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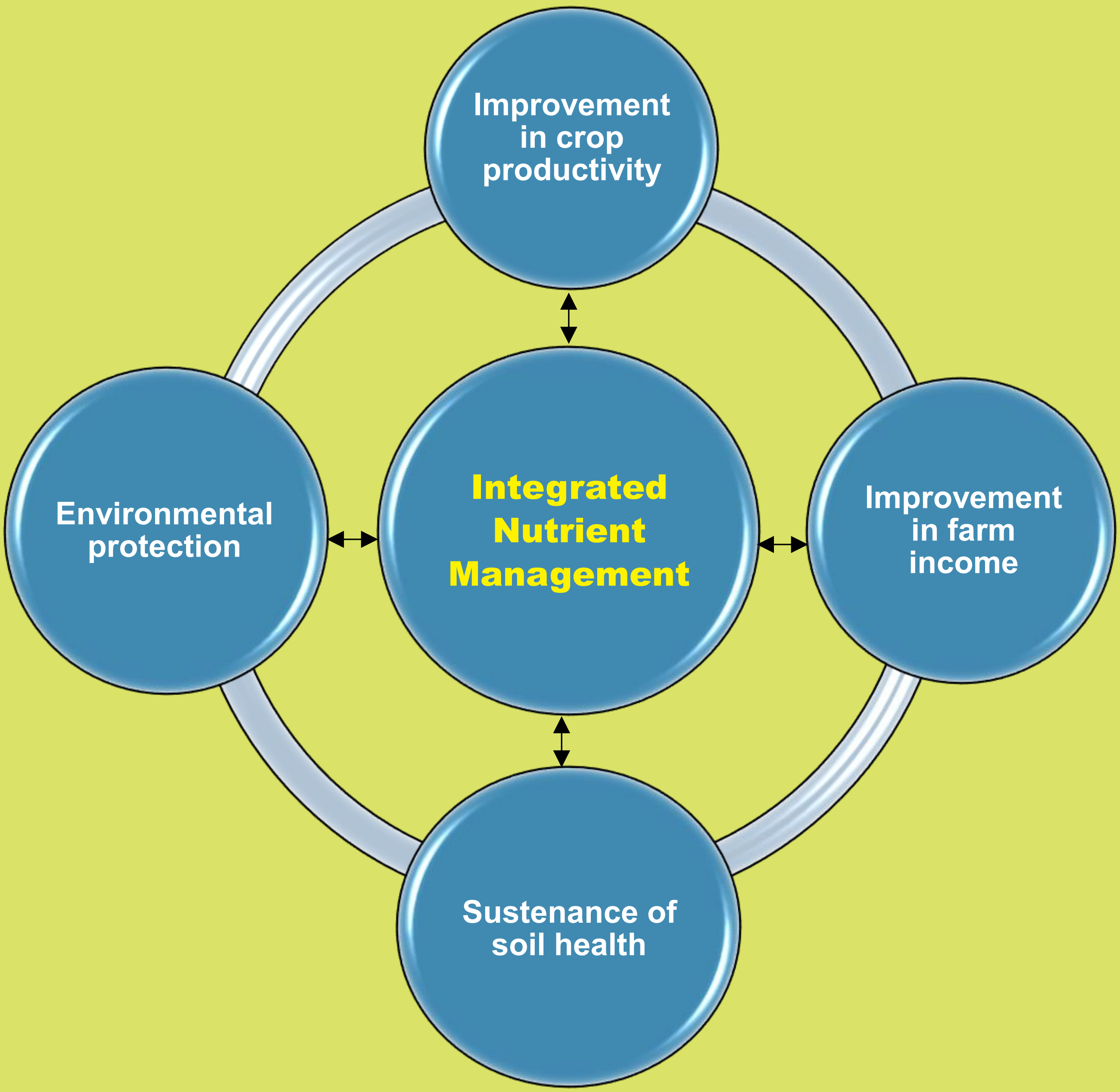

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Our Cover

Cover depicts components of INM and their importance in agriculture

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Integrated Nutrient Management Strategies for Rainfed Agro-ecosystems of India

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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 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

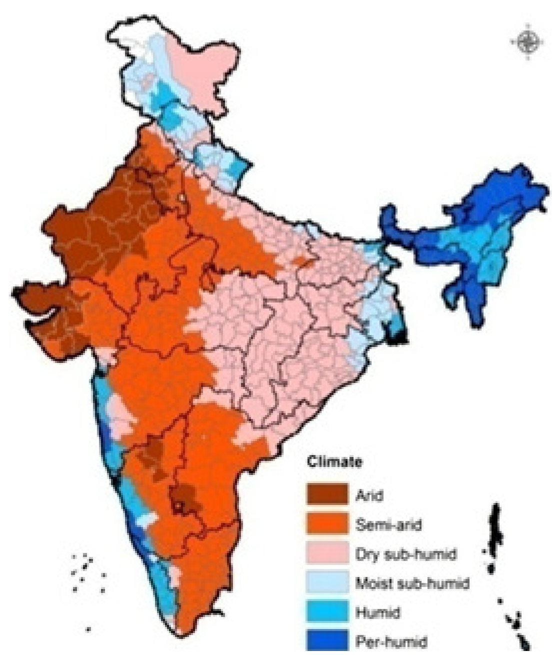

Figure 1. Predominant rainfed dryland regions in India (Arid, Semi-Arid, Dry sub-humid) (Source: Srinivasarao et al., 2015)

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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) Medium to deep (45-90 cm) Deep (>90 cm)	135-145/45 cm 145 - 270/90 cm 300/m
Alfisols and related soils	Shallow to medium (up to 45 cm) Deep (>90 cm)	40 - 70/45 cm (sandy loam) 70-100/45 cm (loam) 180-200/90 cm
Aridisols	Medium to deep (up to 90 cm)	80 - 90/90 cm
Inceptisols	Deep	90 - 100/m (loamy sand) 110 - 140/m (sandy loam) 140 - 180/m (sandy loam)
Entisols	Deep	110 - 140/m (sandy loam) 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

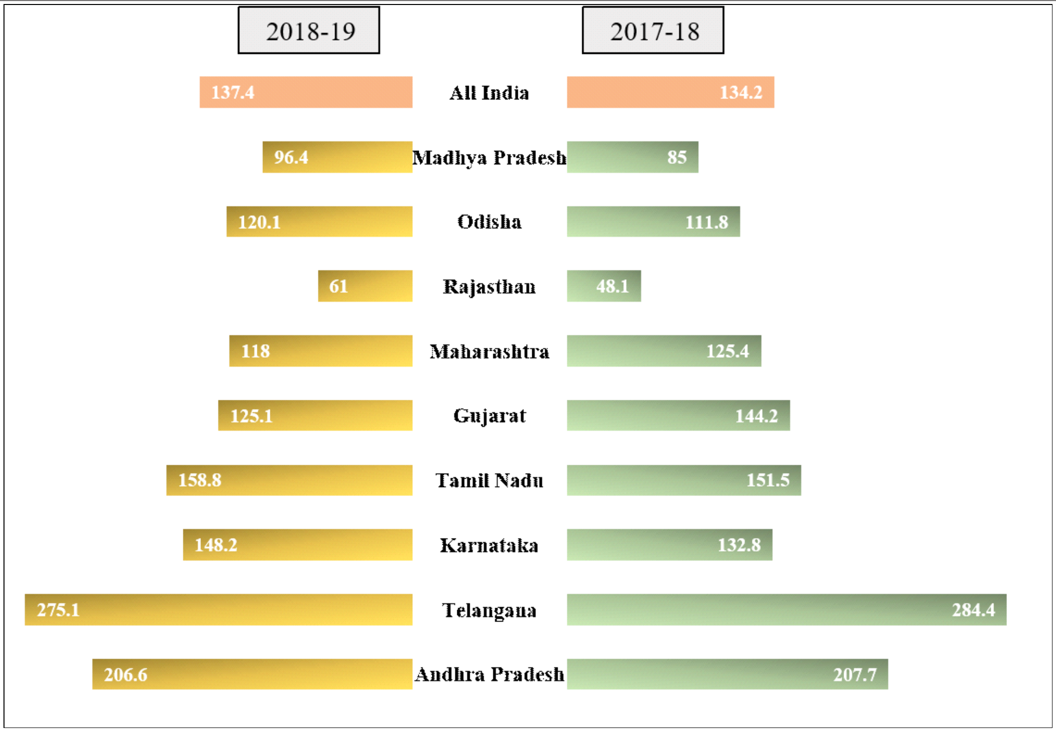

Figure 2. Fertilizer consumption by predominant rainfed states of India during 2017-18 and 2018-19 (Source: FAI, 2019)

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

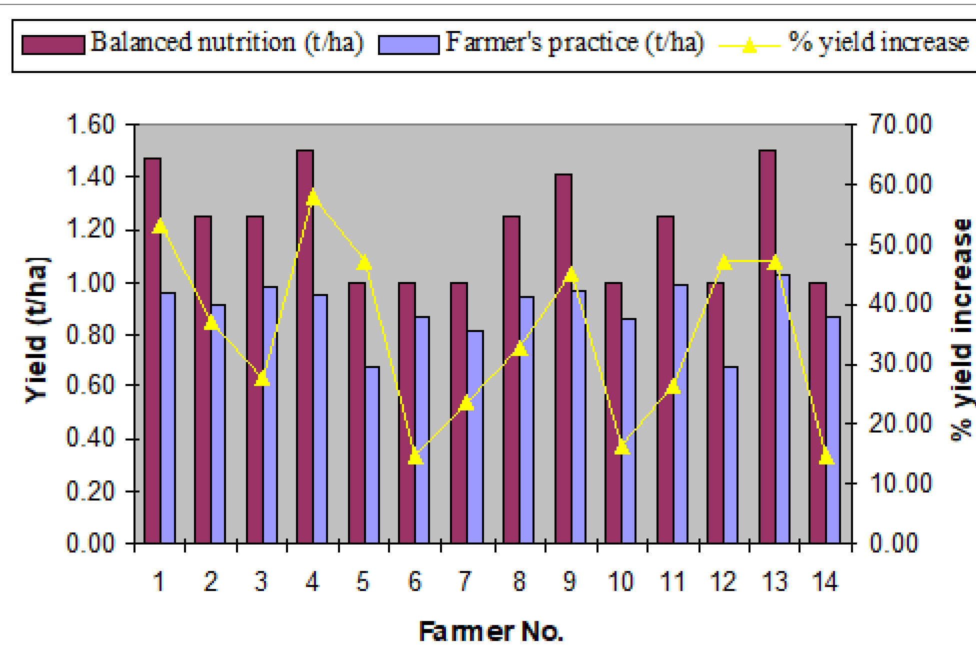

Figure 3. Impact of balanced fertilization in chickpea (var. JG-11) yield in some selected farmer's field of Seethagondi cluster of Adilabad district, Telangana

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

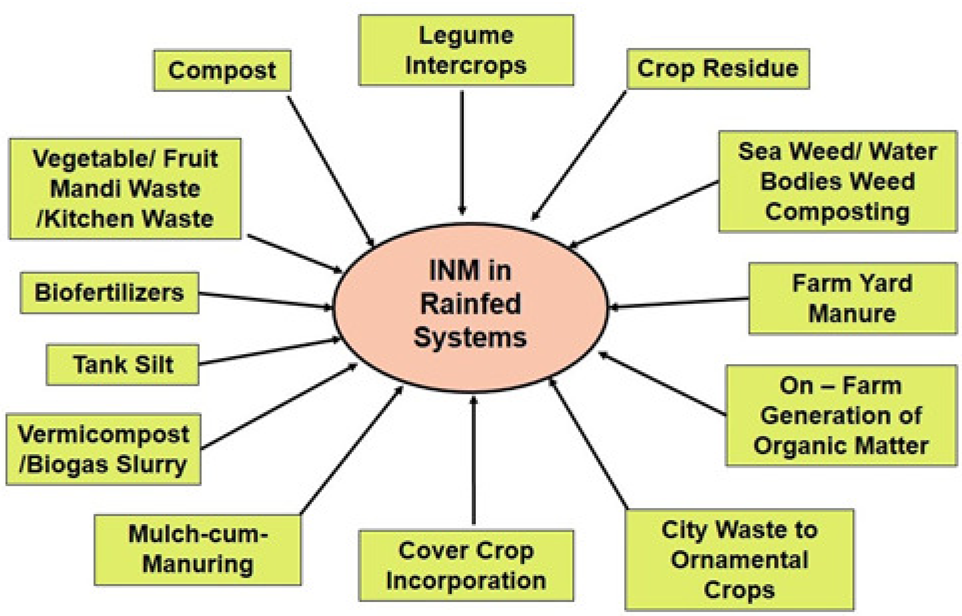

Figure 5. Potential sources of organics along with fertilizers in rainfed INM strategies in India

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)

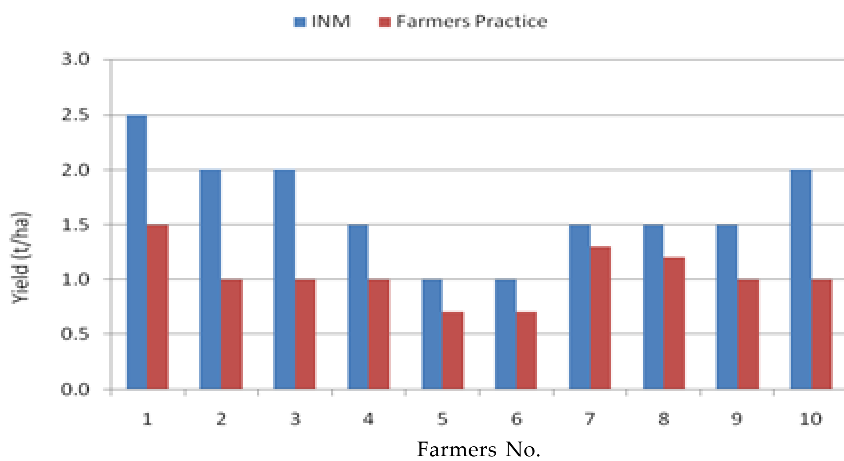

Figure 6. Impact of INM in *rabi* green gram yield in some selected farmers' fields

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

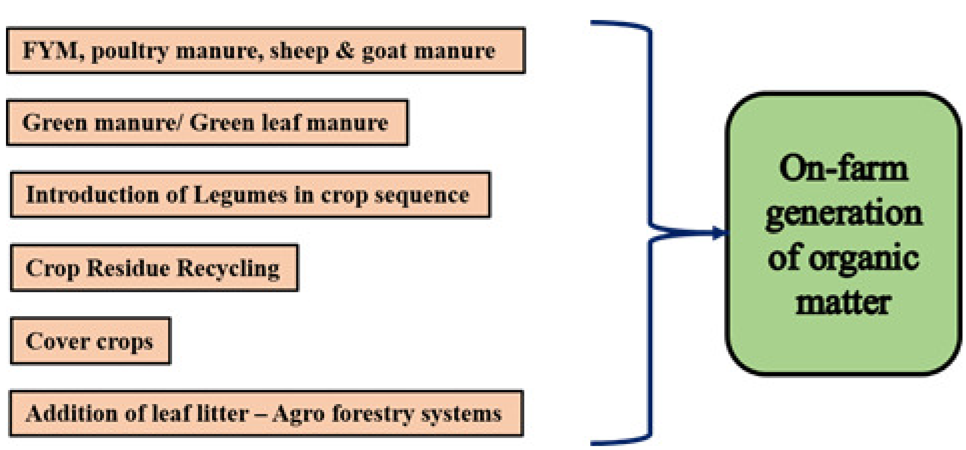

Figure 9. Strategies contributing towards on-farm generation of organic manures (Srinivasarao et al., 2011b; 2013c)

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

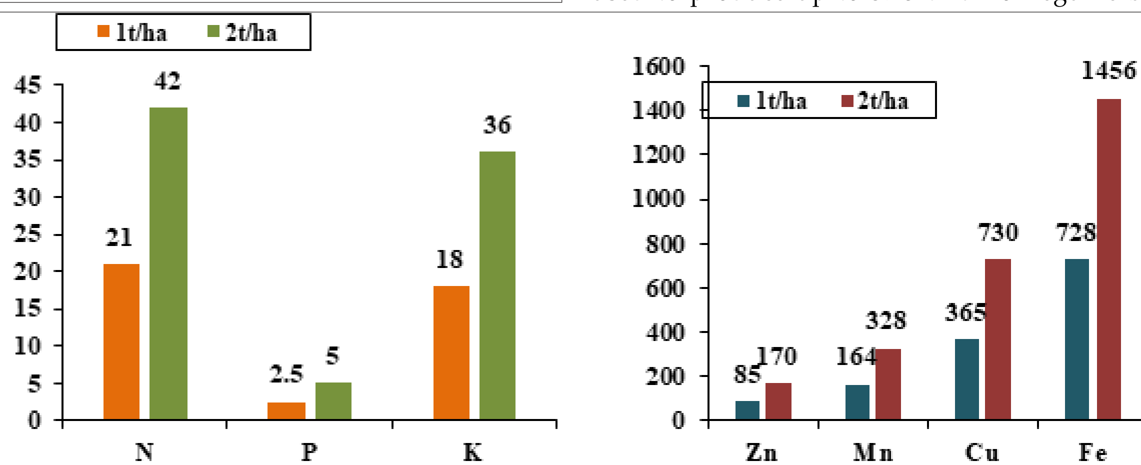

Figure 12. Macro and micronutrient addition through gliricidia green leaf manuring at different levels of manuring (Srinivasarao et al., 2011a, b)

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

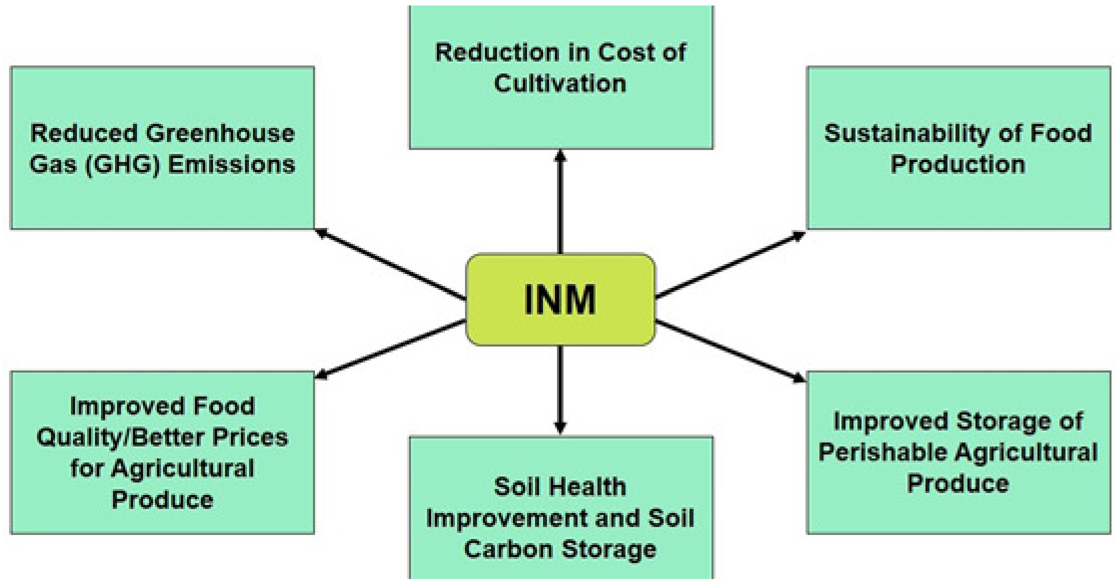

Figure. 19. Benefits of INM implementation at farm and ecosystem level

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

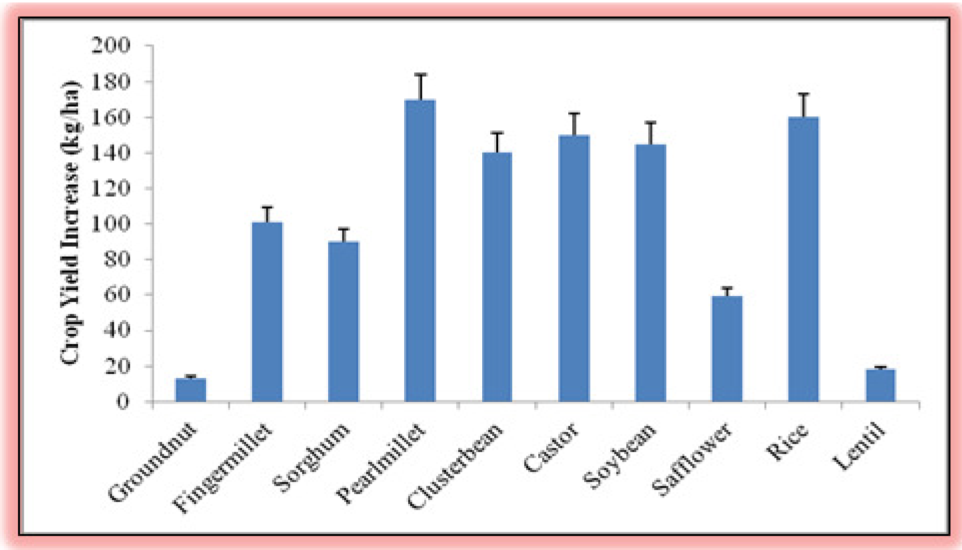

Figure 20. Increase in crop yield (kg ha^{-1}) for every t ha^{-1} increase in SOC stock in the root zone under various INM practices in different rainfed production systems (Srinivasarao et al. 2014a)

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

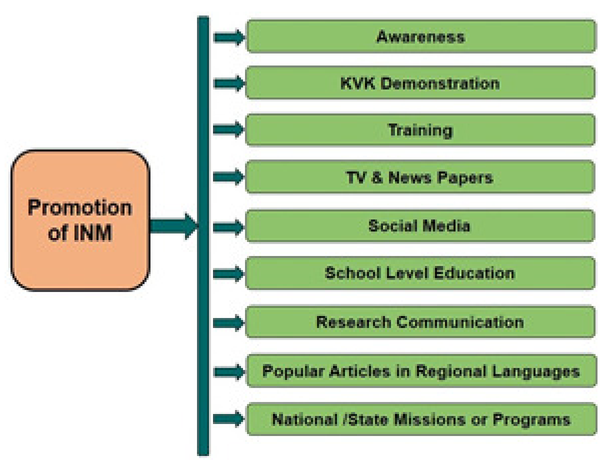

Figure 23. Promotion of INM implementation to village adoption level

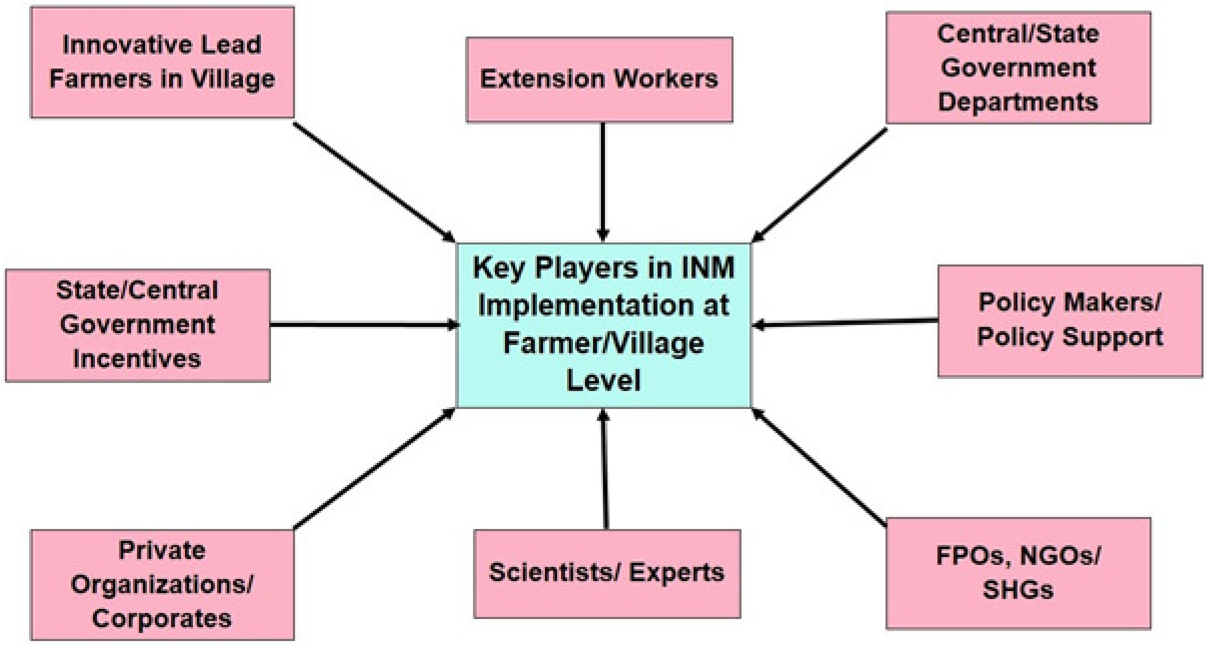

Figure 24. Key players in implementation of INM strategies at farm or village level

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.

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