha$^{-1}$ | 5.1 | | |
| | | | W | NPK | 100-50-25 | 3.8 | 100.0 | Nayak et al., 2012 |
| | | | | NPK + FYM | NPK + 7.3 t ha$^{-1}$ | 4.5 | | |
| 13 | Kalyani, West Bengal | 1986-2009 (23) | R | NPK | 120-60-40 | - | | |
| | | | | NPK + FYM | 60-60-40 + 7.3 t ha$^{-1}$ | - | 63.2 | Nayak et al., 2012 |
| | | | W | NPK | 100-60-40 | - | | |
| | | | | NPK + FYM | NPK + 7.3 t ha$^{-1}$ | - | | |

*Figures in the parenthesis are duration of the experiment; ** R - Rice; W - Wheat

**Table 2. Treatment details of different cropping system under INM practices**

| S. No. | Location/ State | Crop rotation | No of years | NPK Treatments | | NPK + FYM Treatments | | | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Crop 1 | Crop 2 | Crop 1 | Crop 2 | FYM (t $ha^{-1}$) | |
| 1 | Almora, UK | Soybean–Wheat | 1973–03 (30) | 20-35-33 | - | 20-35-33 | - | 10 | Kundu et al., 2007 |
| 2 | Palampur, HP | Maize – Wheat | 1972–96 (25) | 120-26-33 | 90-26-25 | 120-26-33 | 90-26-25 | 10 | Sharma et al., 1998 |
| 3 | Gayeshpur, WB | Rice –Mustard–Sesame | 1986–99 (13) | 80-40-40 | 86-64-53 | 80-40-40 | 86-64-53 | 7.5 | Mandal et al., 2007 |
| 4 | Kalyani, WB | Rice–Berseem | 1985–05 (20) | 60-40-40 | 25-50-50 | 60-40-40 | 25-50-50 | 10 | Majumder et al., 2008 |
| 5 | New Delhi | Maize–Wheat–Cowpea (F) | 1971–03 (32) | 120-26-40 | 20-40-20 | 120-26-40 | 20-40-20 | 15 | Rudrappa et al., 2006 |
| 6 | Ranchi, JH | Soybean–Wheat | 1971–02 (30) | 25-26-33 | 80-26-33 | 25-26-33 | 80-26-33 | 10 | Manna et al., 2005 |
| 7 | Nagpur, MH | Cotton–Sorghum | 1986–95 (9) | 60-13-25 | 60-13-25 | 60-13-25 | 60-13-15 | 15 | Venugopalan and Pundarikakshudu, (1998) |
| 8 | Jabalpur, MP | Soybean–Wheat–Maize (F) | 1972–94 (28) | 20-35-16.6 | 120-35-33.2 | 20-35-16.6 | 120-35-33.2 | 15 | Hati et al., 2007 |
| 9 | Indore, MP | Soybean–Wheat | 1995–00 (6) | 120-26-33 | | 120-26-33 | - | 10 | Behera et al., 2007 |
| 10 | Akola, Maharashtra | Sorghum–Wheat | 1988–01 (12) | 100-50-40 | 120-60-60 | 100-50-40 | 120-60-60 | 10 | Manna et al., 2005 |
| 11 | Bellary, Karnataka | Maize–Chickpea | 1978–01 (23) | 60-30-30 | 20-60-20 | 60-30-30 | 20-60-20 | 5 | Vineela et al., 2008 |
| 12 | Hyderabad AP | Sorghum–Castor | 1995–01 (6) | 60-0-0 | - | 60-0-0 | - | 2 | Sharma et al., 2005 |
| 13 | Coimbatore, Tamil Nadu | Finger millet–Maize–Cowpea(F) | 1972–92 (20) | 90-45-17.5 | 135-67-35 | 90-45-17.5 | 135-67-35 | 12.5 | Murugappan et al., 1998 |
| 14 | Cuttack, Odisha | Rice –Rice | 1984–04 (10) | 60-40-40 | 80-40-40 | 60-40-40 | 80-40-40 | 5 | Nayak et al., 2009 |
| 15 | Trivandrum, Kerala | Cassava | 1977–90 (13) | 100-44-83 | - | 100-44-83 | - | 12.5 | John et al., 1998 |

identify the cause of the negative effect but higher nutrient supplying capacity of the soils of IGP (Ladha et al., 2003) and depth of soil up to which C-sequestration were estimated also must be critically examined.

Impact of INM on C-sequestration was also analysed in 15 other than rice-wheat cropping systems in India. The 15 predominant cropping systems include maize-, soybean-, pulses- and rice-based systems (**Table 2**). Meta-data obtained from published literature were critically examined for the assessment. Among the cropping systems studied, the maize-wheat cropping system had highest carbon sequestration potential under NPK+FYM system as compared to the NPK alone. The INM had higher carbon sequestration potential in majority of cropping systems over NPK (**Figure 4**) (except 5 cropping systems). The possible mechanism is that the high lignin content in FYM caused greater accumulation of recalcitrant-C compared to other fractions (Paustian et al., 1992). Carbon sequestration data even in NPK system showed that without any direct application of organic matter in soils, it could also sequester C through balanced application of NPK, probably due to higher crop-biomass addition to soil over the period. However, application of FYM along with inorganic fertilizers eventually led to an additional build-up of SOC in soil, irrespective of sites and cropping systems studied in different parts of India.

Apart from this, in several other studies carbon sequestration was analysed under different INM practices, where rice straw, green manure, pig manure, poultry manure, biochar etc., were added with inorganic fertilizers. In all the cases, the higher C sequestration was observed under different INM treatments over NPK (**Table 3**).

Global food production has to be increased by 60-70% by 2050 to tackle the burgeoning demand from increasing population (Bruinsma, 2009). However, increment of yield accompanies with several unavoidable challenges like, environmental unsustainability, energy crisis, GHGs emissions, etc. (Wheeler and van Braun, 2013; IPCC, 2018). Further, besides food supply, the modern civilization has quenchless demands for natural resources for

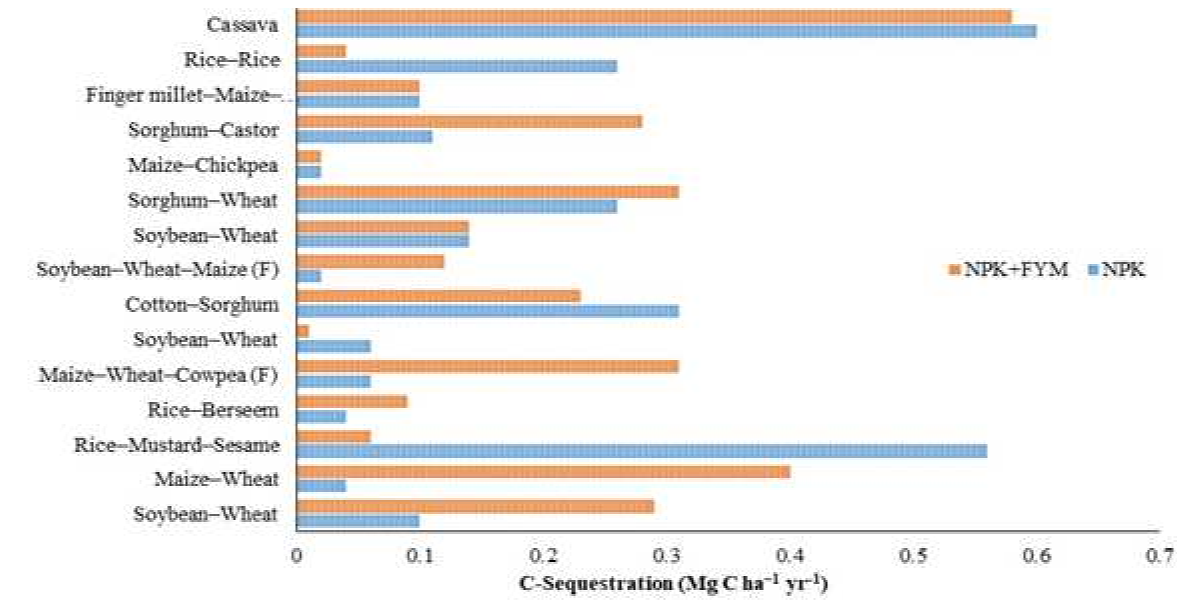



**Figure 4. Carbon sequestration of different cropping systems in India under INM (FYM+NPK) practices**

urbanization, infrastructure and disposal of wastes (urban, industrial and cyber). Now, the actual challenge for us is not only to maximize productivity, but also to maintain balance among complex landscape of production, environment and social equity (Godfray et al., 2010). The agriculture associated GHGs other than $CO_2$ namely, $N_2O$ and $CH_4$ have higher global warming potential which causes climate change (Simpson et al., 2014). Globally, agriculture sector contributes around 20-25% of total GHGs emissions. The trend for global non-$CO_2$-GHG emissions in agricultural sector since 1990 indicated that after a short decline for the last decade of the 20$^{th}$ century, these have been continuously increasing. Frequent use of synthetic fertilizers and pesticides in the recent past might be the primary cause for continuous increase in global GHG emissions by agricultural sector. The unscientific use of fertilizer, especially nitrogen (N), is one of the major causes of environmental pollution such as ground water contamination, eutrophication and GHG emissions (Davidson et al., 2014). Therefore, location-specific integrated (organic + inorganic) innovative practices need to be standardized which could assure higher yields with minimal deterioration of environmental quality (Mueller et al., 2012). Currently,

**Table 3. Carbon sequestration in rice - rice cropping system under different INM treatments**

| S. No. | Country | Year | Cropping | Treatment | Carbon sequestration | Reference |
|---|---|---|---|---|---|---|
| 1 | Northeast Thailand | 1972-2012 | Rice-rice | Control | 12.86 t ha$^{-1}$ | Thammasom et al., 2016 |
| | | | | BC | 17.31 t ha$^{-1}$ | |
| | | | | RS | 14.52 t ha$^{-1}$ | |
| 2 | Wangcheng, South China | 1981-2007 | Rice-rice | | 21.5 g kg$^{-1}$ | Zhang et al., 2011 |
| | | | | Control | | |
| | | | | RS | 22.57 g kg$^{-1}$ | |
| 3 | Nanchang, South China | 1984-2008 | Rice-rice | | 14.15 g kg$^{-1}$ | Zhang et al., 2011 |
| | | | | Control | | |
| | | | | GM | 19.61 g kg$^{-1}$ | |
| 4 | Wuchang, South China | 1981-2009 | Rice-rice | Control | 20.3 g kg$^{-1}$ | |
| | | | | PiM | 25.93 g kg$^{-1}$ | Zhang et al., 2011 |
| 5 | Bangladesh | 2010-2012 | Rice-rice | Control | 22.03 t ha$^{-1}$ | Rahman et al., 2016 |
| | | | | CD | 26.42 t ha$^{-1}$ | |
| | | | | PM | 28.3 t ha$^{-1}$ | |
| | | | | RS | 23.43 t ha$^{-1}$ | |

Note: BC = Biochar; RS = Rice straw; GM = Green manure; PiM= Pig manure; CD = Cow dung; PM = Poultry manure chemical fertilizers, especially N fertilizer, have been misused, especially in intensive agricultural systems both in developed and developing countries (Peng et al., 2002; Zhang et al., 2012a). Therefore, agricultural ecosystems suffer from imbalanced chemical-nutrient loads that many a time leads to nutrient losses through leaching, runoff, volatilization, emissions, immobilization, and subsequent low nutrient-use efficiency. Scientific use of chemical fertilizer by balanced fertilization and integrated nutrient management (inorganic + organic) can significantly minimize nutrient losses and subsequently reduce the GHG emissions and enhance carbon (C) sequestration (Zhang et al., 2011, 2012b; Bhattacharyya et al., 2016). Thus, promising site-specific nutrient management strategies with less environmental impact and reduce the GHGs emissions are the future needs.

World is experiencing higher agricultural production accompanied with significant natural resources degradation, including soil, nutrient and organic carbon. Global climate change could further negatively impact the land resources and agriculture production (Bruinsma, 2009; IPCC 2014, 2018). There is a direct trend of climate change leading to land degradation and vice-versa. So, finding ways and means to reverse this trend is necessary, and to do so, identifying strategies that would promote more production, less GHGs emission and sustainable agricultural-development is necessary. The motto is that the increased crop production and productivity should not come at the expense of the environmental degradation (Chen et al., 2011; IPCC 2014, 2018). Therefore, agro-ecological base approaches like resource conservation, conservation agriculture, integrated nutrient management, climate resilient agriculture, and climate smart agriculture must be followed at local to regional scale. Agricultural soil is one of the important sources of and sinks for GHGs causing as well as mitigating global warming and climate change (Janssens et al., 2003; Bhattacharyya et al., 2016).

The GHG emissions can be mitigated by sequestrating carbon or reducing outgoing fluxes (emission) of $N_2O$, $CH_4$ and $CO_2$ from the system to atmosphere. Eventually, a management practice affects more than one GHG, by more than one mechanism and sometimes in opposite ways; so the net benefits depend on net trade-off of emission of all the three gases ($CO_2$, $CH_4$ and $N_2O$) (Robertson and Grace, 2004; Koga et al., 2006; Bhattacharyya et al., 2016). The options for mitigating $CH_4$ emissions from rice are altering water-management by promoting intermittent irrigation; through mid-season drainage; improving organic C storage by facilitating aerobic degradation of organic matter through composting/ incorporating it into soil during dry period; introduction of rice-cultivars with effective tillers; and promoting cultivars having high root-oxidative-activity. Regulating N-fertilization to an optimal level would further reduce the GHG emissions by curbing direct $N_2O$ emissions and indirectly by reducing the $CO_2$ fluxes from the system (Nayak et al., 2015).

Meta-data of fourteen (14) experiments on INM-GHGs emission in rice-maize, wheat, soybean and oilseed-based cropping system were done for South-East Asia (**Table 4**). The addition of FYM with NPK was taken as INM system in order to maintain uniformity. The

**Table 4. Impact of INM on GHGs emission at different cropping systems**

| Country | Cropping system | Change in GHGs under INM as compared to NPK (Control) | | Reference |
|---|---|---|---|---|
| | | $CH_4$ (%) | $N_2O$ (%) | |
| India | Soybean - Wheat | 14 | -25 | Lenka et al., 2016 |
| Zimbabwe | Rapeseed | - | 35-47 | Nyamadzawo et al., 2014 |
| China | Maize, winter wheat | - | 41.6 | Cai et al., 2013 |
| China | Maize, winter wheat | - | -7 | Ding et al., 2013 |
| India | Rice | 9 | - | Sharma et al., 2015 |
| India | Rice | 16 | - | Sharma et al., 2015 |
| India | Rice - Rice | -44 | -25 | Bhattacharyya et al., 2013 |
| Bangladesh | Rice - Rice | -4 | - | Ali et al., 2014 |
| India | Rice - Rice | -25 | 16 | Bhattacharyya et al., 2012 |
| India | Rice - Rice | - 38 | 25 | Das and Adhya, (2014) |
| India | Rice - Rice | -25 | 12 | Das and Adhya, (2014) |
| China | Rice - Rice | 26.5 | 42.8 | Wang et al., 2015 |
| Vietnam | Rice - Rice | -28 | 39.2 | vanTrinh et al., 2016 |
| Vietnam | Rice - Rice | -133 | -35.4 | Pandey et al., 2014 |

Minus sign shows the reduction in emission

**Table 5. Impact of different component of INM on GHGs emission from different cropping systems**

| S. No. | Country | Year | Cropping | Treatment | Reduction in GHGs emission (%) | | References |
|---|---|---|---|---|---|---|---|
| | | | | | $CH_4$ | $N_2O$ | |
| 1 | Northeast Thailand | 1972-2012 | Rice-rice | RS | -70.6 | - | Thammasom et al., 2016 |
| 2 | India | 2008-2011 | Rice-rice | RS | -24.6 | 16 | Bhattacharyya et al., 2012 |
| | | | | RS+GM | -32.5 | 38.9 | |
| 3 | Philippines | 2003-2012 | Rice-rice | RS | 111.5 | -113.0 | Sander et al., 2014 |
| 4 | China | 2005-2012 | Rice-wheat | RS/WS | -117.2 | -387.5 | Zhang et al., 2015 |

RS = Rice straw; GM = Green manure; WS = Wheat straw

FYM is an important nutrient source for agricultural cropping systems. Reduction in GHG ($CH_4$ and $N_2O$) emissions are affected by INM under different cropping systems in India as well as other countries (**Table 4**). In India, Bangladesh and Vietnam under rice-rice cropping system, the $CH_4$ emission was mostly increased under INM practices over inorganic alone system. However, $N_2O$ emission was primarily reduced under INM over NPK treatments.

Apart from FYM treatments, all other INM components like rice/wheat straw, biochar, green manure, etc., have significant role in GHG emissions. Four different studies were taken to analyse the impact of INM on GHGs mitigation (**Table 5**). However, most of the cases, the GHG emissions were enhanced by the addition of different INM components over the NPK treatment. In India, $CH_4$ emission was enhanced by 24.6 and 32.5%; however, $N_2O$ emission was decreased by 16 and 38.9% under rice-straw (RS) and rice straw + green manure (RS+GM) treatments, respectively (Bhattacharyya et al., 2012). Similarly, in Northeast Thailand and China, the GHGs emissions were also increased by the application of RS/WS over NPK.

Deep placement of urea briquettes (big granules) in the rice paddy could reduce the $CH_4$ and $N_2O$ emissions by 15-20% as compared to urea-broadcasting (Chatterjee et al., 2018). The application of potassium (K) and sulphate ($SO_4^{2-}$) fertilizer in balanced proportion in INM could reduce the $CH_4$ emission. Addition of K increases the oxidizing power of roots as well as enhancess the iron oxidation, which subsequently oxidize methane and reduces its emission. On the other hand, sulphate competes with $CO_2$ and acetate for electron donor in submerged anaerobic soils, hence, reduces the methane production. Therefore, application of potassium sulphate ($K_2SO_4$) in low land rice ecology (Wassmann et al., 1993) is a good option for GHG mitigation. In this connection, use of phosphorus or potassium or any micronutrient cation as sulphate fertilizer is a meaningful option for reduction of methane emission. Manures with a low C:N ratio (C:N <20:1) are always preferred for reducing $CH_4$ emissions as compared to manure/compost with high C:N ratio, as freshly prepared manures having higher C:N ratio favour methanogenesis in the submerged soil. Substitution of fertilizer-N through manure (on equivalent-N basis) could reduce $N_2O$ emissions from the rice-systems as compared to application of inorganic fertilizer alone (Bhattacharyya et al., 2012).

### Integrated Nutrient Management for Climate Change Adaptation

Efficient use of plant nutrients is highly critical for adaptation to climate change. With hotter temperatures and changing precipitation patterns, nutrient availability will further reduce. The adverse impact of climate change on crop yield could be compensated with more and efficient use of plant nutrients. For example, yield reduction because of late sowing of rice as a result of delayed onset of monsoon can be compensated with higher application of N. Improved nutrient management also offers promising opportunities for mitigating GHG emission. For example, technologies including matching N supply with crop demand, using proper fertilizer formulation and right method of application, use of N-transformation inhibitors, optimizing tillage, irrigation and drainage and growing of suitable crop cultivars are some of the potential technologies to reduce $N_2O$ emissions.

The INM has good climate change adaptation potential in terms of imparting additional drought tolerance to crop by water saving and enhancing the water holding capacity of soil. Some component of INM could further promote plant growth even under climate-stress conditions. For example, the need-based nitrogen management by leaf colour chart (LCC) or through chlorophyll meter (Ali et al., 2015a) as a component of INM could reduce the N requirement of rice from 12.5 to 25%, with no loss in yield and higher N use efficiency. At the same time as an adaptation measure, this practice helps in storing additional soil water to the tune of 1392 litres (L) $ha^{-1}$ (Lakshmanan et al., 2015). Similarly, use of green manure as a component of INM could help in storing 1.4 kL $ha^{-1}$ of extra water in the top 30 cm of soil for every 0.01% increase in SOC (carbon stock increase by 1.28 t $ha^{-1}$) and showed a good adaptation capacity in water-deficit condition. Application of biofertilizers like *Azospirillum* and cyanobacteria as a part of INM could save 30–35% of urea and yield increase was between 194 to 271 kg $ha^{-1}$ in *rabi* rice. At the same time, *Pseudomonas* and *Azobacter* as an adaptation measure could prevent the growth and establishment of crop pathogens (Mishra et al., 2012) and improved the soil fertility. Soil amendment in INM, like biochar having high porosity also contributes towards increased water retention and helps in climate change adaptation. Further, the particulate nature of biochar combined with a specific chemical structure enables it to give resistance to microbial degradation in soils (Cheng et al., 2008). Moreover, when applied to sandy soils, it may also contribute to reduce the nitrous oxide emissions from these soils. On the adaptation font, it could increase the water holding capacity of soil by 11% (Cayuela et al., 2014). Therefore, the site-specific INM practices could be considered as a component of 'Climate Smart Agriculture' as it would increase the farmers' adaptation to climate change impacts (*e.g.*, by increasing the buffering capacity of soils to water and nutrients), reducing GHG emissions (by increasing yield; soil carbon sequestration; increasing nutrient use efficiency), and at the same time enhancing the food security (by sustaining crop yields and farmers' income).

A comprehensive literature search revealed that INM enhances crop yields by 8–150% compared with conventional practices, increases water-use efficiency and the economic returns to farmers, while improving grain quality and soil health and sustainability (Wu and Ma, 2015). Evidences indicate that INM practice could be an innovative and environment-friendly strategy for sustainable agriculture worldwide. In addition to facilitating adaptation to climate change in the agriculture sector, the INM approach is also sensitive to changes in climatic conditions and could produce negative effects if soil and crop nutrients are not monitored systematically and changes to fertilizer practices are not made accordingly. In the case of small-scale farmers, these costs may represent too high a proportion of the total variable cost of production, thus ruling out an inorganic fertilizer as a feasible option.

Mitigation and adaptation are often viewed as separate activities, the former aiming to reduce greenhouse-gas emissions and the latter helping to adjust the expected increases in emission of greenhouse gases. However, when it comes to agriculture, the adaptation measures can also generate significant mitigation effects (Pathak et al., 2016). The most common strategies suggested for climate change adaptation include alternate land-use management, intensification of agriculture, crop diversification and conservation agriculture. All these strategies require a suitable nutrient management strategy including INM, which can have significant benefits for adaptation as well mitigation.

## Conclusion

The key of INM approaches is using all possible sources of nutrients to optimize nutrient supply with crop demand in order to reduce nutrient losses and improving crop yield both in spatial and temporal scale. The continuous overuse of chemical fertilizers in association with low resource-use efficiency causes serious environmental pollution; therefore, the use of INM is of fundamental importance for plant growth and environmental concerns. We conclude that the INM provides a "win-win" opportunity to simultaneously increase the crop yield and mitigate the climate change (reduce environmental impact). However, approaches adapted for INM should also be site-specific and must be tailored to local circumstances, as there is no "one-size-fits-all" solution to the complex problems of small holder farmers in diverse agricultural systems. Thus, a demand-driven approach to development programmes would be crucial for future widespread diffusion of INM-driven climate change adaptation and mitigation.

## Acknowledgement

Authors acknowledge the support of National Fellow Project (Agri. Edn. /27/08/NF/2017-HRD; EAP-248) and are grateful to Director of ICAR-National Rice Research Institute (NRRI).

## References

Ali, M.A., Farouque, M.G., Haque, M. and Ul Kabir, A. 2012. Influence of soil amendments on mitigating methane emissions and sustaining rice productivity in paddy soil ecosystems of Bangladesh. *Journal of Environmental Science and Natural Resources* **5**, 179-185.

Ali, M.A., Kim, P.J. and Inubushi, K. 2015. Mitigating yield-scaled greenhouse gas emissions through combined application of soil amendments: a comparative study between temperate and subtropical rice paddy soils. *Science of the Total Environment* **529**, 140-148.

Ali, M.A., Hoque, M.A. and Kim, P.J. 2013. Mitigating global warming potentials of methane and nitrous oxide gases from rice paddies under different irrigation regimes. Ambio, 42(3), pp.357-368.

Ali, M.A., Oh, J.H. and Kim, P.J. 2008. Evaluation of silicate iron slag amendment on reducing methane emission from flood water rice farming. *Agriculture, Ecosystems and Environment* **128**, 21-26.

Ali, M.A., Sattar, M.A., Islam, M.N. and Inubushi, K. 2014. Integrated effects of organic, inorganic and biological amendments on methane emission, soil quality and rice productivity in irrigated paddy ecosystem of Bangladesh: field study of two consecutive rice growing seasons. *Plant and Soil* **378**, 239-252.

Ali, M.A., Thind, H.S., Sharma, S. and Singh, Y. 2015a. Site-specific nitrogen management in dry direct-seeded rice using chlorophyll meter and leaf colour chart. *Pedosphere* **25**, 2–81.

Baker, J.T. 2004. Yield responses of southern US rice cultivars to $CO_2$ and temperature. *Agricultural and Forest Meteorology* **122(3-4)**, 129-137.

Banger, K., Toor, G.S., Biswas, A., Sidhu, S.S. and Sudhir, K. 2010. Soil organic carbon fractions after 16-years of applications of fertilizers and organic manure in a Typic Rhodalf in semi-arid tropics. *Nutrient Cycling in Agroecosystems* **86**, 391-399.

Behera, U.K., Sharma, A.R. and Pandey, H.N. 2007. Sustaining productivity of wheat–soybean cropping system through integrated nutrient management practices on the Vertisols of central India. *Plant and Soil* **297**, 185-199.

Benbi, D.K. and Senapati, N. 2010. Soil aggregation and carbon and nitrogen stabilization in relation to residue and manure application in rice–wheat systems in northwest India. *Nutrient Cycling in Agroecosystems* **87**, 233-247.

Bharali, A., Baruah, K.K., Bhattacharyya, P. and Gorh, D. 2017. Integrated nutrient management in wheat grown in a northeast India soil: impacts on soil organic carbon fractions in relation to grain yield. *Soil and Tillage Research* **168**, 81-91.

Bhattacharyya, P., Dash, P.K., Swain, C.K., Padhy, S.R., Roy, K.S., Neogi, S., Berliner, J., Adak, T., Pokhare, S.S., Baig, M.J. and Mohapatra, T. 2019. Mechanism of plant mediated methane emission in tropical lowland rice. *Science of The Total Environment* **651**, 84-92.

Bhattacharyya, P., Nayak, A.K., Mohanty, S., Tripathi, R., Shahid, M., Kumar, A., Raja, R., Panda, B.B., Roy, K.S., Neogi, S. and Dash, P.K. 2013. Greenhouse gas emission in relation to labile soil C, N pools and functional microbial diversity as influenced by 39 years' long-term fertilizer management in tropical rice. *Soil and Tillage Research* **129**, 93-105.

Bhattacharyya, P., Roy, K.S. and Nayak, A.K. 2016. *Greenhouse Gas Emission from Agriculture*. Narendra Publishing House Pvt. Ltd., New Delhi.

Bhattacharyya, P., Roy, K.S., Neogi, S., Adhya, T.K., Rao, K.S. and Manna, M.C. 2012. Effects of rice straw and nitrogen fertilization on greenhouse gas emissions and carbon storage in tropical flooded soil planted with rice. *Soil and Tillage Research* **124**, 119-130.

Bhattacharyya, T., Pal, D.K., Easter, M., Batjes, N.H., Milne, E., Gajbhiye, K.S., Chandran, P., Ray, S.K., Mandal, C., Paustian, K. and Williams, S., 2007. Modelled soil organic carbon stocks and changes in the Indo-Gangetic Plains, India from 1980 to 2030. *Agriculture, Ecosystems and Environment* **122**, 84-94.

Biswas, C.R. and Benbi, D.K., 1996. Sustainable yield trends of irrigated maize and wheat in a long-term experiment on a loamy sand in semi-arid India. *Nutrient Cycling in Agroecosystems* **46**, 225-234.

Bruinsma, J., 2009. June. The resource outlook to 2050: by how much do land, water and crop yields need to increase by 2050. In Expert meeting on how to feed the world in (Vol. 2050, pp. 24-26).

Cai, Y., Ding, W. and Luo, J. 2013. Nitrous oxide emissions from Chinese maize–wheat rotation systems: a 3-year field measurement. *Atmospheric Environment* **65**, 112-122.

Cai, Z., Liu, G., Zhang, J. and Li, Y., 2014. Development of an activity-directed selection system enabled significant improvement of the carboxylation efficiency of Rubisco. *Protein & Cell* **5(7)**, 552-562.

Cayuela, M.L., van Zwieten, L., Singh, B.P., Jeffery, S., Roig, A. and Sanchez-Monedero, M.A. 2014). Biochar's role in mitigating soil nitrous oxide emissions: a review and meta-analysis, *Agriculture, Ecosystems and Environment* **191**, 5–16.

Chatterjee, D., Mohanty, S., Guru, P.K., Swain, C.K., Tripathi, R., Shahid, M., Kumar, U., Kumar, A., Bhattacharyya, P., Gautam, P. and Lal, B. 2018. Comparative assessment of urea briquette applicators on greenhouse gas emission, nitrogen loss and soil enzymatic activities in tropical lowland rice. *Agriculture, Ecosystems and Environment* **252**, 178-190.

Chen, X.P., Cui, Z.L., Vitousek, P.M., Cassman, K.G., Matson, P.A., Bai, J.S., Meng, Q.F., Hou, P., Yue, S.C., Römheld, V. and Zhang, F.S., 2011. Integrated soil–crop system management for food security. *Proceedings of the National Academy of Sciences* **108(16)**, 6399-6404.

Cheng, C.H., Lehmann, J. and Engelhard, M. 2008. Natural oxidation of black carbon in soils: changes in molecular form and surface charge along a climosequence, *Geochimica et Cosmochimica Acta* **72**, 1598–1610.

Das, S. and Adhya, T.K., 2014. Effect of combine application of organic manure and inorganic fertilizer on methane and nitrous oxide emissions from a tropical flooded soil planted to rice. *Geoderma* **213**, 185-192.

Dash, P.K., Bhattacharyya, P., Roy, K.S., Neogi, S. and Nayak, A.K. 2019. Environmental constraints' sensitivity of soil organic carbon decomposition to temperature, management practices and climate change. *Ecological Indicators* **107**, pp. 105644.

Davidson, E.A., Galloway, J.N., Millar, N. and Leach, A.M. 2014. N-related greenhouse gases in North America: innovations for a sustainable future. *Current Opinion in Environmental Sustainability* **9**, 1-8.

Ding, W., Luo, J., Li, J., Yu, H., Fan, J. and Liu, D. 2013. Effect of long-term compost and inorganic fertilizer application on background $N_2O$ and fertilizer-induced $N_2O$ emissions from an intensively cultivated soil. *Science of the Total Environment* **465**, 115-124.

Duxbury, J.M. 2001. Long-term yield trends in the rice-wheat cropping system: results from experiments and northwest India. *Journal of Crop Production* **3(2)**,.27-52.

Ge, T., Yuan, H., Zhu, H., Wu, X., Nie, S.A., Liu, C., Tong, C., Wu, J. and Brookes, P. 2012. Biological carbon assimilation and dynamics in a flooded rice-soil system. *Soil Biology and Biochemistry* **48**, 39-46.

Ghosh, P.K., Das, A., Saha, R., Khakrang, Tripathi, A.K., Munda, G.C. and Ngachan, S.V. 2009. Long-term effect on soil quality in acid soil of North-East India. *Soil Research* **47**, 372-379.

Ghosh, S., Wilson, B., Ghoshal, S., Senapati, N. and Mandal, B. 2012. Organic amendments influence soil quality and carbon sequestration in the Indo-Gangetic plains of India. *Agriculture, Ecosystems and Environment* **156**, 134-141.

Gilley, J.E. and Risse, L.M. 2000. Runoff and soil loss as affected by the application of manure. *Transactions of the ASAE* **43(6)**, 1583.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. and Toulmin, C. 2010. Food security: the challenge of feeding 9 billion people. *Science* **327(5967)**, 812-818.

Gregorich, E.G., Drury, C.F. and Baldock, J.A. 2001. Changes in soil carbon under long-term maize in monoculture and legume-based rotation. *Canadian Journal of Soil Science* **81**, 21-31.

Hati, K.M., Swarup, A., Dwivedi, A.K., Misra, A.K. and Bandyopadhyay, K.K., 2007. Changes in soil physical properties and organic carbon status at the topsoil horizon of a Vertisol of Central India after 28 years of continuous cropping, fertilization and manuring. *Agriculture, Ecosystems and Environment* **119**, 127-134.

Hussain, S., Peng, S., Fahad, S., Khaliq, A., Huang, J., Cui, K. and Nie, L. 2015. Rice management interventions to mitigate greenhouse gas emissions: a review. *Environmental Science and Pollution Research* **22**, 3342-3360.

IPCC. 2014. *Fifth Assessment Report "Climate Change 2014: Mitigation of Climate Change"*. Working Group III and the 39$^{th}$ Session of the Intergovernmental Panel on Climate Change, Berlin, Germany.

IPCC. 2018. Global Warming of 1.5° C: *An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Intergovernmental Panel on Climate Change.

Janssen, B.H. 1993. Integrated nutrient management: the use of organic and mineral fertilizers. In *The Role of Plant Nutrients for Sustainable Food Crop Production in Sub-Saharan Africa* ( H. van Reuler and W.H. Prins, Eds.) pp. 89–105. VKP: Leidschendam, The Netherlands.

Janssens, I.A., Freibauer, A., Ciais, P., Smith, P., Nabuurs, G.J., Folberth, G., Schlamadinger, B., Hutjes, R.W., Ceulemans, R., Schulze, E.D. and Valentini, R. 2003. Europe's terrestrial biosphere absorbs 7 to 12% of European anthropogenic $CO_2$ emissions. *Science 2003 June 6* **300(5625),** 1538-42.

John, S.K., Mohan Kumar, C.R., Ravindran, C.S. et al. 1998. Long-term effect of manures and fertilizers on cassava production and soil productivity in an acid Ultisol. In *Proceedings of National Workshop on Long-term Soil Fertility Management through Integrated Plant Nutrient Supply* (A. Swarup et al., Eds.), Indian Institute of Soil Science, Bhopal.

Koga, N., Sawamoto, T. and Tsuruta, H. 2006. Life cycle inventory-based analysis of greenhouse gas emissions from arable land farming systems in Hokkaido, Northern Japan. *Soil Science and Plant Nutrition* **52**, 564-574.

Kukal, S.S., Rehana, R. and Benbi, D.K. 2009. Soil organic carbon sequestration in relation to organic and inorganic fertilization in rice–wheat and maize–wheat systems. *Soil and Tillage Research* **102**, 87-92.

Kundu, S., Bhattacharyya, R., Prakash, V., Ghosh, B.N. and Gupta, H.S. 2007. Carbon sequestration and relationship between carbon addition and storage under rainfed soybean–wheat rotation in a sandy loam soil of the Indian Himalayas. *Soil and Tillage Research* **92**, 87-95.

Kuzyakov, Y. and Gavrichkova, O. 2010. Time lag between photosynthesis and carbon dioxide efflux from soil: a review of mechanisms and controls. *Global Change Biology* **16**, 3386-3406.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh, P., Kundu, A.L. and Sakal, R., 2003. How extensive are yield declines in long-term rice–wheat experiments in Asia? *Field Crops Research* **81**, 159-180.

Lakshmanan, A., Geethalakshmi, V. and Nagothu, U.S. 2015a. Impacts of microbial inoculants on productivity, methane flux and carbon sequestration in rice ecosystem, *Technical Brief No*. **14**. Tamil Nadu Agricultural University, Coimbatore.

Lal, R., 2004. Soil carbon sequestration in India. *Climatic Change* **65**, 277-296.

Lenka, N.K., 2018. Role of integrated plant nutrient management in mitigation and adaptations to climate change. *SAARC TRAINING Manual on Integrated Nutrient Management for Improving Soil Health and Crop Productivity*, pp.60.

Lenka, S., Lenka, N.K., Singh, A.B., Singh, B. and Raghuwanshi, J. 2016. Global warming potential and greenhouse gas emission under different soil nutrient management practices in soybean–wheat system of Central India. *Environmental Science and Pollution Research* **24**, 4603-4612.

Majumder, B., Mandal, B. and Bandyopadhyay, P.K. 2008. Soil organic carbon pools and productivity in relation to nutrient management in a 20-year-old rice–berseem agroecosystem. *Biology and Fertility of Soils* **44**, 451-461.

Mandal, B., Majumder, B., Bandyopadhyay, P.K., Hazra, G.C., Gangopadhyay, A., Samantaray, R.N., Mishra, A.K., Chaudhury, J., Saha, M.N. and Kundu, S. 2007.

The potential of cropping systems and soil amendments for carbon sequestration in soils under longterm experiments in subtropical India. *Global Change Biology* **13**, 357-369.

Manna, M.C., Swarup, A., Wanjari, R.H., Ravankar, H.N., Mishra, B., Saha, M.N., Singh, Y.V., Sahi, D.K. and Sarap, P.A. 2005. Long-term effect of fertilizer and manure application on soil organic carbon storage, soil quality and yield sustainability under sub-humid and semi-arid tropical India. *Field Crops Research* **93**, 264-280.

Mishra, D.J., Rajvir, S., Mishra, U.K. and Kumar, S. 2012. Role of bio-fertilizer in organic agriculture: a review. *Research Journal of Recent Sciences* **2**, 39–41.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N. and Foley, J.A. 2012. Closing yield gaps through nutrient and water management. *Nature* **490(7419)**, 254-257.

Murugappan, V., Santhy, P., Selvi, D. et al. 1998. Long-term fertilizer experiment with intensive cropping on an Inceptisol. In *Proceedings of National Workshop on Long-term Soil Fertility Management through Integrated Plant Nutrient Supply* (A. Swarup et al., Eds.), Indian Institute of Soil Science, Bhopal.

Nayak, A.K., Gangwar, B., Shukla, A.K., Mazumdar, S.P., Kumar, A., Raja, R., Kumar, A., Kumar, V., Rai, P.K. and Mohan, U. 2012. Long-term effect of different integrated nutrient management on soil organic carbon and its fractions and sustainability of rice–wheat system in Indo Gangetic Plains of India. *Field Crops Research* **127**, 129-139.

Nayak, D., Saetnan, E., Cheng, K., Wang, W., Koslowski, F., Cheng, Y.F., Zhu, W.Y., Wang, J.K., Liu, J.X., Moran, D. and Yan, X. 2015. Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture. *Agriculture, Ecosystems and Environment* **209**, 108-124.

Nayak, P., Patel, D., Ramakrishnan, B., Mishra, A.K. and Samantaray, R.N. 2009. Long-term application effects of chemical fertilizer and compost on soil carbon under intensive rice–rice cultivation. *Nutrient Cycling in Agroecosystems* **83**, 259-269.

Nyamadzawo, G., Wuta, M., Nyamangara, J., Smith, J.L. and Rees, R.M. 2014. Nitrous oxide and methane emissions from cultivated seasonal wetland (dambo) soils with inorganic, organic and integrated nutrient management. *Nutrient Cycling in Agroecosystems* **100**, 161-175.

Pandey, A., Vu, D.Q., Bui, T.P.L., Mai, T.L.A., Jensen, L.S. and de Neergaard, A. 2014. Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. *Agriculture, Ecosystems and Environment* **196**, 137-146.

Pathak, H., Jain, N., Bhatia, A., Kumar, A. and Chatterjee, D. 2016. Improved nitrogen management:(a key to climate change adaptation and mitigation. *Indian Journal of Fertilisers* **12(11)**, 151-162.

Paustian, K., Parton, W.J. and Persson, J. 1992. Modeling soil organic matter in organicamended and nitrogenfertilized longterm plots. *Soil Science Society of America Journal* **56**, 476-488.

Peng, S.B., Huang, J.L., Zhong, X.H., Yang, J.C., Wang, G.H., Zou, Y.B., Zhang, F.S., Zhu, Q.S., Buresh, R. and Witt, C. 2002. Challenge and opportunity in improving fertilizer-nitrogen use efficiency of irrigated rice in China. *Agricultural Sciences in China* **1(7)**, 776-785.

Prasad, B. and Sinha, S.K., 2000. Long-term effects of fertilizers and organic manures on crop yields, nutrient balance, and soil properties in rice-wheat cropping system in Bihar. In *Long-Term Soil Fertility Experiments in Rice-Wheat Cropping Systems*. **Rice-Wheat Consortium Paper Series 6**, pp. 105-119.

Rahman, F., Rahman, M.M., Rahman, G.M., Saleque, M.A., Hossain, A.S. and Miah, M.G. 2016. Effect of organic and inorganic fertilizers and rice straw on carbon sequestration and soil fertility under a rice–rice cropping pattern. *Carbon Management* **7(1-2)**, 41-53.

Regmi, A.P., Ladha, J.K., Pathak, H., Pasuquin, E., Bueno, C., Dawe, D., Hobbs, P.R., Joshy, D., Maskey, S.L. and Pandey, S.P. 2002. Yield and soil fertility trends in a 20-year rice–rice–wheat experiment in Nepal. *Soil Science Society of America Journal* **66**, 857-867.

Robertson, G.P. and Grace, P.R. 2004. Greenhouse gas fluxes in tropical and temperate agriculture: the need for a full-cost accounting of global warming potentials. In *Tropical Agriculture in Transition - Opportunities for Mitigating Greenhouse Gas Emissions?* pp. 51-63. Springer, Dordrecht.

Rudrappa, L., Purakayastha, T.J., Singh, D. and Bhadraray, S. 2006. Long-term manuring and fertilization effects on soil organic carbon pools in a Typic Haplustept of semi-arid sub-tropical India. *Soil and Tillage Research* **88**, 180-192.

Saikia, P., Bhattacharya, S.S. and Baruah, K.K. 2015. Organic substitution in fertilizer schedule: impacts on soil health, photosynthetic efficiency, yield and assimilation in wheat grown in alluvial soil. *Agriculture, Ecosystems and Environment* **203**, 102-109.

Sander, B.O., Samson, M. and Buresh, R.J. 2014. Methane and nitrous oxide emissions from flooded rice fields as affected by water and straw management between rice crops. *Geoderma* **235**, 355-362.

Sharma, K.L., Mandal, U.K., Srinivas, K., Vittal, K.P.R., Mandal, B., Grace, J.K. and Ramesh, V. 2005. Long-term soil management effects on crop yields and soil quality in a dryland Alfisol. *Soil and Tillage Research* **83**, 246-259.

Sharma, S.K., Singh, Y.V., Tyagi, S. and Bhatia, A. 2015. Influence of rice varieties, nitrogen management and planting methods on methane emission and water productivity. *Paddy and Water Environment* **14**, 325-333.

Sharma, S.P., Sharma, J. and Subehia, S.K. 1998. Long-term effects of chemical fertilizers on crop yields, nutrients uptake and soil environment in western Himalayan soils. In *Proceedings of National Workshop on Long-term Soil Fertility Management through Integrated Plant*

*Nutrient Supply* (A. Swarup et al., Eds.), Indian Institute of Soil Science, Bhopal.

Simpson, D., Arneth, A., Mills, G., Solberg, S. and Uddling, J. 2014. Ozone – the persistent menace: interactions with the N cycle and climate change. *Current Opinion in Environmental Sustainability* **9**, 9-19.

Singh, G., Jalota, S.K. and Singh, Y. 2007. Manuring and residue management effects on physical properties of a soil under the rice–wheat system in Punjab, India. *Soil and Tillage Research* **94**, 229-238.

Smith, P., Fang, C., Dawson, J.J. and Moncrieff, J.B. 2008. Impact of global warming on soil organic carbon. *Advances in Agronomy* **97**, 1-43.

Swarup, A., Manna, M.C., Singh, G.B., 2000. Impact of land use and management practices on organic carbon dynamics in soils of India. In *Global Climate Change and Tropical Ecosystems* (R. Lal, J.M. Kimble and B.A. Stewart, Eds.), pp. 261–281. Advances in Soil Science. CRC Press, Boca Raton, FL.

Tesfai, M., Moed, I. and Greipsland, I. 2016. Integrated soil management practices: adaptation and mitigation to climate change. In *Climate Change and Agricultural Development*, pp. 177-200). Routledge.

Thammasom, N., Vityakon, P., Lawongsa, P. and Saenjan, P. 2016. Biochar and rice straw have different effects on soil productivity, greenhouse gas emission and carbon sequestration in Northeast Thailand paddy soil. *Agriculture and Natural Resources* **50(3)**, 192-198.

Tian, K., Zhao, Y., Xu, X., Hai, N., Huang, B. and Deng, W. 2015. Effects of long-term fertilization and residue management on soil organic carbon changes in paddy soils of China: a meta-analysis. *Agriculture, Ecosystems and Environment* **204**, 40-50.

van Kessel, C. and Hartley, C. 2000. Agricultural management of grain legumes: has it led to an increased in nitrogen fixation? *Field Crops Research* **65**, 165-181.

Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R. and Six, J. 2011. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant and Soil* **339**, 35-50.

Venugopalan, M.V. and Pundarikakshudu, R. 1998. Long-term fertilizer experiment in Cotton based cropping in rainfed Vertisols. *Proceedings of National Workshop on Long-term Soil Fertility Management through Integrated Plant Nutrient Supply* (A. Swarup et al., Eds.), Indian Institute of Soil Science, Bhopal.

Vineela, C., Wani, S.P., Srinivasarao, C., Padmaja, B. and Vittal, K.P.R. 2008. Microbial properties of soils as affected by cropping and nutrient management practices in several long-term manurial experiments in the semi-arid tropics of India. *Applied Soil Ecology* **40**, 165-173.

van Trinh, M., Tesfai, M., Borrell, A., Nagothu, U.S., Bui, T.P.L. and Quynh, V.D., 2017. Effect of organic, inorganic and slow-release urea fertilisers on $CH_4$ and $N_2O$ emissions from rice paddy fields. *Paddy and Water Environment* **15(2)**, 317-330.

Wang, W., Sardans, J., Lai, D.Y., Wang, C., Zeng, C., Tong, C., Liang, Y. and Peñuelas, J. 2015. Effects of steel slag application on greenhouse gas emissions and crop yield over multiple growing seasons in a subtropical paddy field in China. *Field Crops Research* **171**, 146-156.

Wassmann, R., Papen, H. and Rennenberg, H. 1993. Methane emission from rice paddies and possible mitigation strategies. *Chemosphere* **26**, 201-217.

Wheeler, T. and von Braun, J. 2013. Climate change impacts on global food security. *Science* **341(6145)**, 508-513.

Wortman, S.E., Galusha, T.D., Mason, S.C. and Francis, C.A. 2012. Soil fertility and crop yields in long-term organic and conventional cropping systems in Eastern Nebraska. *Renewable Agriculture and Food Systems* **27**, 200-216.

Wu, W. and Ma, B. 2015. Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: a review. *Science of the Total Environment* **512**, 415-427.

Yadav, R.L., Dwivedi, B.S., Prasad, K., Tomar, O.K., Shurpali, N.J. and Pandey, P.S. 2000. Yield trends, and changes in soil organic-C and available NPK in a long-term rice–wheat system under integrated use of manures and fertilizers. *Field Crops Research* **68**, pp.219-246.

Yaduvanshi, N.P.S. and Swarup, A. 2005. Effect of continuous use of sodic irrigation water with and without gypsum, farmyard manure, pressmud and fertilizer on soil properties and yields of rice and wheat in a long-term experiment. *Nutrient Cycling in Agroecosystems* **73**, 111-118.

Zhang, F., Cui, Z., Chen, X., Ju, X., Shen, J., Chen, Q., Liu, X., Zhang, W., Mi, G., Fan, M. and Jiang, R. 2012a. Integrated nutrient management for food security and environmental quality in China. *Advances in Agronomy* **116**, 1-40.

Zhang, F., Cui, Z., Fan, M., Zhang, W., Chen, X. and Jiang, R. 2011. Integrated soil–crop system management: reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. *Journal of Environmental Quality* **40**, 1051-1057.

Zhang, L., Zheng, J., Chen, L., Shen, M., Zhang, X., Zhang, M., Bian, X., Zhang, J. and Zhang, W. 2015. Integrative effects of soil tillage and straw management on crop yields and greenhouse gas emissions in a rice–wheat cropping system. *European Journal of Agronomy* **63**, 47-54.

Zhang, W., Xu, M., Wang, X., Huang, Q., Nie, J., Li, Z., Li, S., Hwang, S.W. and Lee, K.B. 2012b. Effects of organic amendments on soil carbon sequestration in paddy fields of subtropical China. *Journal of Soils and Sediments* **12**, 457-470. ■

Indian Journal of Fertilisers **16** (4) : 400-402, April 2020

# FAI Activities

## Training Programme on Challenges and Strategies for Fertilizer Industry

The Fertiliser Association of India - Northern Region (FAI-NR) organized a training programme on **Challenges and Strategies for Fertilizer Industry** during February 12-15, 2020. Sixty-five participants from seventeen companies attended the programme. The training programme was inaugurated by Mr. Satish Chander, Director General, FAI, New Delhi.

In his inaugural address, Mr. Satish Chander stated that Mr. Rakesh Kapur, Joint Managing Director, IFFCO was to come to inaugurate this programme. However, due to his pressing engagement in New Delhi, he was unable to come. Mr. Rakesh Kapur has conveyed his good wishes for the success of this programme.

DG, FAI requested the participants to be informal and participative and get the doubts cleared from the learned faculty. He further stated that all subjects from production/import to sale of fertilizers to farmers will be covered in the training programme and the same will be quite useful and wished the participants a comfortable stay in Jaisalmer.

DG, FAI mentioned that food security has to be sustained to feed the burgeoning population of the country. The food grain production reached a level of 285 million metric tonnes (MMT) in 2018-19 and is expected to be more in the current year. Similarly, production of horticultural crops is on rise. The country produced more than 300 MMT of horticultural crops in 2018-19. Fertilizer has played and would continue to play an important role in enhancing agricultural production. The other sources of plant nutrients such as bio-fertilizers, organic manures, recycling of crop residue etc., cannot meet full nutrient requirement of the crops. He also gave his opinion about zero budget-farming where only cow dung and urine are to used. Issue is whether without fertilizer, India can ensure food security. Organic farming is practiced only in 2% area of the world. To feed the projected population of 1.7 billion by 2050, food grain requirement will be 400 MMT. He stated that plant nutrient requirement may reach to 60 MMT (45 MMT from fertilizers + 15 MMT from organic and biological sources) in 2050 from present level of 34 MMT (27 MMT from fertilizer + 7 MMT from organic and biological sources).

DG, FAI underlined that synthesis of ammonia a basic ingredient for production of fertilizers in 1900s had been the land mark of the inventors-Haber-Bosch. Half of the world population would have been deprived of food if this invention would not have taken place.

Mr. Satish Chander then made a presentation on Fertilizer Policies-Issues and Challenges. He gave an outline of capacity, production, consumption and import of different fertilizer products/raw materials/ feedstock, nutrient use pattern with time, etc.


Mr. Satish Chander lighting the lamp at the inaugural session

He mentioned that fertilizer industry is a world class industry in terms of operational efficiency, energy use and environmental standards. DG, FAI mentioned that energy consumption of urea plants has come down to 5.88 Gcal/MT in 2018-19 from 8.87 Gcal/MT in 1987-88. The water consumption has reduced from 12.0 $M^3$/MT in 1990-91 to 6.3 $M^3$/MT of urea in 2018-19. The industry has been performing the onerous task of reaching subsidy to the farmers on behalf of the government for more than 40 years. Despite high energy cost, indigenous production of urea from the existing plants is cheaper than imported urea. Indigenous gas based plants saved subsidy of about Rs. 140,000 crores during the period 2006-07 to 2018-19. Urea pricing/subsidy policy formulated in 1970s continues. Due to stagnant of MRP for last several years despite steep increase in cost, the share of subsidy in total cost of urea increased from 7% in 1980-81 to 79% in 2019-20. On the other hand, the share of subsidy in total cost of DAP and MOP is only 30% and 26%, respectively.

Mr. Satish Chander also covered major issues of the urea sector such as non-revision of fixed cost, tightening of energy norms 4 times after implementation of NPS policy without recognizing investments in energy saving projects, declining share of domestic gas, un-remunerative production beyond reassessed capacity, etc. He presented the figures of requirement of fertilizer subsidy vis-à-vis budget allocation from 2015-16 to 2019-20. The subsidy arrears may be around Rs. 60,000 crores at the end of 2019-20. He also stated that earlier subsidy payment was linked to fertilizers reaching the district. Now it is based on sales through POS machines under DBT system. There is a time lag of 6 to 8 months from manufacture to sale of urea due to seasonal demand. Therefore, there is a requirement of additional working capital of at least 6 months. Currently urea policy

Participants with DG, FAI, Faculty and FAI Officials

provides only 45 days working capital. Further there is no provision in the policy from payment of interest on delayed payment of subsidy.

While deliberating on policy for P&K fertilizers, Mr. Satish Chander mentioned that P&K fertilizers are governed by nutrient based subsidy (NBS) policy since 2010. He further mentioned that basic economic principle of keeping import duty on inputs lower than finished products is being violated in the sector. Customs duty on ammonia and finished products is same at 5%. Therefore, faulty taxation regime for the sector discourages domestic production.

DG, FAI presented a list of policies formulated in recent period. These include new urea policy 2015, pooling of gas price, 100% coating of urea with *neem* oil, revision in specification of *neem* coated urea, inclusion of freight reimbursement for coastal shipping/inland water ways, implementation of GST effective from 1$^{st}$ July, 2017, rationalization of size of urea bag to 45 kg, revision of dealer's margin of urea to Rs. 354 per MT, extension of present energy norms for further period of 2 years i.e. upto March, 2020, further continuation of target energy norms for 5 years w.e.f. 1$^{st}$ April 2020, withdrawal of additional VAT on input in Gujarat and Uttar Pradesh and direct benefit transfer of fertilizer subsidy to farmers, etc

Mr. Satish Chander in his concluding remarks emphasized on the need for timely payment of fertilizer subsidy to the industry, payment of increase in fixed cost of urea under Modified NPS-III with minimum level of Rs. 2300/MT, etc. He suggested for complete reform in urea policy by bringing it under NBS policy initially and decontrol the fertilizer sector. There is a need for withdrawal/reduction in customs duty on raw materials for manufacture of P&K fertilizers and early payment of input tax credit under GST.

Earlier in his welcome address, Dr. D.S. Yadav, Director (Marketing), FAI, New Delhi explained the objectives of the programme and briefed about the course content to be covered by the faculty. He apprised the participants about the FAI, its activities and training programmes organized and different publications brought out by the Association. He made an appeal to the participants to become professional members of the FAI to get benefit from the activities of the FAI.

Mr. Harinder Kaushik, Officer, FAI-NR, New Delhi proposed a vote of thanks to the Chief Guest, invitees, faculty and participants..

The four day residential training programme covered important topics, namely Efficient Nutrient Management for Sustainable Agriculture by Dr. K.K. Singh, Group Head - Agri-services, Adventz Group, Pune; Fertilizer and Raw Material Scenario and Challenges in Fertilizer Marketing; Production, Consumption and Marketing of Specialty Fertilizers by Dr. D.S. Yadav; Salient Features of Fertilizer Control Order (FCO) 1985 by Dr. Ravindra Yadav, Assistant Director, CFQC&TI, Faridabad; Improving Productivity and Cost Optimization of Ammonia and Urea Fertilizer Plants and also of Complex Fertilizer Plants by Mr. Manish Goswami, Chief (Technical), FAI, New Delhi; Assessment of DBT in Fertilizer Sector by Mr. S. Kundu, Head (Corporate Affairs), Adventz Group, Bengaluru; Logistics Operations and Cost Optimization by Mr. K.U. Thankachen, Director (Marketing), RCFL, Mumbai; Effective Fertilizer Marketing Strategies in Changing Environment by Mr. T.S. Rao, Chief General Manager (Marketing), KRIBHCO, Noida; International Trade and Port Operations by Dr. Satish Maheshwari, Consultant, NFL, Noida; and Performance Management System by Mr. Nakul Pathak, Senior General Manager, IFFCO, New Delhi.

Mr. V.S. Sirohi, Marketing Director, KRIBHCO, Noida was the chief guest at the valedictory session and distributed certificates to the participants at the end of the programme.

Beginning his address Mr. Sirohi stated that he was pleased to interact with wide spectrum of executives of the fertilizer industry. Fertilizer is vital for agricultural development and agriculture in the country largely depends on behaviour of south-west monsoon. He mentioned that even the drought prone area like Rajasthan, Maharashtra, Odisha, Telangana and Andhra Pradesh also received good rains in the current year of 2019-20. The rainfall was deficient in West Uttar Pradesh and Haryana. However, these states have good irrigation facilities. He stated that the country may achieve record production of food grains in 2019-20. Mr. Sirohi gave product-wise sale of fertilizers from April 2019 to January, 2020. Except MOP, the sale of other fertilizer products remained high compared to corresponding period of 2018-19. Except NP/NPK, the production of other fertilizer products remained more during the period. However, import of DAP and MOP declined. Further, he pointed out that there has been no significant addition in capacity of P&K fertilizers over the years. However, there may be addition of about 6.5 MMT in capacity of urea by 2022 or so with start of production of 5 new plants. With this, the import of urea may be negligible.

Mr. Sirohi deliberated on the challenges related to DBT scheme. He stated that there are still many issues such as non-availability of network in remote areas; sales of fertilizers by retailers without using POS machines thereby resulting in blockage of subsidy to the manufacturers/importers; non-functioning of POS machines and time taken in their repairs; mismatch of finger points of the buyers; increase in working capital requirement of urea units to 6 months, etc. He further stated that unless the sale of fertilizers by the retailers through POS machines is not made mandatory, fertilizer industry will always be sufferer.


Mr. V.S. Sirohi giving certificate to a participant

Mr. Sirohi also discussed about the fertilizer policies and challenges being faced by the industry. He underlined that Government of India should device a system for direct transfer of fertilizer subsidy to the farmers in true sense as in case of DBT in other sectors.

Mr. Sirohi stated that bringing efficiency in production, energy conservation, logistics, warehousing, distribution, inventory management and credit management (faster realization of money) is the key to minimize operations cost. In view of the competitive market, he advocated for creating brand equity at the market place and every brand should have an USP in primary, secondary and territory market.

On behalf of participants, Mr. Pavan Bet, Senior Manager (Electrical), RCFL, Thal, Raigad, Maharashtra and Mr. Vinod Kumar Godara, Junior Sales Officer, IPL, Jalandhar, Punjab shared their views about the programme and appreciated the course content and faculty of the programme. Participants found the programme very useful and educative.

Mr. Harinder Kaushik proposed a formal vote of thanks at the end of programme. ■

# Fertilizer Scene

Production of fertilizer nutrients N and $P_2O_5$ showed mixed growth during February 2020 over February 2019. Production of N at 1.156 million metric tonnes (MMT) registered increase of 4.4%, during the period. However, production of $P_2O_5$ at 0.366 MMT during February 2020 fell by 4.7% over February 2019. Among the major fertilizers, production of urea and SSP increased by 6.6% and 5.7%, respectively, during February 2020 over February 2019. Whereas, production of DAP and NP/NPK complex fertilizers decreased by 6.5% and 6.3%, respectively, during the period. Capacity utilization of N increased from 92.7% during February 2019 to 96.8% during February 2020. Conversely, in case of $P_2O_5$, it reduced from 64.7% to 61.5% during the same period. Production of N surpassed the target by 4.6 thousand tonnes during February 2020. However, production of $P_2O_5$ fell short from its target by 40.6 thousand tonnes during the same month.

Compared to the previous month, i.e., January 2020, production of N & $P_2O_5$ declined by 6.8% and 9.9%, respectively, during February 2020.

Production of total fertilizer nutrients ($N+P_2O_5$) at 17.114 MMT during April/February 2019-20 showed a positive growth of 4.8% over the corresponding period in the previous year. Both N and $P_2O_5$ witnessed positive growth during the period. Production of N at 12.665 MMT and $P_2O_5$ at 4.449 MMT registered increase of 4.1% and 6.8%, respectively, during April/February 2019-20 over April/February 2018-19. Among the major fertilizers, production of urea, DAP and SSP increased by 3.2%, 22.8% and 5%, respectively, during April/February 2019-20 over April/February 2018-19. However, production of NP/NPK complex fertilizers fell by 2.5% during the period. Most of the NP/NPK complex fertilizers registered fall in production during April/February 2019-20 over April/February 2018-19 except 20-20-0-13 (APS), 24-24-0 (ANP), 15-15-15 and 17-17-17, which witnessed positive growth during the period. Capacity utilization of N and $P_2O_5$ increased from 92.4% and 63.9% during April/February 2018-19 to 99.6% and 68%, respectively, during April/February 2019-20.

Production of N and $P_2O_5$ fell short from the target by 930.1 thousand tonnes and 532.3 thousand tonnes, respectively, during April/February 2019-20. T**able** given below shows production of N and $P_2O_5$ during February 2020 and April/February 2019-20 and compares with the corresponding period in the previous year.

**All India Production Target, Production and Capacity Utilisation of N and $P_2O_5$**
**February 2020 & 2019 and April/February 2019-20 & 2018-19**

| Item | Jan. 2019^P | Feb. 2020^P | Feb. 2019 | ± % variation in Feb. 2020 over Feb. 2019 | Cumulative (April /February) 2019-20 P | Cumulative (April /February) 2018-19 | ± % variation in April/Jan. 2019-20 over April/Jan. 2018-19 |
|---|---|---|---|---|---|---|---|
| | ('000 tonnes) | | | | ('000 tonnes) | | |
| **I. NITROGEN (N)** | | | | | | | |
| **A. Target of Production** | **1276.3** | **1151.3** | **1198.1** | **-3.9** | **13595.0** | **13218.6** | **2.8** |
| **B. Production** | **1240.7** | **1155.9** | **1107.5** | **4.4** | **12664.9** | **12166.3** | **4.1** |
| a) Straight fertilizers | 1042.8 | 980.7 | 918.7 | 6.7 | 10522.8 | 10172.4 | 3.4 |
| b) Complex fertilizers * | 197.9 | 175.2 | 188.7 | -7.2 | 2142.1 | 1993.9 | 7.4 |
| **C. Capacity Utilisation (%)** | **103.9** | **96.8** | **92.7** | | **99.6** | **92.4** | |
| **II. PHOSPHATE ($P_2O_5$)** | | | | | | | |
| **A. Target of Production** | **451.1** | **406.2** | **433.0** | **-6.2** | **4981.6** | **5051.8** | **-1.4** |
| **B. Production** | **405.9** | **365.6** | **383.7** | **-4.7** | **4449.3** | **4164.7** | **6.8** |
| a)Straight fertilizers (through SSP) | 51.5 | 50.4 | 47.6 | 5.9 | 627.6 | 597.5 | 5.0 |
| b) Complex fertilizers * | 354.4 | 315.2 | 336.1 | -6.2 | 3821.7 | 3567.2 | 7.1 |
| **C. Capacity Utilisation (%)** | **68.3** | **61.5** | **64.7** | | **68.0** | **63.9** | |

P = Provisional. Note: Totals may not exactly tally due to rounding of figures. * = DAP+ NP/NPKs

**RNI No.: DEL ENG/2005/14813** Delhi Postal Regd. No.: DL-SW-1/4072/2018-2020
Posted without Prepayment of Postage under Licence No. U(SE)-01/2018-2020

Printed and Published by D. Ramakrishnan for The Fertiliser Association of India, FAI House,10, Shaheed Jit Singh Marg, New Delhi - 110067
Published from The Fertiliser Association of India, FAI House, 10 Shaheed Jit Singh Marg, New Delhi - 110067
Editor : Satish Chander