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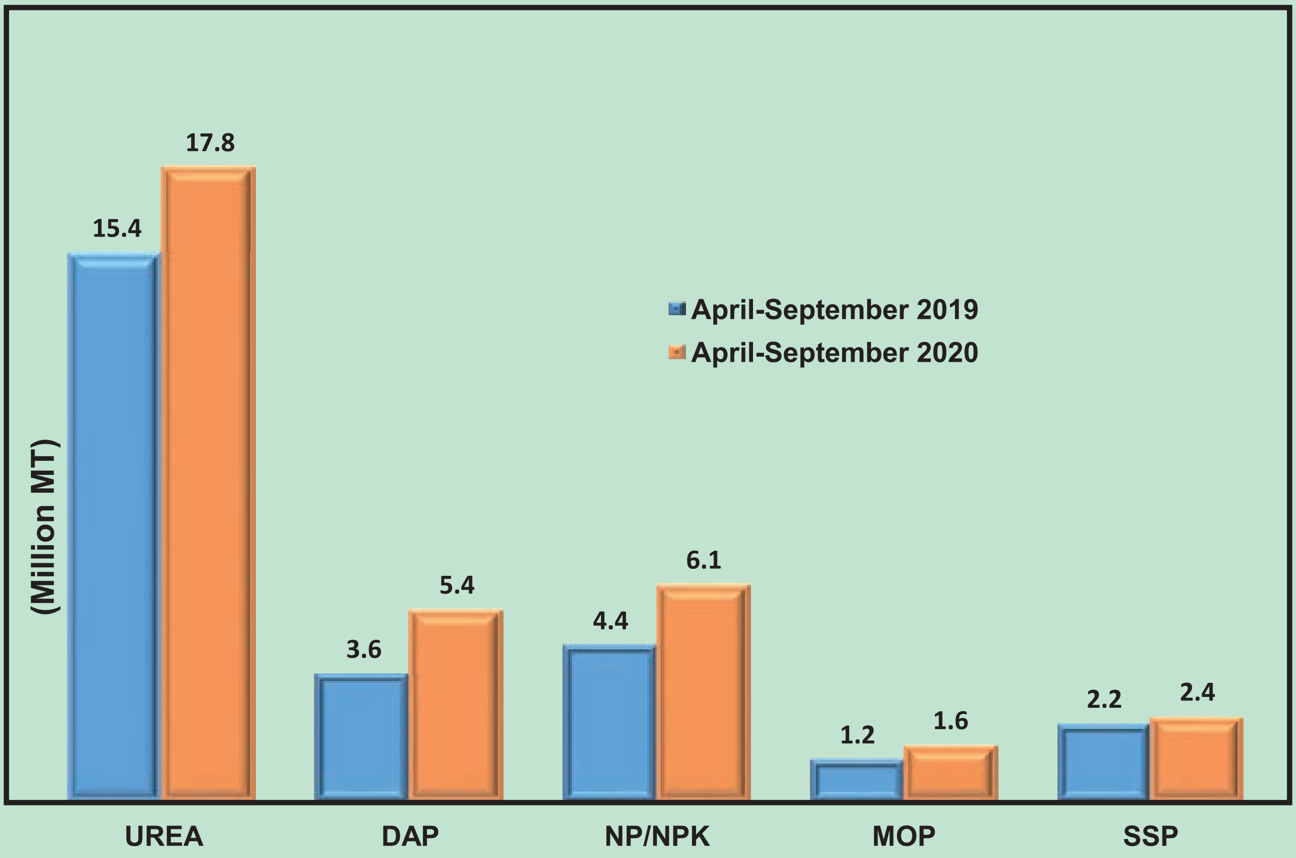

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Economic and Environmental Benefits of Integrated Nutrient Management in Indian Agriculture

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Abstract

Intensive agricultural operations involving external usage of chemical fertilizers is a concern in terms of escalating input as well as environmental issues in the post-Green Revolution period. Progressively affluent population and food demand have further laid stress on the agricultural soils for higher productivity. The total nutrient ($N+P_2O_5+K_2O$) consumption during 2018-19 was 27.23 million tonnes (Mt) and it is likely to increase to around 48.0 Mt by 2050. Persistent decline in soil health and the quality of environment are the major constraints coming in the way of achieving sustainability in Indian agriculture. It is, therefore, pivotal to consider inclusion of organic manures, biofertilizers, crop residues, etc., in cultivation to bridge the gap between nutrients added and removed, thereby assuring the optimum nutrient balance in soil systems. Improving crop production without harming the environmental resources and mitigating climate change must be the priority in today's agriculture. Integrated nutrient management (INM) approach is an effective way to deal with low productivity and nutrient-poor soils. Current paper highlights the economic benefits of adopting INM in different agroecological systems and its advantages on environment assessed in terms of improving nutrient use efficiency, soil carbon build-up, climate adaptation, and greenhouse gas (GHG) mitigation. Recent literature on the effect of INM practice involving various treatment combinations of organic and inorganic nutrient sources under different cropping systems shows the benefits in crop yields, net returns, and B:C ratio. Strong evidence is presented in this paper to demonstrate that INM is a climate-resilient, effective and innovative practice for agriculture that brings sustainability in the ecosystem.

Key words: Soil health, food security, INM approach, economic and environmental benefits, diverse agroecosystems, climate resilient agriculture, sustainability.

Introduction

India is world's second largest populated country and most of its people belong to agrarian community. Agriculture sector is the backbone of country's economy as it contributes to the GVA (Gross value added) 16.5% as reported in Economic Survey 2019-20. Only agriculture sector can help in achieving nation's food security but in the view of restricted land usage and increased population pressure, food security has become a great challenge to the humankind. To overcome this challenge, scientists encouraged the use of chemical fertilizers and high yielding varieties. Subsequently, quantity of the chemical fertilizer application increased to maintain the production rates to satisfy the nation's needs. India needs to take huge initiatives to ensure its food and nutritional security. These initiatives must contain solutions for the low gross domestic product (GDP) per capita, market constraints, shortage of land and irrigation, etc. Nation's food security is a combination of food availability, access and its utilization. It is also interlinked with food prices, agricultural growth, environmental changes, etc. About 14.8% of the population and 38.4% of children (below 5 years) remain malnourished in India. Based on the four parameters (affordability, quality, availability and safety), India ranked 76th out of 113 countries as per evaluation of the Global Food Security Index (GFSI).

Since 1960s, Green Revolution facilitated overcoming of production problems and considerably increased the food grain production. Currently, the production of food grains, pulses, oilseeds, fruits, vegetables, and flower and aromatics is about 284.83, 25.23, 31.31, 97.35, 184.39, and 3.65 million tonnes (Mt), respectively. The production rates for the period ranging from 2012-13 to 2017-18 are presented in **Figure 1**. Even though it is a triumph, Green Revolution in agriculture is frequently criticized for being focused on only two cereal grains (wheat and rice) and putting so much stress on agroecosystems. Globally, the crop yields are continuously increasing year after year, yet the required increment to meet the food demand by 2050 is insufficient. The annual increment of yields of key global crops *viz.*, rice, maize, wheat and soybean are 1.0%, 1.6%, 0.9%, and 1.3%,

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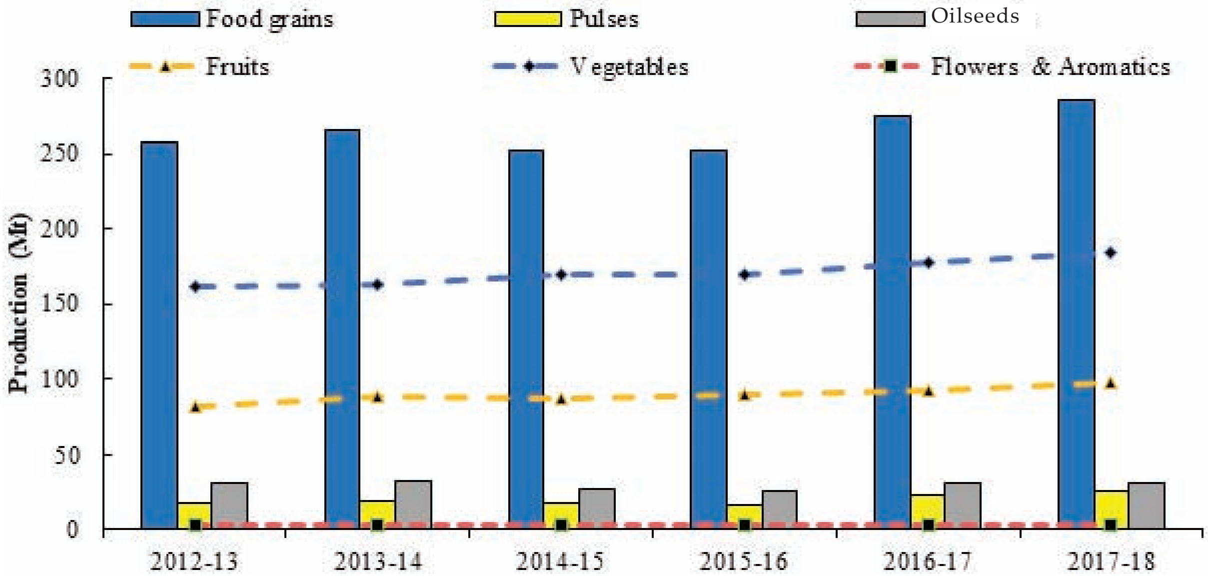


Figure 1. Production rates of food grains, pulses, oilseeds, fruits, vegetables, and flowers and aromatics in India (ICAR Data Book 2019)

respectively. However, the required rate of production increment to double by 2050 is 2.4% yr^{-1} (Ray et al., 2013). In contrast, there is stagnation in the growth of crop yields in India. As per the analysis, the yield records from 1961 to 2008 show that there is a stagnation of maize, rice, and wheat of about 31%, 36%, and 70%, respectively (Ray et al., 2012). Key reason for this yield stagnation is soil degradation (NAAS, 2018; Agribusiness, 2018). Imbalanced use of chemical fertilizers for maximizing crop production has been cited to be responsible for the deterioration of soil quality. Status of nitrogen (N) in Indian soils is very low. Deficiencies of phosphorus (P), potassium (K), sulphur (S), zinc (Zn), boron (B), iron (Fe) and manganese (Mn) are 80%, 50%, 41%, 36%, 23%, 13% and 7%, respectively. Such deficiencies are mainly due to low nutrient use efficiencies (NUE): 30-50% for N, 15-25% for P, 50-60% for K, 8-12% for S, and 2-5% for micronutrients. Imbalanced application of fertilizers, residue burning and climate change are further posing a risk to the sustainability of soil health. Manna et al. (2007) and Srinivasarao et al. (2013a) observed that the application of recommended doses of NPK without input of farmyard manure (FYM) leads to decline in production of biomass (especially the root biomass) and its return into the soil; this is responsible for decline in soil organic matter (SOM). A serious problem of soil degradation, manifesting in terms of decline in SOM is degrading the environment, limiting the crop productivity, and adversely impacting the human wellbeing. Globally, more than 50% of the applied fertilizer to the cultivated lands is lost to the environment, leaving adverse impacts on the quality of water, soil, air, biodiversity and ecosystems (Lassaletta et al., 2014). Fertilizer application in India is already more than that of the cropland in the U.S. Thus, to reduce the nutrient losses to the environment, improving soil quality by restoring SOM content, and to bring resilience in soil and agroecosystems, we have to focus more on improving fertilizer use efficiency (FUE) by integrating fertilizers with organic amendments rather than simply increasing the rate of inputs.

Different Models of INM

Integrated nutrient management encompassing the conjunctive use of chemical fertilizers and organic amendments would prove advantageous for soil health management and improvement of soil fertility as well as the overall crop productivity. Balanced fertilization in INM approach is nothing but the application of nutrient sources in the right proportion with suitable methods specific to crop and agroclimatic situation leading to soil health building and enhancing NUE (Srinivasarao et al., 2008). Organic manures play a significant role in INM package; increase the soil organic carbon (SOC) content which proliferates the microbial activity in soil, helps retain soil moisture longer and reduces the leaching of plant nutrients besides imparting drought tolerance during dry spells. Advantages of INM practices have been reported in hundreds of researches in the Indian subcontinent (Srinivasarao et al., 2013a; Sharma et al., 2019; Bijay-Singh and Ali, 2020).

Various sources of soil organic amendments are accessible to growers as on-farm materials *viz.*, crop residue, weed biomass, green manures, compost, animal bedding material, seri-waste, etc., and also off-

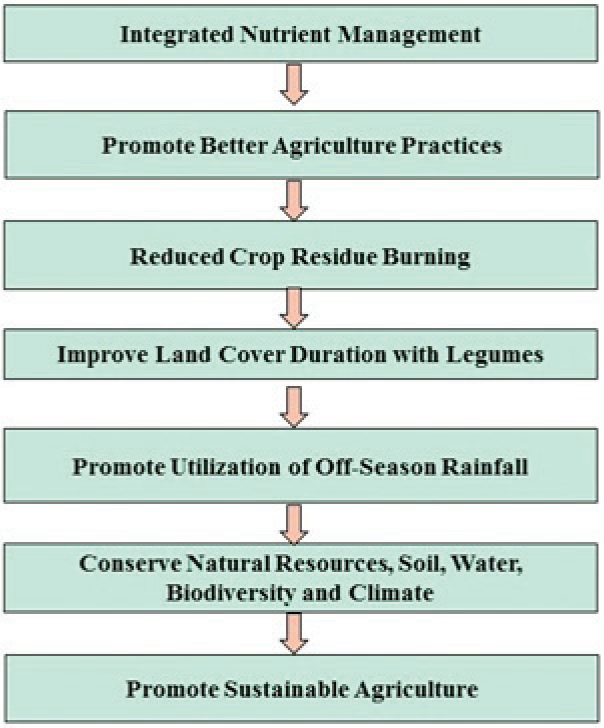


Figure 2. Impact of INM on better agriculture practices in India

farm wastages *viz.*, municipal bio-solids, poultry manure, coir pith, biochar, tank silt, etc. INM encompasses a holistic approach to nutrient management for crop production, and involves judicious combination of fertilizers, bio-fertilizers, organic manures (FYM, compost, vermicompost, biogas sludge), green manures, crop residues, etc. There are several benefits of adopting INM in agriculture. The impact of INM on better agricultural practices in India is presented in **Figure 2**.

The basic concept of INM model is the adjustment of soil fertility and supplementation of plant nutrients in an available form at optimum level in order to sustain the crop productivity and optimization of advantages of plant nutrients from all possible resources in an integrated approach (Srinivasarao et al., 2017). Concept of INM started in late 1980s, importantly to solve the issues related to micronutrient deficiencies and deterioration of soil health. The major objectives of INM involved were i) restoration of soil carbon content, ii) improvement of NUE, iii) soil health maintenance, iv) minimization of chemical fertilizers and their adverse impact on environment, v) ensuring increased crop productivity, and vi) development of sustainable agriculture.

Adoption of new interventions has added new dimensions in the INM system. Improved farm mechanization, conservation agriculture system intensification (CASI) technologies, various organic amendments and renewed focus on recycling of existing natural organic nutrient flows further broaden the concept of INM to make it more context-specific for local environmental conditions (Wu and Ma, 2015). As shown in **Table 1** there are plenty of organic and inorganic nutrient source combinations adopted in the INM model.

Economic Benefits of INM

The economic benefits such as improved crop yields, reduced cost of cultivation, increased marginal and net returns, and benefit:cost (B:C) ratio of INM under different agroecosystems are discussed briefly below.

Cereal-based System

Maruthupandi and Jayanthi (2018) evaluated various INM treatment combinations under rice-maize cropping system. Among all those, application of 100% RDF + vermicompost @ 5 t ha^{-1} significantly influenced the rice grain equivalent yield (system yield) *i.e.*, 15,327 kg ha^{-1} by augmenting the availability of nutrients for a shorter period. Further, the total cost of cultivation and net returns also observed were higher (Rs. 83,610 and Rs. 1,46,287 ha^{-1}) under this combination. Such results were followed by the application of 100% RDF + goat manure as pond silt @ 5 t ha^{-1} (**Figure 3**). System yields of rice were increased with the use of organic manures in combination with inorganic fertilizers (Ali et al., 2012).

Yield and net returns of wheat have been increased by 31.6% through the application of 150:75:00 NPK kg ha^{-1} + FYM @ 5 t ha^{-1} + seed inoculation of *Azotobacter* + PSB + sulphur @ 40 kg ha^{-1} (through gypsum) as compared to other treatments (Desai et al., 2015). Among numerous INM practices, application of 5.0 t vermicompost + 75% recommended dose of NPK gave maximum maize equivalent yield, gross return, net return and B:C ratio over other INM practices. However, when biofertilizers *viz. Azotobacter* and PSB were applied in conjunction with RDF (NPK), net returns of the system (**Figure 4**) also showed improvement due to increased nutrient solubility, growth and development of maize under maize + mung bean intercropping (Yadav et al., 2016). Rice–potato–mung bean (RPM) cropping systems gave 3.2–5.9 t ha^{-1} yr^{-1} higher productivity than the rice–wheat (RW) cropping system (Sharma and Sharma, 2004).

Significantly highest grain yield and sustainability yield index (SYI) of both the crops were obtained in treatments which had received organic amendments in combination with mineral fertilization over unfertilized control and 100% fertilized treatments under maize-black gram cropping system **(Figure 5)**,

Table 1. Various INM strategies under different agroecosystems

Crop	INM strategies under different agroecosystems	Source
Rice	Poultry manure at 5 t ha^{-1} with fertilizer N at 40 kg ha^{-1}	Yadvinder-Singh et al. (2009)
Rice	25% N through vermicompost or *Sesbania* green manure combined with 75% RDF-N (RDN)	Singh et al. (2018)
Maize –Wheat	10 t of FYM ha^{-1} along with recommended NPK fertilizers	Brar et al. (2015)
Hybrid rice	50% RDF and 50% RDN through mustard oil cake	Mondal et al. (2016)
Maize -Cauliflower - Cowpea	Soil test + organics + biofertilizers + lime	Sarkar et al. (2020)
Rice	Press mud cake at 5 t ha^{-1} along with 60 kg fertilizer N ha^{-1}	Yadvinder-Singh et al. (2008)
Rice - Wheat system	Rice husk ash (RHA) and bagasse ash (BA) along with RDF	Thind et al. (2012)
Groundnut – Finger millet	FYM 10 tonne ha^{-1} + 100% RDF (NPK)	Srinivasarao et al. (2009)
Soybean-based	6 tonne FYM ha^{-1} + 20 kg N ha^{-1} + 13 kg P ha^{-1}	
Pearl millet-based	50% N (inorganic fertilizer) + 50% N (FYM)	
Tomato	150N – 60P – 60K (kg ha^{-1}) – *Azotobacter* – phosphate solubilizing bacteria (50 g culture kg^{-1} seed)	Kumar and Srivastava (2006)
Brinjal	75N – 37.5 P – 22.5 K (kg ha^{-1}) – FYM (12.5 Mg ha^{-1}) – *Azospirillum* (50 g culture kg^{-1} seed) – phosphate solubilizing bacteria (100 g culture kg^{-1} seed)	Nanthakumar and Veeraragavathatham (2001)
Rose	60 N (gm^{-2}) – GYM (5 kg m^{-2})	Singh (2006)
Bitter gourd	70 N – 25 P – 25 K (kg ha^{-1}) – *neem* cake (2.5 t ha^{-1})	Rekha and Gopalkrishnan (2001)
Papaya	50% RDF (100 N – 100 P_2O_5 – 125 K_2O g plant^{-1}) - *Azotobacter* sp @ 50 g plant^{-1} – phosphate solubilizing bacteria @ 2.5 g m^{-2}	Singh and Varu (2013)
Guava	50% RDF (250 g N – 100 g P_2O_5 - 250 K_2O g plant^{-1}) - FYM @ 25 kg plant^{-1} – vermicompost @ 5 kg plant^{-1}	Dwivedi (2013)
Sapota	1500 g N – 1000 P_2O_5 – 500 g K_2O plant^{-1} – 75 kg FYM plant^{-1} – 12.5 g plant^{-1} phosphate solubilizing bacteria	Dalal et al. (2004)
Banana	50% RDF- FYM @ 20 kg plant^{-1} – *Azotobacter* sp. @ 50 g plant^{-1} – phosphate solubilizing bacteria @ 50 g plant^{-1} – VAM @ 250 g plant^{-1}	Patil and Shinde (2013)

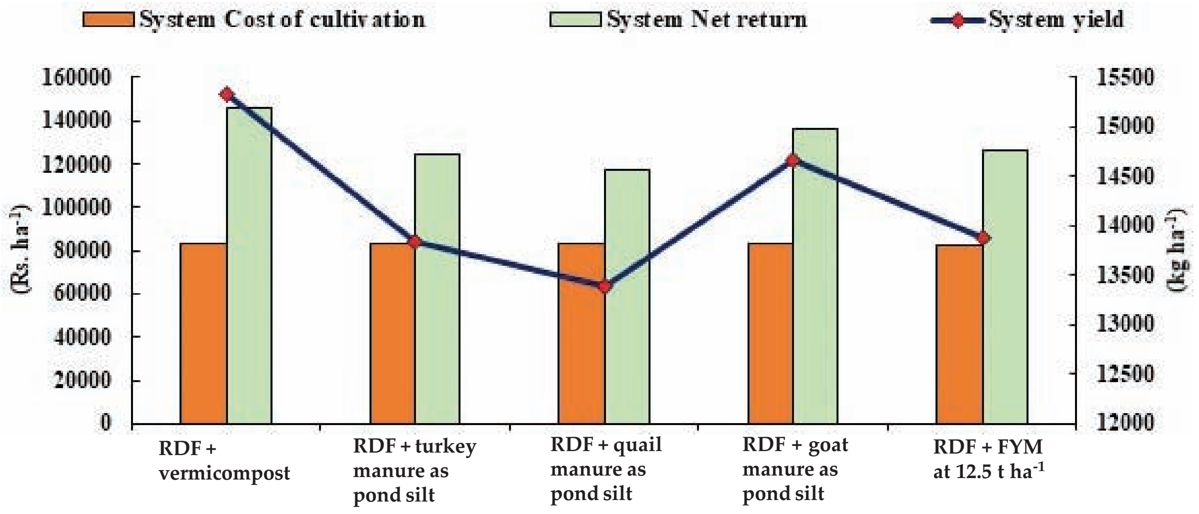


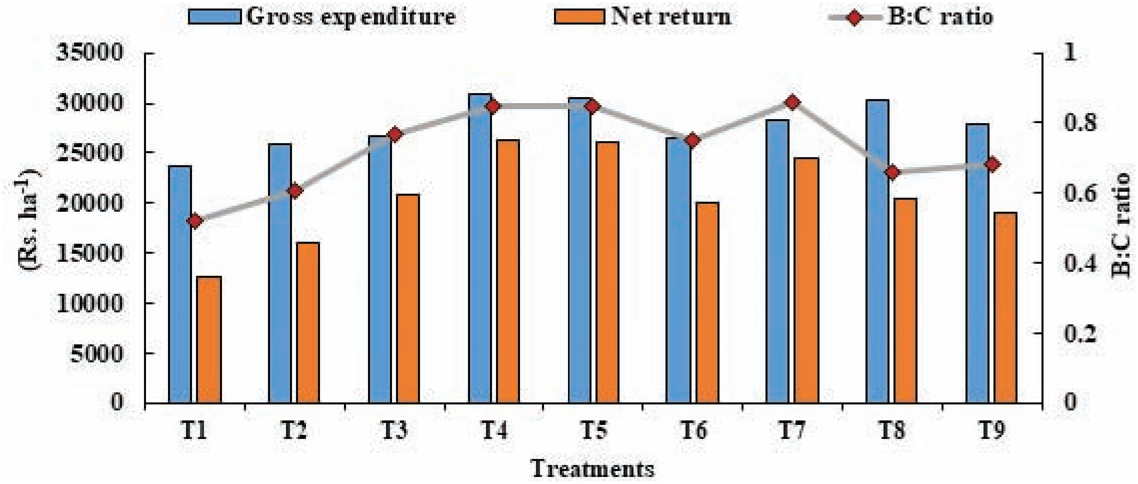
Figure 3. Impact of INM on cost of cultivation, net returns, and yield under rice-maize cropping system (Source: Maruthupandi and Jayanthi, 2018)

thereby showing the beneficial effects of addition of organic amendments on crop performance (Srinivasarao et al., 2019).

Millet-based System

Combined application of FYM @ 2.5 t ha^{-1} along with RDF of 120 kg N + 60 kg P_2O_5 ha^{-1} and seed inoculation with *Azotobacter* and phosphate solubilizing bacteria (PSB) resulted **(Table 2)** in significantly higher grain yield (3.63 t ha^{-1}) of summer pearl millet, net returns (Rs. 43,435 ha^{-1}) and B:C ratio (1.94) (Thumar et al., 2016).

Supplement of FYM @10 t ha^{-1} increased the grain yield of sorghum by 28.16% (Jat et al., 2013). They also recorded the highest net returns with B:C ratio of 1.93

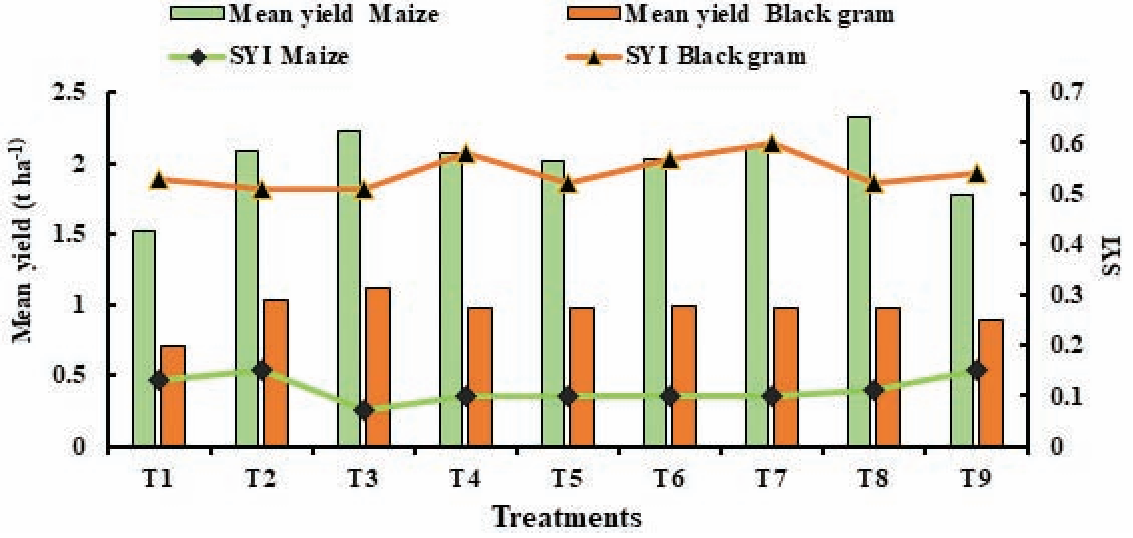


T1: Control; **T2:** 75% RDF of NPK; **T3:** 100% RDF of NPK; **T4:** 5.0 t vermicompost + 75% RDF of NPK + *Azotobacter* + 75% N and RDF of P&K; **T5:** PSB + 75% P & RDF of N & K; **T6:** *Azotobacter* + PSB.+75% NP and RDF of K; **T7:** *Azotobacter* + PSB +5.0 t vermicompost and 50% RDF of NPK

Figure 4. Effect of INM on gross expenditure, net returns and B:C ratio of maize crop (Source: Yadav et al., 2016)

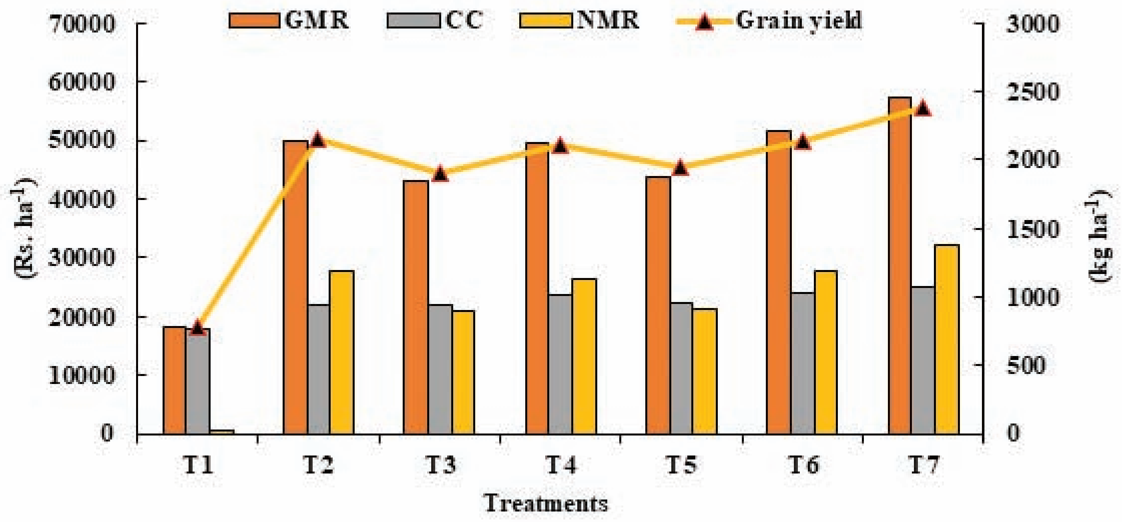
Table 2. Impact of INM on summer pearl millet yield and profitability (Source: Thumar et al., 2016)

Treatments	Grain yield (t ha^{-1})	Gross return (Rs. ha^{-1})	Net return (Rs. ha^{-1})	B:C ratio
T_1 : RDF (120-60-00 NPK kg ha^{-1})	3.12	56,810	37,047	1.87
T_2 : T_1 + 5 t FYM ha^{-1}	3.46	62,704	37,941	1.53
T3 : T_1 + 5 t bio-compost ha^{-1}	3.40	61,728	34,465	1.26
T8 : T_1 + 2.5 t biocompost ha^{-1} + *Azotobacter* + PSB	3.52	63,934	40,301	1.71
T_9 : T_1 + 2.5 t FYM ha^{-1} + *Azotobacter* + PSB	3.63	65,818	43,435	1.94
T_{14} : 50% RDF + 2.5 t biocompost ha^{-1} + 2.5 t FYM ha^{-1} + *Azotobacter* + PSB	3.00	54,550	30,705	1.29



T1: Control; **T2:** 100% RDF of NP; **T3:** 25 kg ha^{-1} N (FYM) + 25 kg N ha^{-1} (urea) + 30 kg P ha^{-1}; **T4:** 25 kg ha^{-1} N (compost) + 25 kg N ha^{-1} (urea) + 30 kg P ha^{-1}; **T5:** 25 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1} (urea) + 30 kg P ha^{-1}; **T6:** 15 kg ha^{-1} N (FYM) + 10 kg N ha^{-1} (crop residue) + 25 kg N ha^{-1} (urea) + 30 kg P ha^{-1}; **T7:** 15 kg ha^{-1} N (FYM) + 10 kg N ha^{-1} (compost) + 25 kg N ha^{-1} (urea) + 30 kg P ha^{-1}; **T8:** 15 kg ha^{-1} N (FYM) + 10 kg N ha^{-1} (green leaf) + 25 kg N ha^{-1} (urea) + 30 kg P ha^{-1}, and **T9:** 100% recommended N (urea) without P

Figure 5. Mean yield and sustainability yield index (SYI) as influenced by the INM in maize – black gram cropping sequence under different treatments (Source: Srinivasarao et al., 2019).



T1: Control; **T2:** 100% RDN; **T3**: 75% RDN + 25% N through press mud; **T4**: 75% RDN + 25% N through vermicompost; **T5**: 75% RDN + 25% N through FYM; **T6**: 75% RDN + 25% N through FYM+ $ZnSO_4$ @ 20 kg ha^{-1}; **T7**: 75% RDN + 25% N through vermicompost + ZnSO4 @ 20 kg ha^{-1}

Figure 6. Impact of INM on gross monetary returns, cost of cultivation, net monetary returns and yield of sorghum crop (Source: Gaikwad et al., 2018)

over no FYM. Co-inoculation of *Azotobacter* + PSB in sorghum registered highest grain yield and economic returns over no inoculation (Arbad et al., 2008). Biofertilizers transform fixed and in-soluble forms of nutrients into soluble forms and make them readily available to plant and ultimately improve the performance of crop. With their experiment, Gaikwad et al. (2018) showed that application of 75% RDN + 25% N through vermicompost + $ZnSO_4$ @ 20 kg ha^{-1} produced significantly highest sorghum grain yield, gross monetary (Rs. 57,354 ha^{-1}) and net monetary returns (Rs. 32,225 ha^{-1}) and B:C ratio (2.28) (**Figure 6**). Among various INM practices followed for sorghum cultivation, addition of 100% RDF through inorganic fertilizer + biocompost @ 10 t ha^{-1} provided significantly superior grain yield compared to rest of the treatments (Patil et al., 2018). Maximum net returns of Rs. 59,146 ha^{-1} were recorded with this treatment followed by application of 100% RDF through inorganic fertilizer with net returns of Rs. 53,449 ha^{-1}.

Maximum grain yield of finger millet (3.77 t ha^{-1}) was recorded with the application of FYM (10 t ha^{-1}) + biofertilizer + zinc sulphate (12.5 kg ha^{-1}) + borax (5 kg ha^{-1}) + 75% RDF; also the highest gross return (Rs. 72,740 ha^{-1}), net return (Rs. 52,272 ha^{-1}) and B:C ratio (2.55) were observed under this combination (Roy et al., 2018). Combined application of organic and inorganic manures along with biofertilizer led to the enhanced availability of nutrients and improved the soil properties, hence resulting in better root growth and yield.

Oilseed Crops

Higher pod yield, gross returns, net returns and B:C ratio were found in treatment combination of 125% RDN through vermicompost + 50 kg P_2O_5 ha^{-1} under summer groundnut cultivation (Chaudhary et al., 2015). Maximum grain yield of mustard (2.28 t ha^{-1}), maximum gross income (Rs. 81,575 ha^{-1}) and net profit of mustard (Rs. 35,725 ha^{-1}) were recorded in RDF + vermicompost @ 5.0 t ha^{-1} followed by yield of 2.13 t ha^{-1} in RDF + vermicompost @ 2.0 t ha^{-1} + FYM @ 5.0 t ha^{-1} (**Table 3**).

Table 3. Effect INM on grain yield, gross income, net profit and B:C raio of mustard crop (Source: Thaneshwar et al., 2017)

Treatment	Grain yield (t ha^{-1})	Gross income (Rs. ha^{-1})	Net profit (Rs. ha^{-1})	B:C ratio
RDF (120 : 60 : 40 : 30 kg ha^{-1} NPKS)	1.92	69,419	34,049	1.96
RDF + 5.0 t vermicompost ha^{-1}	2.28	81,575	35,725	1.77
RDF + 2.0 t vermicompost ha^{-1} + 5.0 t FYM ha^{-1}	2.13	78,491	33,281	1.73
RDF + 6.0 t FYM ha^{-1}	2.00	72,788	30,938	1.73

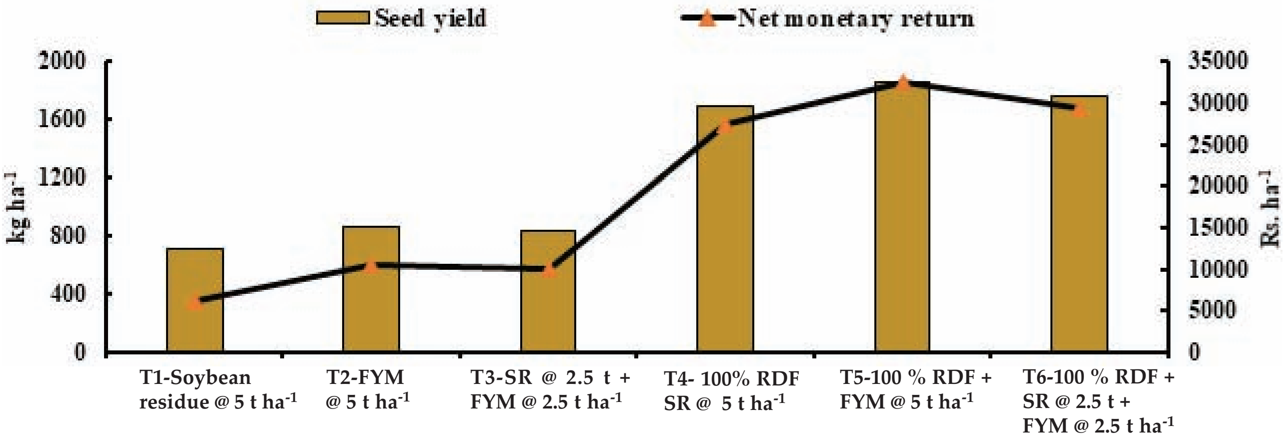


Figure 7. Impact of INM on seed yield and net monetary returns of sunflower crop (Source: Ashok et al., 2018)

Significantly highest sunflower seed yield (1,866 kg ha^{-1}) and net monetary return (**Figure 7**) was recorded with the application of 100% RDF+ FYM @ 5 t ha^{-1} followed by 100% RDF + soybean residue (SR) @ 5 t ha^{-1} and 100 % RDF + SR @ 2.5 t ha^{-1} + FYM @ 2.5 t ha^{-1} (Ashok et al., 2018). Combined use of NPK and FYM produced higher mean pod yield (1,217 kg ha^{-1}) of groundnut with the application of FYM + 50% NPK over recommended NPK (719 kg ha^{-1}) and the control (403 kg ha^{-1}) (Srinivasarao et al., 2012c).

Vegetable Crops

INM practice in potato crop cultivation where FYM, crop residues and bio-fertilizers were combined with RDF benefited the potato tuber yield and net returns (**Figure 8**). Maximum tuber yield (25.80 t ha^{-1}) was obtained in 100% RDF + 20 t FYM ha^{-1} followed by crop residue incorporation and inoculating of seed tubers with bio-fertilizers before planting at both 100% and 75% RDF (25.71 and 24.81 t ha^{-1}, respectively). Higher net returns were also recorded in the INM treatments. Use of FYM in conjunction with chemical fertilizer is an effective means of increasing potato yield (Venkatasalam et al., 2012; Islam et al., 2013). Integrated application of FYM at 10 t ha^{-1} + NPK + dipping seedlings in 1% *Azotobacter* + foliar spray of 20 ppm ferrous ammonium sulphate in tomato cultivation enhanced the growth parameters (Pandey and Chandra, 2013) and the maximum marketable yield of tomato *i.e.*, 102.5 and 95.5 t ha^{-1} obtained, respectively during *kharif* and *rabi* seasons with the B:C ratios of 4.25 and 4.23, respectively.

Application of bacterial fertilizers, alone as well as in combination with micronutrients (Thingujam et al., 2020) significantly enhanced the yields of brinjal (13.10–15.35 t ha^{-1}) over the control (9.83–12.39 t ha^{-1}). Research further showed that the application of

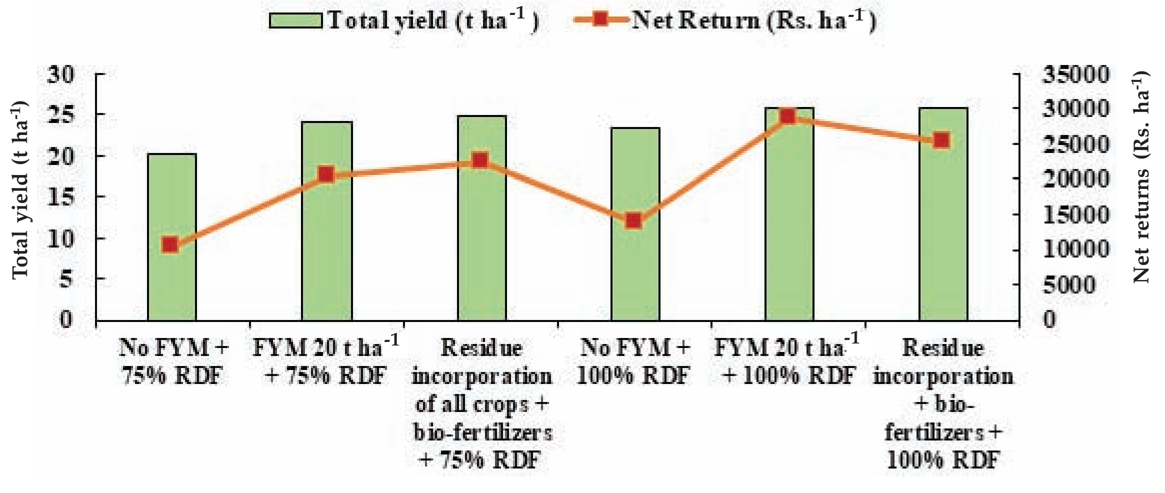


Figure 8. Yield of tuber and net returns of potato (Source: Banerjee et al., 2016)

Table 4. Effect of INM on yield and economics of garland chrysanthemum (Source: Angadi, 2014)

Treatments	Flower yield (t ha^{-1})	Net returns (Rs. ha^{-1})	B:C ratio
Absolute control	2.27	20,600	0.57
100% RDF + FYM (20 t ha^{-1})	6.52	1,16,962	2.54
50% vermicompost (VC) equivalent to RDN + 50% RDF	4.70	73,585	1.63
Azospirillum + 75% RDN + 100% RDP and K	4.20	65,839	1.62
PSB + 75% RDP + 100% RDN and K	6.25	1,15,814	2.86
Azospirillum + 50% VC equivalent to RDN + 50% RDF	5.73	97,360	2.12
PSB + 50% VC equivalent to RDN + 50% RDF	8.15	1,57,860	3.44
Azospirillum + PSB + 50% RDN and P + 100% RDK	4.93	83,720	3.12
Azospirillium + PSB + 50% VC equivalent to RDN+50% RDF	9.65	1,95,135	4.23

boron with *Azospirillum* and PSB benefited the yield, soil nutrient availability and plant nutritional recoveries in brinjal cultivation.

Flower Crops

Integration of *Azospirillum*, PSB, 50% vermicompost equivalent to RDN with 50% recommended NPK produced greater yields of garland chrysanthemum (9.65 t ha^{-1}) with the maximum net returns (Rs. 1,95,135 ha^{-1}) and high B:C ratio (4.23) compared to control (**Table 4**). Better root proliferation, uptake of nutrients and water, and better plant growth were greatly influenced by the effect of vermicompost and biofertilizers combined with inorganic fertilizers.

Supplement of *Azospirillum* + PSB in combination with 50% RDF in China Aster significantly improved the flower diameter, yield and the overall yield per unit area (Chaitra and Patil, 2007). Application of 400 g *neem* cake + 1 g PSB + 1 g *Azotobacter* m^{-2} in rose cultivation significantly increased the number of flowers (201.03) followed by 400 g mustard cake + 1 g PSB +1 g *Azotobacter* m^{-2} (166.88). Vase life (6.0 days) of flowers also increased in the former treatment (Lambat and Pal, 2012). Study conducted by Sunitha and Hunje (2010) showed a significant effect of applying 50% RDF + VC (50% RDF) on number of flowers per plant. Minimum days for sprouting after cutting (18.47 days), maximum plant height at full bloom stage (61.67 cm) were recorded where FYM @ 30 t ha^{-1} + PSB @ 2 g m^{-2} + *Azotobacter* @ 2 g m^{-2} were applied. Presence of *Azotobacter* and PSB helped better nutrient uptake and triggered physiological and biochemical activities (Mayuri et al., 2013).

Fruit Crops

Among different INM treatment combinations studied in sapota fruit cultivation, application of 2/3rd part of RDF + 50 kg FYM + 250 g *Azospirillum* + 250 g *Azotobacter* $plant^{-1}$ significantly enhanced the number of fruits $plant^{-1}$ (327.88), yield $plant^{-1}$ (29.03 kg) and yield ha^{-1} (4.52 t) over control. Combined application of organic and inorganic nutrient sources proved efficient in sustaining higher fruit yield of sapota and soil health in south-eastern Rajasthan (Meena et al., 2019). Combinations of organic and chemical fertilizers have a better influence on synthesis and translocation of metabolites resulting into better fruit yield (Palaniappan and Annadurai, 2000). Similarly, Kumar et al. (2012) also reported the improved yields of lemon under combined fertilization of NPK and organic manures.

Combined application of organic fertilizer with inorganic fertilizer and micronutrients benefited the guava fruit yields over supplementation of NPK through only fertilizers. Guava plants which had received 75% RDF + 10 kg FYM $plant^{-1}$ + micronutrients (Zn+B+Mn @ 0.5%+0.2%+0.1%) produced significantly higher fruit yields (116.76 and 82.36 q ha^{-1} in winter and rainy seasons, respectively) followed by 75% RDF + 10 kg FYM $plant^{-1}$ (106.35 and 79.89 q ha^{-1} in winter and rainy seasons, respectively) over the lowest yields recorded where only 100% NPK had been added **(Figure 9)**.

Environmental Benefits

Improving Nutrient Use Efficiency (NUE)

The widespread utilization of fertilizers has drastically contributed to global food security, but their indiscriminate and long-term application heightens the issues of environmental pollution. The proportion of nutrients not utilized by the crop is at risk of loss to the environment, the susceptibility of loss varies with nutrient, soil and climatic conditions (Roberts, 2008). The use efficiency of applied nutrients has remained extremely low. The utilization efficiency of fertilizer nitrogen seldom exceeds 35% under lowland and 50% under upland conditions while it is 15-25% for P, 50-60% for K, 8-12% for S and 2-5% for most of the micronutrients (FAI, 2017). The simultaneous attainment of high nutrient use efficiency, high crop productivity and environmental protection has become a challenge. This situation calls for adopting efficient strategies which would aid in enhancing the utilization efficiency of applied nutrients. Agronomic indices commonly used to

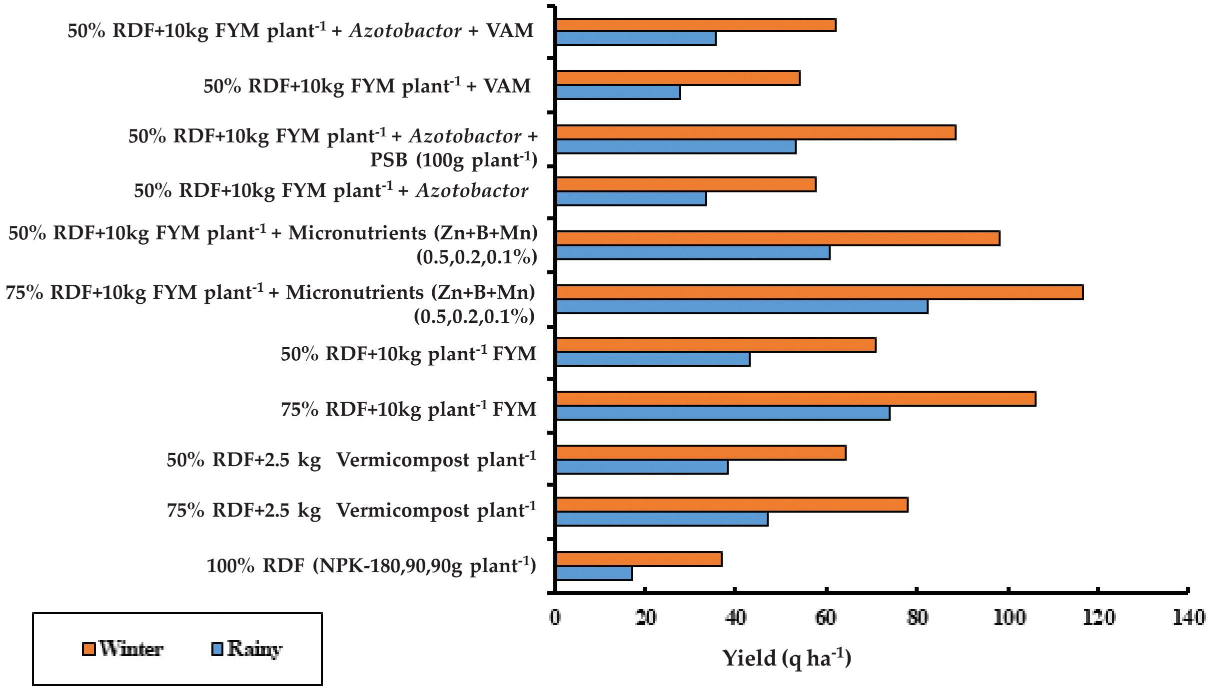


Figure 9. Effect of INM on fruit yield of guava (Source: Gupta et al., 2019)

describe nutrient use efficiency are (i) partial factor productivity (PFP); (ii) agronomic efficiency (AE); (iii) apparent recovery efficiency (RE); and (iv) physiological efficiency (PE) (Mosier et al., 2004). The amalgamation of organic sources and chemical fertilizer (INM) would prove useful in maintaining continuous nutrient supply, check losses and thus help in more efficient utilization of the applied nutrients (Dwivedi et al., 2016).

The impact of integrated use of urea and FYM in sorghum in Vertisols of Solapur under semi-arid conditions on nitrogen use efficiency is presented in **Table 5**.

Soil Carbon Improvement

Soil organic carbon is the principal component of soil organic matter. It assumes importance as an indicator of soil health which plays significant role in elevating crop production levels and attaining environmental sustainability. Low soil organic carbon levels aggravate the problem of soil erosion particularly, resulting in soil degradation posing problems such as decline in soil fertility and loss of soil biodiversity. Soil degradation assumes prominence as a major environmental concern in developing countries. The excessive application of fertilizers practiced with the objective of enhancing production levels leads to multiple hazards, the major ones include loss of soil and water quality. INM emphasizing on the conjunctive use of organic and inorganic sources of nutrients would aid in curtailing the heavy usage of synthetic fertilizers along with enhancing the soil organic carbon levels (Srinivasarao et al., 2020 a, b). Improvement in soil carbon status contributes to better soil aggregate formation resulting in better soil structural stability, water holding capacity, nutrient storage and turnover properties that are fundamental in maintaining and enhancing the soil

Table 5. Nitrogen use efficiency during 22 years of sorghum cropping on Vertisols of semi-arid Solapur (Source: Srinivasarao et al., 2011)

Treatment	Mean yield (kg ha^{-1})	AE$_N$(kg grain kg^{-1} N)	PFP$_N$ (kg grain kg^{-1} N)
Control	608	-	-
25 kg N ha^{-1} (urea)	894	11.5	35.7
50 kg N ha^{-1} (urea)	1,044	8.7	20.9
25 kg N ha^{-1} (FYM)	945	9.5	37.8
25 kg N ha^{-1} (urea) + 25 kg N ha^{-1} (crop residue)	1,048	8.8	20.9
25 kg N ha^{-1} (urea) + 25 kg N ha^{-1} (FYM)	1,087	9.7	21.8
LSD ($P = 0.05$)	120	-	-

quality. Application of 50% RDF coupled with 50% FYM produced higher biomass and subsequently higher C input as crop residues (2.4 Mg C ha^{-1} yr^{-1}) compared to 100% RDF treatment (2.0 Mg C ha^{-1} yr^{-1}) in rice-lentil cropping sequence (Srinivasarao et al., 2012a). The inclusion of legumes in cropping system as a strategy of INM holds potential to improve the soil health. Legumes with deeper root system (*e.g.*, pigeon pea) can explore nutrients from deeper layers of the profiles and recycle them to the surface layer through leaf litter. These crops add C to soil in the form of rhizodeposition also (Srinivasarao et al., 2013b). Recycling the residues of legumes (*i.e.*, soybean) as mulch during the crop growing period or incorporating into the soil along with an appropriate rate of chemical fertilizer can sustain system's productivity, reduce the expenditure incurred on synthetic fertilizers and increase the SOC stock (Srinivasarao et al., 2012b).

Climate Adaptation

Climate change exerts both direct and indirect impacts on agricultural productivity including changing rainfall patterns, droughts and floods. Extreme drought can greatly affect the function, structure and productivity of soil ecosystem. In instances when severe flood occurs, it might result in erosion of soil leaving the land low in organic carbon and nutrient status. Embracing adaptation strategies to combat the hazardous impacts of climate change is crucial. Adaptation refers to actions that aid in reducing the vulnerability to climate change. Nutrient and water management practices exert profound influence on soil properties and ultimately crop production. Organic sources being major components of INM or IPNS aid in enhancing the soil organic matter content. Increased levels of organic matter and associated soil fauna lead to greater pore space with the instantaneous result that water infiltrates more readily and can be held in the soil. Increased water infiltration coupled with high organic matter content consequently results in increased soil storage of water. Organic matter aids in enhancing the stability of soil aggregates and pores through the bonding or adhesion properties of organic materials *viz.*, bacterial waste products, organic gels, fungal hyphae and worm secretions and casts. Also, organic matter mixed with mineral soil materials has a substantial impact in increasing moisture holding capacity. Enhanced moisture retention capacity aids in overcoming the impacts of drought, enhancing resilience of crops to climate change ultimately minimizing the losses which could have incurred otherwise.

Mitigation of Greenhouse Gases (GHGs)

Global warming caused by emission of greenhouse gases (N_2O, CH_4 and CO_2) will exert far reaching and long-term impacts on environment, natural ecosystems and human societies. Agriculture contributes about 42% of the increasing N_2O into the atmosphere, a significant share of this potent greenhouse gas with a global warming potential over a 100-year period being 298 times higher than CO_2 (IPCC, 2007) comes from the manufacture of synthetic fertilizers. Also, application of nitrogenous fertilizers is considered as the most important factor contributing to direct N_2O emissions from agricultural soils. Enhancing food production continues to be an unending demand to meet the needs of burgeoning population. Efficient nutrient management plays significant role in augmenting production and no doubt fertilizers hold prominence as boosters to enhance yields but as they contribute a major share to GHG emanations, curtailing their use by way of nutrient supplementation through utilization of available other nutrient rich sources is a viable option. Inclusion of available organic sources *viz*. FYM, poultry manure, crop residues, and vegetable and market wastes as part of the nutrient management programme along with fertilizers (INM) would prove beneficial in minimizing the usage of synthetically manufactured fertilizers towards crop yield enhancement which ultimately would offset GHG emissions. Huge amount of residue being generated from agricultural sector could be utilized as a source to supplement the nutrient needs of crops. The practice of burning crop residues leads to the emission of CO_2, CH_4 and N_2O which has resulted in multiple environmentally degrading phenomena such as air pollution, global warming, smog and climate change (Mathur and Srivastava, 2019). The incorporation of crop residues or their conversion to biochar through the process of pyrolysis would help in its utilization as soil health enhancer and nutrient supplement to crop aiding in cutting down on the quantity of fertilizer application and accruing multiple benefits *viz*. reduced emission of GHGs, efficient waste management and reduction in expenditure spent on fertilizers. Biochar amendment to soil when carried out sustainably may annually sequester an amount of C equal to 12% of the current anthropogenic CO_2 emissions (Woolf et al., 2010) indicating biochar as a potential source to mitigate GHG emissions. Inclusion of legumes in crop rotation as component of INM practice also could be regarded as a promising approach as these would supplement part of the nitrogen requirement of the crop, lessening the usage of nitrogenous fertilizers ultimately reducing N_2O emissions.

Different economic and environmental benefits of INM are presented in **Figure 10**.

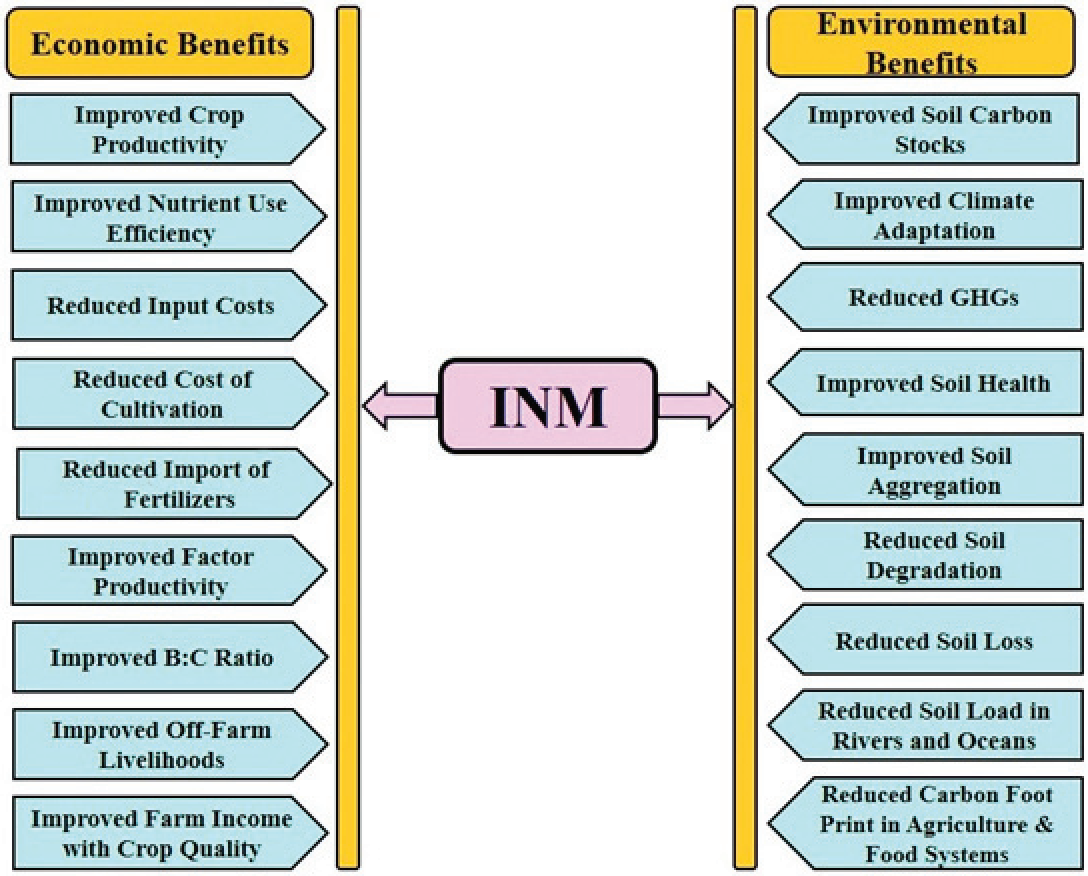


Figure 10. Economic and environmental benefits of integrated nutrient management (INM)

Way Forward

- Farmers need to be further trained and educated about the knowledge of soil degradation and its worse impacts on crop productivity and environment caused by the non-consideration of organic nutrient sources in agriculture.
- To achieve the widespread adoption of INM practices, it should be site-specific and related to the local circumstances as there will be no solution for the complex problems of smallholder farmers.
- Achieving the goals of INM will require expanded efforts nationwide to invent new technologies through the inter-disciplinary team of researchers and make them adaptive at small-holding farmers scale.
- Authentic research trials on large scale to evaluate the performance of INM with respect to economic and environment sustenance is the need of the hour.
- Consideration of locally available resources, indigenous technology and conditions of the farmers is most essential to develop site-specific INM technologies.
- Farmers should be fully educated regarding the actual fertilizer dosages based on soil tests and monitored for the balanced application of organic and inorganic nutrient sources in an integrated manner.
- Policy interventions related to adaptation of INM are critical for judicious management of available nutrient resources, enhancing SOC build-up, avoiding residue burning, and minimizing emission of greenhouse gases.

Conclusions

Agriculture is risk-prone with poor soil fertility and poor crop yields. Majority of the Indian farmers apply fertilizers non-judiciously to harvest more crop yields. Such imbalanced applications neither contribute to improvement in crop yields on long-term basis nor sustain the environment. Moreover, emission of GHGs into atmosphere through such improper agricultural practices is further aggravating the issues related to climate change. In order to promote judicious and balanced nutrient management in agriculture, farmers need to be encouraged to consider the inclusion of organic amendments such as farmyard manure, crop residues, bio-fertilizers, concentrated manures, etc., in conjunction with chemical fertilizers to achieve maximum yields. INM is one such practice that is sustainable in both economic and environment perspectives. Results from the experiments conducted in different agroecosystems have provided the answer on sustenance of crop productivity (improved yields, net returns, B:C ratio, etc.) and soil (improved NUE and SOC build-up) thereby mitigating the impact of climate change through INM adoption. Bringing sustainability in agricultural ecosystem should be our first priority and empowering the farmers needs to be meaningful and result-oriented.

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