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3 Integrated Nutrient Management for Sustainable Crop Production and Improving Soil Health

Rajinder Singh Antil and Dev Raj

Abstract

Integrated nutrient management (INM) is a concept, which aims at the maintenance of soil health and plant nutrient availability in optimum amounts for sustaining soil health and crop productivity through optimization of the benefits from all possible sources of plant nutrients. INM could play an important role in increasing nutrient use efficiency (NUE), food grain production, and maintenance of soil health and increasing the farmer's income through integrated and balanced application of fertilizers. Cropping system is one of the important ingredients of sustainable agriculture system as it provides more efficient cycling of nutrients. Therefore, balanced fertilization must be based on the concept of INM for a cropping system rather than a crop, so that crop productivity of the system as a whole is sustained. Long-term studies conducted in different agroclimatic zones have established the benefits of INM. This chapter overviews the importance of different components of INM in improving NUE, crop productivity, and soil health.

Keywords

Balanced fertilization · Long-term experiments · Organic manures · Crop productivity · Soil health

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Abbreviations

INM	Integrated nutrient management
Mt	Million tonne
NUE	Nutrient use efficiency
N	Nitrogen
P	Phosphorous
K	Potash
S	Sulfur
Zn	Zinc
B	Boron
Fe	Iron
Mn	Manganese
Mo	Molybdenum
HYV	High-yielding varieties
IPNS	Integrated Plant Nutrient Supply
INSAM	Integrated Nutrient Supply and Management
AICRP-IFS	All India Coordinated Research Project on Integrated Farming Systems
FYM	Farmyard manure
LTEs	Long-term experiments
BD	Bulk density
HC	Hydraulic conductivity
WSA	Water-stable aggregates
MWD	Mean weight diameter
IR	Infiltration rate
OC	Organic C
DOC	Dissolved organic carbon
MBC	Microbial biomass carbon
LFC	Light carbon fraction
HFC	Heavy Carbon Fraction
RDF	Recommended dose of fertilizer

3.1 Introduction

Indian agriculture is no longer an unknown one. It has progressed rapidly in recent years and ranks now as the second largest food producer in the world, touching $367 billion in 2014. The country's agricultural production is more than that of the United States, which once supplied food grains to India to meet the domestic food shortage. Unknown to many, India's international trade in agricultural products fetches higher earnings for the country than trade in the services or manufacturing. Food grain production of India has increased from 50.8 (1950–1951) to 284.83 Mt (2017–2018). A fivefold increase in food grain production during the last 67 years combined with inadequate and imbalanced use of nutrients has led to extra mining of all the essential nutrients. Extra mining of nutrients will have to be checked in order to sustain the soil health. The maintenance of soil health is very important to ensure the food and nutritional security of the country. For efficient use of fertilizers, all nutrients must be applied in balanced proportions. The nitrogen (N)/phosphorus (P)/potash (K) consumption ratio (2016–2017) of India was 7.2:2.9:1 against the ideal ratio of 4:2:1. The distortion in NPK consumption ratio is more pronounced among the zones and states of India. The problem of imbalanced fertilizer use in case of secondary and micronutrients is even worse wherein the use is much less compared to the requirement of the crops. So, there is a need to narrow down the NPK consumption ratio to sustain the crop productivity and restore the soil health. *Continuous use of imbalanced fertilizers led to the deterioration in the soil health and stagnate the crop productivity* (Das et al. 2015; Buragohain et al. 2017).

Even though during the 1960s, India has become self-sufficient on the food front as against its large imports, but our soil has been extensively overexploited. If such a situation is continued for a longer time, then there are chances that our productive land may become unproductive. The green revolution technologies, viz., higher uses of chemical fertilizers and pesticides with the adoption of nutrient-responsive and high-yielding varieties (HYV) of crops, have increased the productivity of almost all the crops. However, during the last decades, the compounded growth rates for the production and productivity of major crops generally declined or stagnated compared to the 1980s (Table 3.1). The crop responses to fertilizers are also decreasing consistently (Table 3.2).

There are reports that farmers have to add higher quantities of fertilizers every year to obtain the same yield level as obtained in the previous year. It may be due to the decline in the soil organic matter content, imbalanced use of fertilizers, extra mining of nutrients, and deficiency of secondary and micronutrients. The use of organic manures along with chemical fertilizers may be an effective alternative approach for further improving crop yields and sustaining soil health (Walia et al. 2017; Meena and Yadav 2015).

Table 3.1 Compound growth rates (% per annum) of production and productivity of crops

	Production			Productivity		
Crop	1980–1981 to 1989–1990	1990–1991 to 1999–2000	2001 to 2009–2010	1980–1981 to 1989–1990	1990–1991 to 1999–2000	2001 to 2009–2010
Rice (*Oryza sativa L.*)	3.62	2.02	1.59	3.19	1.34	1.61
Wheat (*Triticum aestivum* L.)	3.57	3.57	1.89	3.00	1.83	0.68
Pulses	1.52	0.59	2.61	1.61	0.93	1.64
Food grains	2.85	2.02	1.96	2.74	1.52	2.94
All major crops	3.19	2.99	1.83	2.56	1.38	2.83

Source: Kumara et al. (2013)

Table 3.2 Decline in crop response to fertilizer

Period	kg food grain per kg nutrients (NPK)
5th Plan (1974–1979)	1:15
8th Plan (1992–1997)	1:7.5
9th Plan (1997–2002)	1:7
10th Plan (2002–2007)	1:6.5
11th Plan (2007–2012)	1:6

Source: FAI, Fertilizer Statistics (1974–1975, 1992–1993, 1997–1998, 2002–2003, 2007–2008); Kumara et al. (2013)

INM is not a new concept. It is an age-old practice when requirements of all the nutrients (primary, secondary, and micronutrients) were met through organic sources. In literature, a few terminologies, viz., Integrated Plant Nutrient Supply (IPNS) and Integrated Nutrient Supply and Management (INSAM), are also used to convey almost similar meaning as that of INM. The advantages of INM are:

- Sustain and improve crop productivity and soil health
- Prevent deficiencies of secondary and micronutrients
- Improve nutrient use efficiency
- Provide favorable effect on the physical, chemical, and biological properties of soils (Singh et al. 2012b)

The application of best nutrient management practices in diverse ecologies and production systems is thus critical to enhance food production and improve farm profitability and resource efficiency. Also, the dimensions of the challenges would require a holistic alliance of policy-makers, agricultural scientists, extension specialists, and the farmers to facilitate INM toward improving the soil health.

3.2 INM Definition/Concept

INM has been defined by different researchers as follows:

- INM is defined as the maintenance or adjustment of soil fertility and supply of plant nutrients to an optimum level for sustaining the desired crop productivity through optimization of benefit from all possible resources of plant nutrients in an integrated manner (Roy and Ange 1991).
- INM is used to maintain or adjust soil fertility and plant nutrient supply to achieve a given level of crop production. This is done by optimizing the benefits from all possible sources of plant nutrients (FAO 1998).
- INM is actually the technical and managerial component of achieving the objective of IPNS under farm situations. It takes into account all factors of soil and crop management including management of all other inputs such as water, agrochemicals, amendments, etc., besides nutrients (Goswami 1998; Meena and Meena 2017).

Table 3.3 Extent of macronutrient deficiency in India

Nutrient	No. of samples analyzed	% are of samples by category		
		Low	Medium	High
N	3,650,004	63	26	11
P	3,650,004	42	38	20
K	3,650,004	13	37	50
S	27,000	40	35	25

Source: Motsara (2002)

3.3 Fertility Status of Soils

The inadequate and imbalanced fertilizer use has caused widespread nutrient (N, P, K, sulfur (S), zinc (Zn), and boron (B)) deficiencies and deterioration in soil health in many parts of India. It has been estimated that in India, 63, 42, 13, and 40% of soils were deficient in N, P, K, and S, respectively (Table 3.3). On an average, 49% of soils have been found deficient in Zn, 15% in iron (Fe), 3% in copper (Cu), 5% in manganese (Mn), 33% in B, and 13% in molybdenum (Mo) (Singh 2001).

3.4 Nutrient Removal and Balance in Soils

At the present level of production, the estimated NPK removal was about 28 Mt which results in a net negative balance of about 10 Mt. Organic manures and biofertilizers contribute to about 4 Mt, which means about 6 Mt negative balance has to be replenished by the soil (Antil and Narwal 2007; Yadav et al. 2017c). Recently, the Government of India has declared the target of doubling food grain production by 2025. It implies that for doubling the productivity, the nutrient removal would be more than double the present level to about 56 Mt. The gap between nutrient supply through all sources and removal would further escalate to more than 12 Mt from the present level of about 6 Mt, provided the contribution of organic and biofertilizer sources is also doubled. Thus, the soil health would further aggravate, which needs urgent attention. Although it is not possible to replenish 100% of nutrients removed by the crops every year, even then an attempt should be made to maximize the recycling of those nutrients which are likely to be deficient in the future. Thus, to meet this negative balance and to sustain the crop productivity and soil health on a long-term basis are possible only through the INM.

3.5 Nutrient Potentials of Organic Resources

India has a vast resource of organic input, and it is very difficult to assess its exact estimate, especially when production of residues, dung, etc. fluctuates every year. Further, the nutrient availability depends on the quality of the substrate technology used and value addition if any. The total available nutrient value of organic resources

Table 3.4 Available organic nutrients in India

Component	Potential availability (Mt)	Actual availability (Mt)	Nutrient value (Mt)
Crop residue	603.46	201.11	4.865
Animal dung	791.66	287.45	3.474
Green manure	4.46 m ha	NA	0.173
Rural compost	184.30	184.30	2.580
City compost	12.20	12.20	0.427
Biofertilizer	0.01	0.0094	0.370
Others	96.60	NA	0907
Total			12.796

Source: Bhattacharya (2007)

in India is 12.796 Mt, and the tappable amount is 8.952 Mt (after 30% deduction). The present utilization of organic nutrient resources has been estimated as 3.75 Mt (Bhattacharya 2007) of plant nutrient that can be made available for agricultural use (Table 3.4). Thus, about 25% of NPK requirement of Indian agriculture could be met by properly utilizing various organic resources (cattle dung, farmyard manure (FYM), crop residues, urban/rural wastes, and green manuring) which are readily available for agricultural use. Hence, there is an urgent need to refine the technologies available on the utilization of organic resources.

3.6 Components of INM

3.6.1 Balanced Fertilization

Balanced fertilization means rational use of fertilization and organic manures in such a manner that would ensure increased crop yields, improve quality of crops and cost/benefit ration, and have least adverse effect on the environment. Balanced fertilization must be based on the concept of INM for a cropping system (Goswami 1997) as this is the only viable strategy advocating accelerated and enhanced use of fertilizer with matching adoption of organic manures and fertilizers so that productivity is maintained for a sustainable agriculture. A balanced fertilization could be achieved through the application of multinutrients in balanced proportion from fertilizers, organic sources, biological sources, and more accurately and precisely through INM on a cropping system basis. Fertilizers continued to be the most important ingredient of INM. The dependence on fertilizers has been increasing constantly because of the need to supply large amounts of nutrients in intensive cropping with high productivity. Nonetheless, fertilizer consumption is not only inadequate but also imbalanced. At present, the consumption ratio of NPK (2016–2017) was about 7:3:1 against the ideal ratio of 4:2:1. The NPK use ratio is quite wide, whereas the application of K, S, and micronutrients is often ignored.

Utilization of fertilizer nutrients by the crops varies from 30 to 50% in the case of N, 15–20% in the case of P, and less than 5% in the case of micronutrients. Thus, a substantial amount of applied nutrients is lost through various pathways. Enhancing nutrient use efficiency should, therefore, be a prioritized area of research for the restoration and improvement of soil health and minimizing the cost of crop production. To increase the fertilizer use efficiency, crop yields and checks further mining of those nutrients, which are likely to be deficient in the future, the balanced amount of fertilizers based on soil testing should be applied. Long-term fertilizer experiment studies spread over a period of 30 years indicated that the application of balanced fertilizer and INM was the best tool for obtaining sustainability in crop yields of soybean and wheat (Tiwari 2008; Yadav et al. 2018a). Adoption of INM for a cropping system is the only viable strategy for accelerated and enhanced use of fertilizers with matching adoption of organic manures and biofertilizers, so that productivity is maintained for sustainable agriculture. Low or imbalanced fertilizer application is one of the important reasons for the low productivity (Singh et al. 2006; Meena and Lal 2018). Balanced fertilization along with organic manures and biofertilizers would be helpful to sustain crop yields and maintain soil fertility.

3.6.2 Organic Resources (Organic Manures, Crop Residues, Composts, Animal Dung, etc.)

Uses of chemical fertilizers alone deteriorate soil fertility and create unfavorable soil physical, chemical, and biological conditions in the intensive cropping system. It can be overcome by use of organics along with fertilizers for health and sustaining crop production. Organic manures have been the time-tested materials for improving the fertility and productivity of soils. Organic manures not only supply macro- and micronutrients but also help improving the physical, chemical, and biological conditions of the soils, and ultimately NUE would be improved. These manures, besides supplying nutrients to the first crop, also leave substantial residual effect on the succeeding crops in the system. Use of organic manures has been continuously declining in Indian agriculture.

3.6.2.1 Organic Manures (Long-Term Experiment (LTE) Results)

The findings of LTEs carried out under AICRP-IFS (AICRP-CS Annual Reports 1992–1993 to 2001–2002) showed that a part of fertilizer N requirements of monsoon crop can be met by adding FYM with the annual production either at par with fertilizer application alone at recommended levels or slightly higher with the INM package (Table 3.5). It was further noticed at few locations that the fertilizer requirements of the winter wheat could be reduced to about 25% by substituting 25% N needs of the preceding monsoon crop through FYM. Eight years of study on INM in rice-wheat systems at Jabalpur (Vertisols) revealed that conjunctive use of 5 t FYM and 6 t green manure (*Parthenium*) with 90 kg N ha^{-1} not only sustained the productivity but also saved nearly 90–100 kg fertilizer N ha^{-1} $year^{-1}$. In addition to saving N, INM practices also improved the soil organic carbon and nutrient (available P and K) status of the soil (Table 3.6).

Table 3.5 Effect of integrated nutrient supply through fertilizers and FYM on the productivity of crops under AICRP-CS

Treatment		Grain yield (t/ha)		
Monsoon	Winter	Monsoon	Winter	Total
Parbhani (sorghum (*Sorghum bicolor*)-wheat) av. of 7 years				
100% NPK	100% NPK	2.97	2.64	5.62
50% NPK+ 50% N (FYM)	100% NPK	2.85	2.78	6.53
Hanumangarh (pearl millet (*Pennisetum glaucum* L.)-wheat) av. of 5 years				
100% NPK	100% NPK	2.72	3.61	6.33
50% NPK+ 50% N (FYM)	100% NPK	2.56	2.40	6.38
Ranchi (maize (*Zea mays* L.)-wheat) av. of 8 years				
100% NPK	100% NPK	2.92	2.71	5.63
75% NPK+ 25% N (FYM)	100% NPK	3.30	2.40	5.70
Varansi (rice-wheat) av. of 5 years				
100% NPK	100% NPK	4.33	3.67	8.00
50% NPK+ 50% N (FYM)	100% NPK	4.71	4.02	8.72

Source: AICRP-IFS Reports (2005–2010); Das et al. (2014)

Table 3.6 Average productivity (t ha^{-1}) of rice-wheat system and nutrient content under 7 years of INM in a vertisol (Jabalpur)

Treatment	Rice (t ha^{-1})	Wheat (t ha^{-1})	Soil nutrient content after 7 years		
			Org. C (%)	P (kg ha^{-1})	K (kg ha^{-1})
N90	4.42	4.19	0.58	21.1	138
N180	5.08	4.70	0/71	18.7	125
N90 + FYM	4.95	4.49	0.74	40.1	230
N90 + GM	4.58	5.07	0.72	39.1	240
Initial			0.60	19.5	195

Source: Singh and Wanjari (2007); Singh et al. (2001); Singh et al. (2002)

Similar kind of advantageous effect of conjoint use of fertilizers and FYM was recorded in soybean/maize-wheat (Table 3.7) and other cropping systems (Singh et al. 2012a, b; Sudhir et al. 2004; Ashoka et al. 2017). Integration of NPK with FYM further increased the yield of both soybean and wheat. At Ranchi, use of lime as an ingredient of INM also significantly improved the productivity of the system.

The LTEs at Pantnagar (Mollisols), Barrackpore (Inceptisols), and Raipur (Vertisols) revealed that incorporation of FYM along with NPK gave the highest production of rice-wheat system (Singh et al. 2012b; Kumar et al. 2017b). Similar trends in the yield were also noted at the other locations. Combined use of fertilizers and organic manure (FYM) increased the productivity of the system with a significant residual effect on the subsequent wheat crop.

An LTE was initiated in winter 1967 to study the savings in fertilizer N at various doses of FYM and their modes of application in pearl millet-wheat cropping system. Results indicated the superiority of the combined use of FYM and N fertilizer in increasing the yield of both pearl millet and wheat crops compared to the application of fertilizer alone. Yield of both the crops responded linearly up to 120 kg N ha^{-1}

Table 3.7 Effect of INM on the productivity (t/ha) of soybean/maize-wheat system under LTFE at different locations

	Ranchi[a]		Jabalpur[b]		Palampur[c]	
Treatments	1972 to 2009		1972 to 2009		1999 to 2009	
Unfertilized	0.61	0.69	0.81	1.24	0.29	0.38
100% N	0.29	0.39	1.02	1.67	0.42	0.37[d]
100% NP	0.87	2.45	1.65	4.07	2.00	1.64
100% NPK	1.50	2.80	1.82	4.42	3.24	2.29
NPK + FYM	1.87	3.33	2.00	4.85	4.66	3.10
NPK + lime	1.80	3.17	–	–	4.11	2.85
CD (P = 0.05)	0.21	0.39	0.26	0.44	0.71	0.50

Source: [a]Mahapatra et al. (2007); [b]Dwivedi et al. (2007); [c]Sharma et al. (2005)
[d]At present yields are zero

at all FYM doses ranging from 0 to 90 t ha^{-1} year^{-1} (Table 3.8). It may be due to the increased demand of N or by increased losses of N with the addition of FYM. Application of FYM to the winter (rabi) season crop has been found to be better as compared to the summer (kharif) season (Antil et al. 2011; Meena et al. 2016a). It might be due to higher losses of nutrients from the summer-applied manure owing to higher temperature.

To study the contribution of FYM on the grain yield of pearl millet and wheat crops, a linear regression was fitted between the intercept of the linear model and the soil organic C content. It has been observed that each unit (0.1%) increase in the soil C content increased the productivity of pearl millet by 272.6 kg ha^{-1} and that of wheat by 1590.9 kg ha^{-1} (Fig. 3.1). Thus, the demand for N by the crops has increased which affected the response. The unit response to fertilizer N (slope of the linear model) was also plotted against the soil C content. It was observed that in the case of pearl millet, the slope also increased linearly with increasing soil C content, but in the case of wheat, there was no specific trend (Fig. 3.1). Better R^2 values in wheat crop were due to the better season for its growth rather than pearl millet, which used to be influenced by rainfall. This experiment was started with a view to save fertilizer N as a consequence of FYM application. But the yield data indicated that by fixing the productivity of the cropping system, we can save fertilizer N, but due to the economic returns from the fertilizer N application, it is not worthwhile to reduce the N supply. However, we can save all other nutrients except N by applying FYM (Antil et al. 2011; Meena and Yadav 2014).

Keeping the results of the above LTE initiated in winter 1967, another LTE was initiated in 1995 to evaluate the impact of continuous application of fertilizers and organic manures (FYM, poultry manure, and press mud) in pearl millet-wheat cropping system. The lowest grain yield of pearl millet and wheat crops was recorded when either 15 t FYM or 7.5 t press mud or 5 t poultry manure ha^{-1} was applied alone (Table 3.9). However, a significant increase in yield was obtained when organic manures were applied in combination with the recommended dose of N, which was comparable with the recommended dose of applied NP alone or NP applied in combination with organic manures, indicating that the amount of N

Table 3.8 Grain yield (q ha^{-1}) of pearl millet and wheat as influenced by the modes and levels of FYM and fertilizer N (averaged from 1982–1983 to 2007–2008)

		Pearl millet				Wheat			
		Level of N (kg ha^{-1})				Level of N (kg ha^{-1})			
FYM mode	FYM level (Mg ha^{-1})	0	60	120	Mean	0	60	120	Mean
	0	12.63	18.81	21.66	17.70	25.11	34.73	41.61	33.81
Kharif	15	15.54	22.23	24.10	20.62	33.53	40.25	45.46	39.75
	30	17.33	21.90	24.09	21.11	36.08	42.39	48.21	42.22
	45	17.88	22.73	26.50	22.37	38.47	43.78	50.19	44.15
Rabi	15	14.52	20.32	22.61	19.15	36.08	44.02	48.28	42.80
	30	16.12	22.69	23.95	20.92	39.94	44.70	51.06	45.23
	45	17.05	21.61	23.79	20.82	41.15	46.11	53.06	46.77
Both	15	17.35	21.65	24.77	21.26	40.26	46.08	52.11	46.15
	30	17.14	23.30	26.27	22.23	41.65	47.92	53.81	47.79
	45	19.55	24.24	27.18	23.66	43.91	48.71	55.12	49.25
Mean		16.51	21.95	24.49		37.62	43.87	49.89	
LSD (0.05)	FYM mode: 3.12; N level: 2.53					FYM mode: 2.98; N level: 2.43			

Source: Antil et al. (2011)

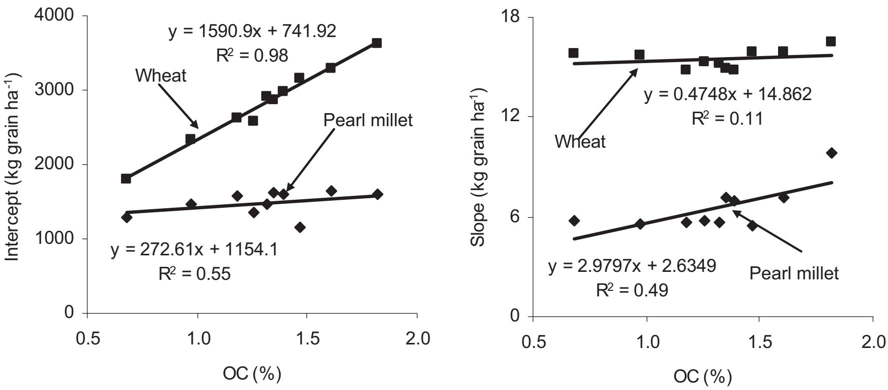

Fig. 3.1 Influence of organic C on the intercept (left) and slope (right) of linear model in pearl millet and wheat after 30 cycles of pearl millet-wheat cropping system (Gupta et al. 2003)

Table 3.9 Grain yield of pearl millet and wheat under different combinations of organic manures and fertilizers (average from 2000–01 to 2013–14)

Organic manures		Fertilizer (kg ha^{-1})		Yield (q ha^{-1})	
Type of manure	Dose (t ha^{-1})	N	P_2O_5	Pearl millet	Wheat
No manure	0	75	30	18.7	33.6
	0	150	60	22.8	47.2
FYM	15	0	0	15.6	23.9
	15	150	0	23.8	50.0
	15	150	30	25.6	54.2
Poultry manure	5	0	0	16.0	25.4
	5	150	30	24.0	48.0
Press mud	7.5	0	0	16.5	24.9
	7.5	75	30	23.2	42.2
	7.5	150	30	25.9	51.4
LSD (P = 0.05)				2.12	2.61

Source: Kumara et al. (2013)

released by organic manures was not good enough to meet the remaining N requirement of the crop (Kumara et al. 2013; Datta et al. 2017b). Organic manures applied to the wheat crop also had a subsequent effect on the pearl millet crop.

The results of 3 years of field demonstrations at a farmer's field indicated that the application of 15 t FYM ha^{-1} year^{-1} in conjunction with RDF increased the productivity of different cropping systems (pearl millet-wheat, wheat-cotton, rice-wheat) compared to the application of RDF alone (Antil and Narwal 2007; Meena et al. 2015d). In addition to yield gains, integrated use of FYM and fertilizers improved the fertility status of the soil.

Singh et al. (2012a) evaluated the effect of balanced and imbalanced application of plant nutrients made in the rice-wheat system on crop productivity and soil

Table 3.10 Treatment combinations and rates of nutrient and organic manures applied to rice and wheat crop each year

Treatment no.	Treatment applied to	
	Rice	Wheat
T_1	Control	Control
T_2	N_{150}	N_{150}
T_3	N_{150} P_{75}	N_{150} P_{75}
T_4	N_{150} $P_{75}K_{75}$	N_{150} $P_{75}K_{75}$
T_5	$N*_{150}$ $P*_{75}K*_{75}Zn*_{25}$	N_{150} $P_{75}K_{75}$
T_6	N_{150} $P_{75}K_{75}Zn_{25}$ + 15 t FYM ha^{-1}	N_{150} $P_{75}K_{75}$
T_7	N_{150} + 7.5 t press mud ha^{-1}	N_{150} $P_{75}K_{75}$
T_8	N_{75} $P_{37.5}K_{37.5}Zn_{25}$ + 20 t green manure ha^{-1}	N_{150} $P_{75}K_{75}$
T_9	N_{150} $P_{75}K_{75}Zn_{25}$ + 7.5 t burnt rice husk ha^{-1}	N_{150} $P_{75}K_{75}$

*N, P, K, and Zn stand for N, P_2O_5, K_2O, and $ZnSO_4$, respectively, and applied in kg ha^{-1} fertilizers. On the other hand, plots receiving combined application of inorganic fertilizers and organic manures received substantial amounts of micronutrients through manures

Source: Singh et al. (2012a)

Table 3.11 Average yield and yield trends of rice in long-term experiment (1997–2009) as affected by different nutrient management practices

Treatment	Average yield[a] t ha^{-1}	Yield change, slope t ha^{-1}	*t* statistics	*P* value
T_1	3.35	−0.055	−3.460	0.005
T_2	6.54	−0.114	−8.357	0.004
T_3	6.76	−0.132	−10.905	0.003
T_4	6.82	−0.134	−11.413	0.002
T_5	8.17	0.053	3.123	0.009
T_6	8.92	0.054	1.439	0.045
T_7	8.24	0.074	2.640	0.022
T_8	8.22	0.048	3.312	0.002
T_9	8.30	0.037	1.559	0.046

Source: Singh et al. (2012a)
[a]Average of 13 years of cropping

health. The treatments included various combinations of plant nutrients and are shown in Table 3.10. The trend in rice grain yield over a 13-year period varied markedly depending upon the nutrient management practices (Table 3.11). The rice grain yield decreased significantly in all the treatments where an imbalanced application of fertilizer nutrient was made. The rate of yield decline was lowest in control (0.055 t ha^{-1} $year^{-1}$) and highest in T_4 (0.134 t ha^{-1} $year^{-1}$) treatment. The grain yield of rice in T_1, T_2, T_3, and T_4 treatments decreased linearly with time, and this declining trend was significant (Table 3.11). The relationship between the initial yield and the yield decline in selected treatments was found significant with the R^2 values of 0.958 (Fig. 3.2). The decline in the rice grain yield in the present study can

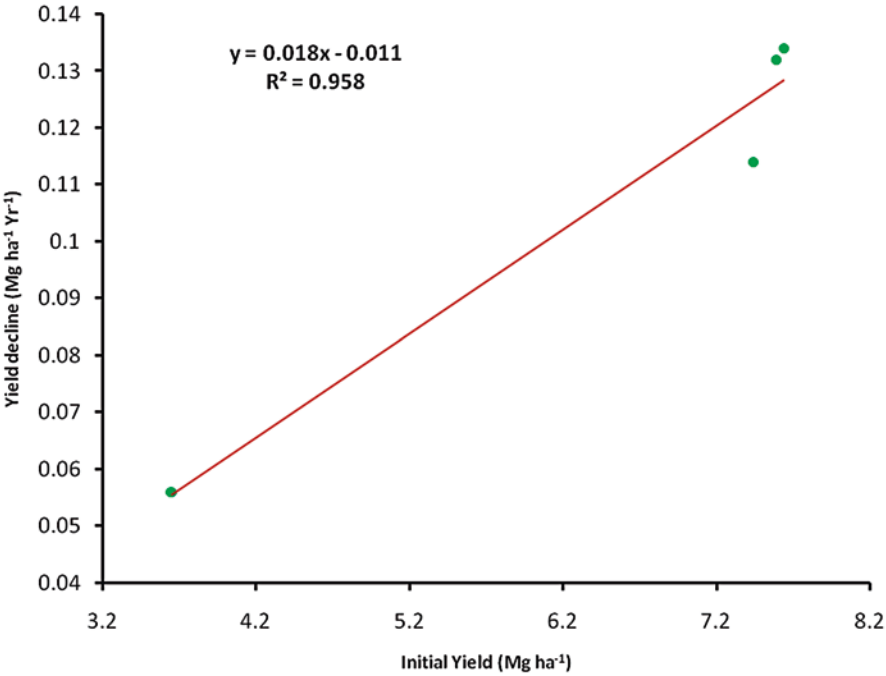

Fig. 3.2 Relationship between first year (1997) rice yield and rice yield decline over 13-year period under selected treatments (Singh et al. 2012a)

be attributed to the gradual decline in soil organic carbon and decreased availability of micronutrients, particularly that of Zn. The rice grain yield tended to increase with time in all the treatments where a balanced dose of chemical fertilizers alone (T_5) or their combined use with organic manures was made (T_6, T_7, T_8, and T_9). However, the magnitude of increase was more in FYM and press mud-amended treatments.

Thirteen years of continuous cropping without the application of adequate quantity of nutrients or their imbalanced application (T_1, T_2, T_3, and T_4) resulted in a significant decrease in grain yield of wheat with time (Singh et al. 2012a; Meena et al. 2015e; Kumar et al. 2018b) and ranged from 0.038 t ha^{-1} year^{-1} in T_1 to 0.116 t ha^{-1} year^{-1} in T_4 treatment (Table 3.12). The decline in wheat yield was significantly correlated ($R^2 = 0.963$) with the initial yield (Fig. 3.3). The data on soil fertility parameters suggested that a gradual decline in soil organic matter and available Zn content of the soil were mainly responsible for the declining trend in rice and wheat yield. The wheat grain yield remained almost stable in treatments which received balanced application of nutrients (T_5) or their application with organic manure in preceding rice crop (FYM, press mud, and green manure) indicating a positive effect on the succeeding wheat crop.

Table 3.12 Average yield and yield trends of wheat in long-term experiment (1997–1998 to 2009–2010) as affected by different nutrient management practices

Treatment	Average yield[a] t ha^{-1}	Yield change, slope t ha^{-1}	*t* statistics	*P* value
T_1	1.65	−0.038	−6.995	0.002
T_2	4.19	−0.094	−11.765	0.001
T_3	4.26	−0.105	−10.124	0.006
T_4	4.33	−0.116	−9.822	0.008
T_5	5.33	−0.026	−1.108	0.291
T_6	5.80	−0.017	−0.585	0.569
T_7	5.56	−0.013	−0.587	0.469
T_8	5.60	−0.014	−0.556	0.588
T_9	5.53	−0.032	−1.169	0.266

Source: Singh et al. (2012a)
[a]Average of 13 years of cropping

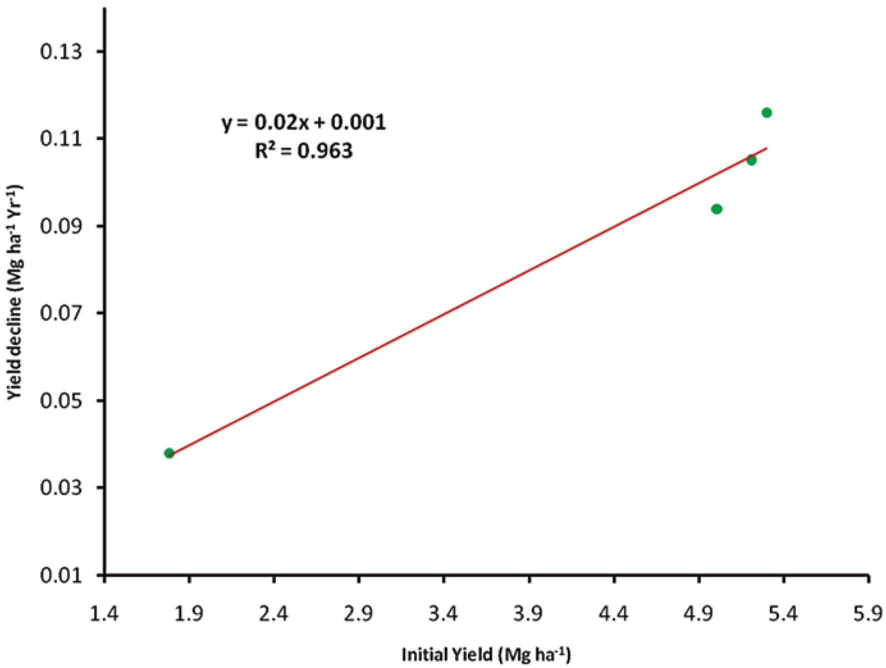

Fig. 3.3 Relationship between first year (1997–1998) wheat yield and wheat yield decline over 13-year period under selected treatments (Singh et al. 2012a)

3.6.2.2 Crop Residues

Crop residues are good sources of plant nutrients and are important components of INM. Crop residues, besides supplying nutrients to the current crop, leave sustainable residual effect on succeeding crop in the system. Recycling of crop residues is a viable strategy to meet at least a part of the nutrient requirement of different crops under various cropping systems. Total crop residue available in India is 603.46 Mt, out of which 201.11 Mt is available as nutrient for recycling with 4.865 Mt nutrient value (Bhattacharya 2007). About 30% N, 60–70% P, and 75% K-contained crop residues are available to the first crop and the rest to the subsequent crop. Crop residue addition improves the soil organic matter content, nutrient use efficiency, soil physical properties (structure and moisture retention), and microbial and enzymatic activity (Antil and Narwal 2007; Yadav et al. 2017b). Residue management under INM has considerable effect on soil microbial biomass C, which was enhanced if the residue is incorporated with the use of green manure (Jaipaul and Negi 2006; Meena et al. 2018a).

Disposal of rice straw in Trans- and Upper Gangetic Plains has emerged as a great problem. In these combined-harvested areas, farmers opt to burn the residues in situ, losing precious nutrients on one hand and polluting environment on the other. Recycling these residues back to fields helps to build stable organic matter in the soil and also to sustain crop yield levels. Stubbles left in the field even in traditional harvesting methods range from 0.5 to 1.5 t ha^{-1} in case of different crops. When mechanical harvesting is done, this amount is much greater. Stubbles of coarse cereals such as sorghum, maize, pearl millet, etc., which are difficult to decompose, are normally collected and burnt during land preparation causing significant loss of plant nutrients. A 7-year study (Yadvinder-Singh et al. 2004) demonstrated that rice and wheat productivity was not adversely affected when rice residue was incorporated at least 10 days, preferably 20 days, prior to the establishment of the succeeding crop. This study showed that rice residue decomposition of about 25% during the pre-wheat fallow period was sufficient to avoid any detrimental effects on wheat yields.

3.6.2.3 Composts

The average quantity of rural and urban compost in India is 184.3 and 12.2 Mt having nutrient values of 2.56 and 0.427 Mt, respectively (Bhattacharya 2007). The effects of enriched (consists of cow dung, crop residue, rock phosphate, pyrite, urea) phosphocompost and ordinary compost were compared with FYM and biogas slurry with and without fertilizer in groundnut-wheat cropping system. It was observed that the pod yield of groundnut increased by 52% due to the application of enriched compost when supplemented with 50% NPK over ordinary compost (Antil and Narwal 2007; Meena et al. 2015c; Sofi et al. 2018). The grain and straw yields of wheat were significantly higher with the agro-industrial waste composts (sewage sludge, distillery effluent, press mud, and poultry waste composts) as compared to their raw materials. Compost-fertilized wheat grain yields were increased by 118% with poultry waste compost followed by press mud compost and recommended dose of NPK fertilizer when compared with unfertilized control (Table 3.13). Agro-industrial waste composts applied with NK (recommended dose) fertilizers except distillery effluent compost produced wheat grain yield comparable to that obtained with NPK (recommended dose) fertilizers, indicating a net saving of 100% of P fertilizer. Hence, instead of using fertilizer alone, the integrated use of compost and

Table 3.13 Effect of different composts, organic amendments, and chemical fertilizer on grain and straw yield of wheat

Treatment	Yield (g pot^{-1}) Grain	Straw
Unfertilized control	3.63b*	4.86b
Sewage sludge	4.26c	6.48c
Sewage sludge compost	7.05g	9.28f
Distillery effluent	3.45b	4.53a
Distillery effluent compost	5.70e	6.81d
Press mud	5.73e	7.02d
Press mud compost	7.21g	10.05g
Poultry waste	6.45f	9.05f
Poultry waste compost	7.92h	10.86h
Chemical fertilizer (120 kg N + 60 kg P_2O_5 + 60 kg K_2O ha^{-1})	7.14g	10.24g
LSD (P = 0.05)	0.32	0.30

Source: Antil et al. (2013)
*Different small letters within columns indicate significance at $P < 0.05$

fertilizer could be more effective and sustainable for wheat productivity (Antil et al. 2013; Dadhich and Meena 2014).

3.6.2.4 Animal Dung

Total population of animal in India is 920.63 million with the dung production of 791.66 Mt having a nutrient (NPK) availability of 3.474 Mt. It has been estimated that about one third of the cattle dung produced is recycled in the fields, and the rest is burnt to meet the fuel demand which is a big loss. If this dung is properly managed, then the productivity of the soil can be increased. Therefore, farmers should be provided alternate sources of energy for cooking so that maximum dung could be used as manure. This problem can be solved if the dung is used in biogas plant. The major problem of direct application of biogas slurry is its transportation; however, the manurial value of biogas slurry is better than that of the compost. This problem can be managed by having two decomposing pits on both sides of the slurry outlet. The capacity of the pits should be sufficient to accommodate 6- month slurry, and all the wastes of the farm and household should be added it to be recycled. In this way, the farmers living in their farms can easily handle their dung properly.

3.6.3 Green Manuring

Green manures mobilize soil nutrient reserves, create conducive environment for soil microbes, and save on mineral nitrogen by fixing atmospheric N. Green manuring of dhaincha (*Sesbania aculeata*), mungbean (*Vigna radiata*), cowpea (*Vigna unguiculata*), and sun hemp (*Crotalaria juncea*) after harvesting of wheat in rice-growing areas of India saves 40–60 kg N ha^{-1} and maintains soil fertility (Antil and

Narwal 2007; Verma et al. 2015c). Application of fertilizers ($N_{150}P_{75}K_{75}Zn_{25}$) along with 15 t FYM ha^{-1} treatment produced higher yield than any other organic-amended treatment. Application of 50% of RDF ($N_{75}P_{37..5}K_{37..5}Zn_{25}$) with dhaincha green manuring produced rice grain yield comparable to that obtained with 100% of RDF ($N_{150}P_{75}K_{75}Zn_{25}$), indicating a saving of approximately 50% of fertilizers (Singh et al. 2012a; Dhakal et al. 2016; Kakraliya et al. 2018). The residual effect of FYM, press mud, green manuring, and burnt rice husk was also observed on the grain yield of succeeding wheat crop and resulted in an increase of 3.5, 2.8, 3.3, and 1.2 q wheat grain ha^{-1}, respectively.

3.6.4 Biofertilizers

Biofertilizers are cost-effective, eco-friendly, and renewable sources of plant nutrients to supplement chemical fertilizers in sustainable agricultural system. Biofertilizers have an important role in improving the nutrient supply and their availability for crop production. They help in increasing the biologically fixed atmospheric N and enhancing native P availability to crop. *Rhizobium* is the most well-known bacterial species that acts as the primary symbiotic fixer of N. *Rhizobium* is a potential biofertilizer for legumes, which saves about 25–50% of recommended dose of N and enriches soil with N for the succeeding crop. The free-living N-fixer, *Azotobacter*, imparts positive benefits to the crops through small increase in N input from BNF; development and branching of roots; production of plant growth hormones; enhancement in N, P, K, and Fe uptake; improved water status of the plants; increased nitrate-reductase activity; and production of antifungal compounds. Bacterial cultures of *Pseudomonas* and *Bacillus* species and fungal culture of *Aspergillus* species help to convert insoluble P into plant-usable forms and thus improve phosphate availability to the crops. Similarly, fungi like vesicular arbuscular mycorrhizae (VAM) increase nutrient uptake particularly that of P due to the increased contact of roots with a larger soil volume. Combined application of 20 t FYM ha^{-1} + 100% RDF + *Azotobacter* spp. + *Pseudomonas striata* recorded significantly higher shelling (%), protein content, oil yield, and pod and haulm yield over control and application of only FYM (@ 10 t ha^{-1}) + *Azotobacter* spp. + *Pseudomonas striata* + 50% RDF (Ghosh et al. 2005; Meena et al. 2016b). The use of biofertilizers should be done along with fertilizers and organic manures in legume and nonlegume-based cropping systems in order to sustain the crop productivity.

3.6.5 Legumes in Rotation

Green manuring with leguminous crops is not only beneficial in enhancing the yield but also improving the fertility of soil. Incorporation and decomposition of legumes have a solubilizing effect of N, P, K, and micronutrients (Zn, Mn, Fe, and Cu) in the soil and mitigate the deficiency of different nutrient elements by way of recycling of nutrients, reducing the leaching and gaseous losses of N and increasing the efficiency of applied plant nutrients. Sun hemp (*Crotalaria juncea*) and dhaincha (*Sesbania aculeata*) are the most important common green manure crops. Legumes could prove an important ingredient of INM when grown for grain or fodder in a cropping system or when introduced for green manuring. Legumes grown as green manure, forage, or grain crops improved the productivity of the rice-wheat cropping system (RWCS) and rejuvenated soil fertility (Yadav et al. 2000; Verma et al. 2015b).

In the rice-wheat cropping sequence, incorporation of mungbean residues after picking the pods significantly increased the yield over fallow treatment. The legume should be introduced in cereal-based crop rotations; it would increase the yield and nutrient use efficiency in succeeding crops following legume and also reduce the mining of N from soils. Studies on INM in rice-groundnut system in acidic soils revealed that use of green manure along with blue green algae gave similar yield as was obtained with 60 kg ha^{-1} fertilizer N and maintained higher available nutrient throughout the year (Ghosh et al. 2005; Meena et al. 2014).

Results from AICRP-IFS indicated that about 25 to 50% N can be saved under rice-wheat, rice-rice, rice-maize, maize-wheat, pearl millet-wheat, and sorghum-wheat cropping systems by growing mungbean as a catch crop. In spite of this, it is very difficult to accommodate a green manure crop within intensive cropping systems, and farmers are not interested to grow green manure crop as there is no direct cash benefit. Under such situations, growing a mungbean crop in summer and incorporation of the aboveground green biomass after picking of pod may serve as green manuring (Dwivedi et al. 2002; Datta et al. 2017a; Layek et al. 2018).

3.7 Effect of INM on Soil Health

3.7.1 Soil Physical Properties

Among the different physical properties of soil, bulk density (BD) has been considered as an important parameter for the assessment of soil health, mainly due to its relationships with the other soil state (strength and porosity) and rate (moisture retention and flow characteristics) variables. Soil aggregation, a physical property related to soil structure, is greatly influenced with the addition of organic resources. Hati et al. (2006) reported that addition of NPK along with FYM significantly improved soil aggregation, soil water retention, microporosity, and available water capacity and reduced the BD of the soil at 0–30 cm depth (Hati et al. 2006). The study suggests that addition of balanced fertilizers along with organic manures sustains a better soil physical environment and higher crop productivity. Das et al. (2014) reported that application of NPK fertilizers along with FYM or green gram residue + FYM or cereal residue improved the soil aggregation and structural stability and resulted in a higher C content in macroaggregates under the rice-wheat cropping system. The hydraulic conductivity (HC), water-stable aggregates (WSA) > 0.25 mm, and mean weight diameter (MWD) increased significantly with the addition of FYM. However, the addition of FYM reduced the BD. The values of

HC, WSA > 0.25 mm, and MWD were significantly higher when FYM was applied in both (rabi and kharif) the seasons compared to that applied either in rabi or kharif season (Antil et al. 2011; Kumar et al. 2018a). HC; moisture retention at 0, 0.1, 0.3, and 1.0 bar; and infiltration rate (IR) significantly increased with the increasing levels of FYM after 23 cycles of pearl millet-wheat cropping system (Table 3.14). On the other hand, dispersion percentage and BD decreased significantly with the application of FYM. Organic C (OC) was positively correlated with IR ($r = 0.97$), HC ($r = 0.89$), and moisture retention ($r = 0.94$) and negatively with BD ($r = -0.93$) and dispersion percentage ($r = -0.75$).

No significant differences in soil pH and EC were observed under different treatments after completion of the fourth cropping cycles; however, BD of soil almost remained close to the initial value under 100% organic and INM (50% organic +50% inorganic) treatments (Dubey et al. 2014; Meena et al. 2015b), while an increase in BD was observed under 100% inorganic applied treatment (Table 3.15).

The soil strength and IR increased significantly by incorporating green manure, wheat cut straw, and FYM in the fertilization schedule (Table 3.16). However, a reduction in BD was observed (Walia et al. 2010). Combined use of NPK and FYM in soybean (*Glycine max*)-wheat system resulted in 5.6% lower BD than NPK alone after the fourth cropping cycle (Bandyopadhyay et al. 2010; Yadav et al. 2018b). Reductions in BD due to the application of cattle manure (Nyamangara et al. 2001), poultry manure (Tejada and Gonzales 2008), and FYM (Bandyopadhyay et al. 2011) in LTEs have been observed. These reductions in BD could likely be attributed to the higher organic matter built up in soil (Hati et al. 2006; Varma et al. 2017a), better aggregation and consequent increase in total porosity, decrease in the degree of compaction (Leroy et al. 2008; Meena et al. 2018c), and increased root growth (Bandyopadhyay et al. 2010; Ram and Meena 2014).

3.7.2 Soil Chemical Properties

Several studies have shown that the application of organic manure in conjunction with fertilizers increased the soil OC and available N contents and their fractions more effectively than the application of fertilizers alone (Gong et al., 2009; Bijay-Singh 2018a; Meena et al. 2015a). Continuous application of FYM for a period of 33 years in pearl millet-wheat cropping system increased OC and available P and K content of the soil. Initial level of P and K of soil can be maintained with the application of 8.2 and 2.4 t FYM ha^{-1} $year^{-1}$, respectively (Antil et al. 2011; Meena et al. 2017c). Due to the linear response of N application up to 120 kg N ha^{-1} in the plots receiving 90 t FYM ha^{-1}, the savings in fertilizer N is not possible. These results indicate that application of 15 t FYM ha^{-1} $year^{-1}$ is sufficient to maintain the nutrient (except N) status of P and K of soil to its initial level. Hence, the application of P and K fertilizers can be avoided with the application of organic manures.

Application of NP fertilizers for 16 years in pearl millet-wheat cropping system decreased the OC content of soil from its initial level. However, the application of organic manures alone or in combination with NP fertilizers increased the OC

Table 3.14 Effect of FYM levels on some physical properties of soil after 23 cycles of pearl millet-wheat cropping system

FYM level (Mg ha^{-1})	OC (%)	BD (Mg m^{-3})	Dispersion percentage	HC (cm h^{-1})	IR (cm h^{-1}) after		Moisture retention (at different bars)			
					30 min	105 min	0	0.1	0.3	1.0
0	0.94	1.48	56.94	0.28	0.6	0.3	42.7	24.8	16.9	10.6
15	1.22	1.44	53.24	0.41	0.9	0.6	46.5	27.4	18.0	12.5
30	1.30	1.32	50.16	0.41	1.8	1.2	48.0	28.4	18.3	13.4
45	1.36	1.31	48.47	0.45	2.1	1.4	49.6	28.8	19.4	13.8
LSD (0.05)	0.09	0.08	1.13	0.18	ND	ND	0.5	0.4	0.3	0.2

Source: Antil et al. (2011)

Table 3.15 Effect of different nutrient management treatments on the properties of the soil on completion of fourth cropping cycle

Treatment	pH	EC (dS m^{-1})	OC (g kg^{-1})	BD (Mg m^{-3})	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
Initial	7.4	0.51	7.0	1.35	264	12.6	282
100% organic	7.2	0.49	7.8	1.36	288	13.0	297
100% inorganic	7.2	0.51	7.1	1.40	271	12.4	271
50% organic +50% inorganic	7.2	0.50	7.4	1.37	278	12.7	291

Source: Dubey et al. (2014)

Table 3.16 Effect of chemical fertilizers and organic manures on the physical properties of soil measured in 2007 after 23 years of cropping

Fertilizer rate (% of recommended NPK)		Bulk density (Mg m^{-3})	Soil strength (MPa)	Infiltration rate (cm h^{-1})
Rice	Wheat			
Control	Control	1.45	1.30	2.72
100	100	1.46	1.43	6.06
50 + 50% N (FYM)	100	1.39	0.97	4.48
50 + 50% N (WCS)	100	1.42	1.07	3.24
50 + 50% N (GM)	100	1.41	1.03	4.24
LSD (0.05)		0.02	0.17	0.114

Source: Walia et al. (2010)

significantly (Table 3.17). Application of organic manures with or without NP fertilizers could not sustain the initial level of N. However, soil fertility with respect to P, K, and micronutrients can be maintained with the application of organic manures (15 t FYM or 7.5 t press mud or 5 t poultry manure ha^{-1} $year^{-1}$) in conjunction with the recommended dose of N under pearl millet-wheat cropping systems. Hence, the application of P, K, and micronutrient fertilizers can be avoided with the application of organic manures (Kumara et al. 2013; Dadhich et al. 2015; Mitran et al. 2018). These results confirm the findings of the long-term experiment initiated in 1967 that we can save 100% of P, K, and micronutrient fertilizers, but we cannot save N through the combined application of organic manures with NP fertilizers.

The soil OC stock and C sequestration rate were calculated after 16 cycles of pearl millet-wheat cropping sequence. The results indicated that the soil OC stock decreased with greater magnitude (26, 127.4 kg ha^{-1}) in 75 kg N + 30 kg P_2O_5 ha^{-1} for 16 years (Table 3.18), whereas it was 71, 129.9 kg ha^{-1} with 15 t FYM ha^{-1}.

Table 3.17 Effect of long-term application of organic manures and fertilizers on organic C (%), available N, P, K, Zn, Mn, Fe, and Cu (mg kg^{-1}) status of soil after 16 cycles of pearl millet-wheat cropping sequence

Type of manure	Dose ($t\ ha^{-1}$)	Fertilizer ($kg\ ha^{-1}$)		OC	N	P	K	Zn	Mn	Fe	Cu
		N	P_2O_5								
No manure		75	30	0.36	64.5	8.9	173.4	0.72	3.30	5.02	0.48
		150	60	0.43	67.5	9.6	178.4	0.76	3.55	5.03	0.50
FYM	15	0	0	1.01	82.6	26.0	294.4	1.84	4.29	7.29	0.78
	15	150	0	0.98	82.7	26.9	298.4	1.80	4.57	7.27	0.81
	15	150	30	1.12	84.6	28.0	302.4	1.79	4.59	7.27	0.76
Poultry manure	5	0	0	0.59	78.4	28.6	247.4	1.65	3.81	6.82	0.72
	5	75	30	0.58	80.9	29.0	253.4	1.72	3.92	6.80	0.69
Press mud	7.5	0	0	0.73	95.7	27.1	253.6	1.73	4.00	6.99	0.74
	7.5	75	30	0.76	95.7	27.2	261.4	1.79	4.01	7.10	0.77
	7.5	150	30	0.75	98.3	27.3	267.4	1.81	4.14	8.09	0.77
Initial in 1995				0.39	98	12.6	217	–	–	–	–
LSD (P = 0.05)				0.05	2.2	0.2	2.6	0.01	0.064	0.043	0.020

Source: Kumara et al. (2013)

Table 3.18 Long-term effects of organic manures and fertilizers on soil organic carbon stock (kg ha^{-1}) and carbon sequestration rate (kg ha^{-1} year^{-1}) in surface soil (0–15 cm) after 16 cycles of pearl millet and wheat cropping sequence

Organic manures		Fertilizer (kg ha^{-1})			
Type of manure	Dose (t ha^{-1})	N	P_2O_5	Soil OC stock	C sequestration rate
No manure	0	75	30	668	−18.8
	0	150	60	774	25.0
FYM	15	0	0	1818	387.5
	15	150	0	1764	368.8
	15	150	30	2016	456.3
Poultry	5	0	0	972	93.8
Manure	5	150	30	1044	118.8
Press mud	7.5	0	0	1314	212.5
	7.5	75	30	1368	225.0
	7.5	150	30	1350	231.3
LSD (P = 0.05)				112	17.3

Source: Kumara et al. (2014)

Taking into consideration the amount of FYM, poultry manure and press mud were added during the period of 16 years of soil OC stock of soil such as 71, 129.9, 36, 288.0, and 49, 448.4 kg ha^{-1}, respectively (Kumara et al. 2014; Meena et al. 2017a). The major portion of soil OC is retained through clay-organic matter interactions, indicating the importance of the inorganic part of the soil as substrate to bind the organic carbon. However, recommended doses of NP fertilizers tended to have more soil OC stock in soil compared to half recommended doses of NP fertilizers and further increase of soil OC stock in combined application of fertilizers with FYM, poultry manure, and press mud.

The C sequestration rate was shown in negative trends with greater magnitude (−18.8 kg ha^{-1} year^{-1}) in 75 kg N + 30 kg P_2O_5 ha^{-1} for 16 years (Table 3.18), whereas it was 387.5 kg ha^{-1} year^{-1} with 15 t FYM ha^{-1}. Taking into consideration the combined application of fertilizers with FYM, poultry manure and press mud were added during the period of 16 years of C sequestration rate of soil, such as 456.3, 118.8, and 225.0 kg ha^{-1} year^{-1}, respectively (Kumara et al. 2014). The increase in C sequestration rate of soil with the addition of organic manures plus NP fertilizers might be due to better crop growth with accompanying higher root biomass generation and higher return of plant residues on the surface. The study established that the regular application of recommended doses of NP fertilizer under pearl millet-wheat cropping sequence reduced the negative soil OC trends.

Application of FYM as a component of INM increased the OC content of the soil, and the increase ranged from 0.03 to 0.06% year^{-1} under different cropping systems (pearl millet-wheat, wheat-cotton, rice-wheat). The cumulative increase in OC content of the soil under different cropping systems (pearl millet-wheat, wheat-cotton, rice-wheat) has been presented in Fig. 3.4a. The available P content of the soil also increased in all the demonstrations at the farmer's field in all the cropping

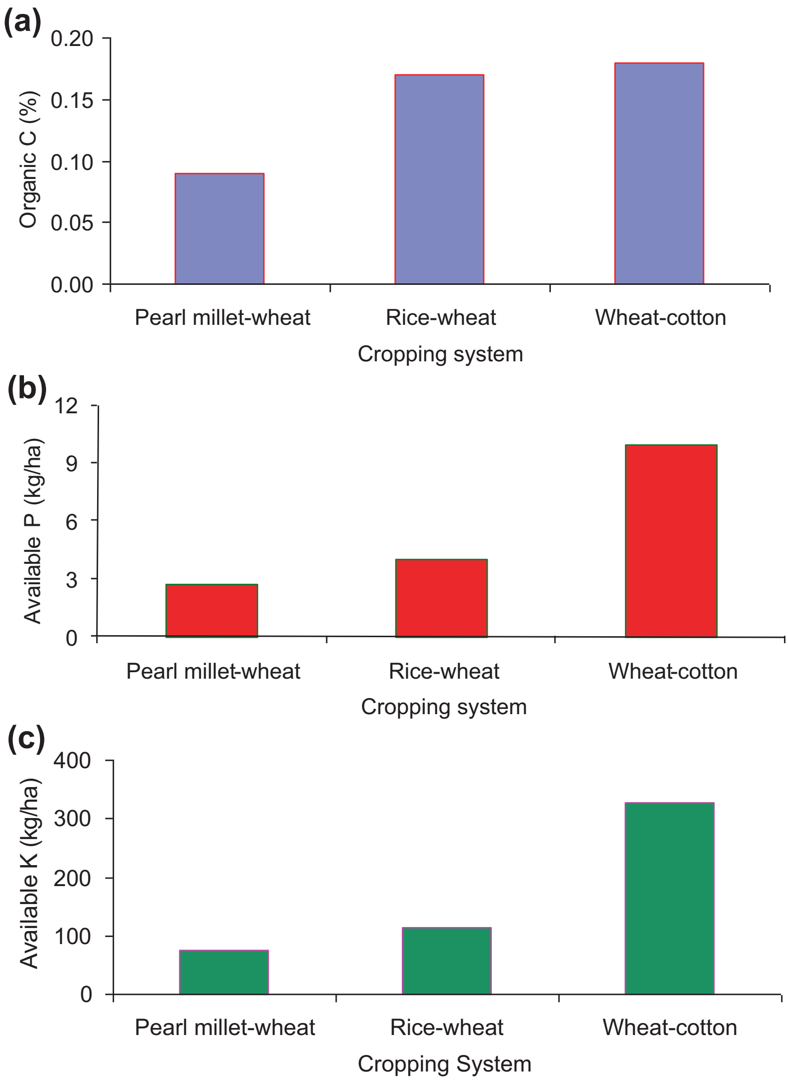

Fig. 3.4 Influence of FYM on the buildup of organic C (**a**), available P (**b**), and K (**c**) in soil as the components of INM under various wheat-based cropping systems

systems, and the rate of increase was ranging from 0.9 to 3.3 kg ha^{-1} year^{-1}. The cumulative increase in the available P content of the soil has been presented in Fig. 3.4b. Continuous application of FYM can increase the available P content of the soil to a level, which is sufficient to meet the requirement of the wheat crop. The maintenance of the available K content of the soil with fertilizer application is very difficult because it leads to luxury consumption. It has been observed in the long-term field experiments as well as in the demonstrations at farmer's fields that there is sufficient buildup of the available K content of the soil due to the application of

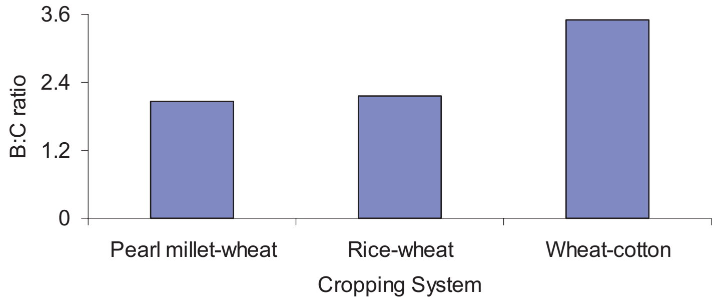

Fig. 3.5 Influence of INM on B:C ratio of various wheat-based cropping systems

FYM. The rate of increase ranged from 25 to 109 kg ha^{-1} year^{-1}. The cumulative increase in the available K content of the soil has been presented in Fig. 3.4c. It has been observed that the plots receiving FYM did not show the deficiency of Zn and Fe in any crop.

It exhibits not only the higher productivity and maintenance of soil fertility but is also economical, and the benefit/cost ratio of FYM use ranged from 2.07 to 3.5 (Antil and Narwal 2007; Sihag et al. 2015) in different cropping systems (pearl millet-wheat, wheat-cotton, rice-wheat) (Fig. 3.5). Thus, this technology can be easily followed by the farming community for increasing the productivity of different cropping systems.

The application of N alone or in combination with P or NPK or NPKZn maintained the initial levels of available N after 13 cycles of rice-wheat cropping (Singh et al. 2012a; Yadav et al. 2017a). The combined application of inorganic fertilizers and FYM or press mud or green manure (T_6 to T_8) increased the available N significantly over the initial level, and this increase varied from 14 to 24 kg ha^{-1}. The available P content of the soil decreased significantly in control (T_1) and in T_2 treatment where no P application was made. However, application of P through mineral fertilizers (T_3, to T_5) or its combined use with organic manures (T_6 to T_9) showed an increase of 6–18 kg ha^{-1} in available P. Application of K through inorganic fertilizers alone (T_4 and T_5) or their combined use with organic sources showed an increase of 54–76 kg ha^{-1} in the available K status of the soil, while in the absence of K application (T_1 to T_3), the available K content decreased between 81 and 101 kg ha^{-1} over its initial value in 13 years of continuous rice-wheat cropping (Singh et al. 2012a; Meena et al. 2017b).

Seven years of rice-wheat cropping system without any fertilizers or organic amendments decreased (4.4 to 3.5 g kg^{-1}) the total soil C significantly over its initial level (Sekhon et al. 2009; Verma et al. 2015a). It indicates that C added through plant residues in the rice-wheat cropping system was not sufficient to maintain the soil C content to its initial levels.

Thirteen years of rice-wheat cropping system without any fertilization also decreased the OC content of soil from its initial status of 4.2 g kg^{-1} soil to 3.0 g kg^{-1} soil (Table 3.19). Balanced application of inorganic fertilizers (T_5) resulted in

Table 3.19 Effect of different treatments on organic carbon and available nutrient (N, P, and K) content of soil after 13 cycles of rice-wheat cropping system

Treatment no.	OC (g kg^{-1})	Available nutrient (kg ha^{-1})		
		N	P	K
T_1	3.0	105	16	240
T_2	3.7	140	14	228
T_3	3.8	142	30	224
T_4	4.0	140	32	356
T_5	5.0	144	33	359
T_6	6.9	156	39	378
T_7	7.4	160	42	365
T_8	5.7	150	36	381
T_9	4.9	146	34	362
Initial values	4.2	136	24	305
LSD (0.05)	0.9	11	8	16

Source: Singh et al. (2012a)

significantly higher accumulation of soil OC as compared N_{150} (T_2), $N_{150}P_{75}$ (T_3), and $N_{150}P_{75}K_{75}$ (T_4) treatments.

Continuous application of FYM (T_6), press mud (T_7), and green manure (T_8) for 13 years increased soil OC by 1.9, 2.4, and 0.7 g kg^{-1}, respectively, in surface soil over inorganic fertilizer-only treatment (T_5). This increase in soil carbon accounted for 14.5, 15.8, and 5.3% of C added through FYM, press mud, and green manure, respectively. The available N decreased significantly with time in control over their initial status in soil (Table 3.13). Application of organic manures in conjunction with fertilizer under rice-wheat cropping system improved the OC, available P, K, and the micronutrient content of the soil.

Thirty-one years of maize-wheat-cowpea (fodder) cropping system influenced the soil OC (0–30 cm soil depth) significantly. The highest (6.5 g kg^{-1}) soil OC (0–15 cm) was observed in the NPK + FYM treatment. Significantly higher soil OC was found in the NPK treatment as compared to the control and N treatment. The soil OC was similar to the initial level (4.4 g kg^{-1}) in the control and N-fertilized plots after 31 years, whereas in FYM and NPK + FYM treatments, the soil OC increased over the initial level by 38.6 and 63.6%, respectively (Hati et al. 2006; Kumar et al. 2017a).

Bijay-Singh (2018b) did a meta-analysis of the data published on crop yields and soil parameters in maize-wheat, rice-rice, and rice-wheat cropping systems from LTEs. The buildup of soil OC in the upland system was less as compared to the lowland systems. The application of the recommended doses of NPK fertilizers resulted in the buildup of soil OC over no-fertilizer application in all the three cropping systems (Table 3.20). Decrease in soil OC content in the no-fertilizer application (control) from the initial values might be due to cultivation of the soil in the maize-wheat cropping system.

Table 3.20 Average soil OC content at the start (initial) of long-term experiments on maize-wheat, rice-wheat, and rice-rice cropping systems and in no-fertilizer (N, P, and K) control and optimum N, P, and K fertilizer level treatments

Cropping system	Number of experiments	Duration (years)	Soil OC (g kg^{-1})		
			Initial	No-fertilizer control	Optimum N, P, and K fertilizer levels
Maize-wheat	12	6–25	6.4	5.8	6.8
Rice-wheat	10	9–27	14.3	14.9	16.3
Rice-rice	23	6–26	16.7	18.1	19.6

Source: Bijay-Singh (2018a, b)

3.7.3 Soil Biological Properties

Generally, enzyme activities in the soil are closely related to the organic matter content. Application of balanced amounts of nutrients and manures improved the organic matter and MBC content of soils, which corresponded with higher enzyme activity (Mandal et al. 2007). Soil microbial biomass constitutes a transformation matrix for organic matter in soil and acts as an active reservoir for plant-available nutrients. It is established that soil microbial carbon and soil enzymes respond more quickly to changes in environment sand agronomic practices than does the soil organic carbon. The dissolved organic carbon (DOC), microbial biomass carbon (MBC), light carbon fraction (LFC), and heavy carbon fraction (HFC) content of soil increased significantly, increasing the levels of FYM. However, the increase in DOC, MBC, LFC, and HFC was highest in 15 Mg ha^{-1} followed by 10 and 5 Mg ha^{-1} (Kumara 2013; Varma et al. 2017b; Gogoi et al. 2018). Application of NPK fertilizers alone or in combination with FYM and green manuring improved soil microbial biomass C, urease activity, and alkaline phosphatase activity but had little effect on the dehydrogenase activity (Goyal et al. 1999).

Application of organic manures alone or in combination with N or NP fertilizers significantly increased dehydrogenase, alkaline phosphatase, and urease activity as compared to the application of fertilizers alone (Sheoran 2015; Dhakal et al. 2015). However, combined application of organic manures and fertilizers significantly decreased the dehydrogenase and urease activity compared with the organic manures applied alone, while alkaline phosphatase activity showed the reverse trend (Table 3.21).

3.8 Effect of INM on NUE

Use efficiency of different nutrients continues to be extremely low, and its enhancement has remained a prime concern at all times. Long-term studies indicated that INM helped in enhancing the use efficiency of N at different locations (Dwivedi et al. 2016; Meena et al. 2018b). In Inceptisols (Ludhiana), the N use efficiency in maize recorded under 100% N (alone) was 16.7%, which increased to 23.5, 36.4,

Table 3.21 Effect of long-term application of organic manures and fertilizers on soil enzyme activity

Type of manure	Dose (Mg ha^{-1})	Fertilizer (kg ha^{-1}) N	P_2O_5	Dehydrogenase activity (µg TPF g^{-1} 24 h^{-1})	Alkaline phosphatase activity (µg PNP g^{-1} h^{-1})	Urease activity (µgNH$_4^+$-N g^{-1} h^{-1})
No manure	0	75	30	36.53	572.25	58.81
	0	150	60	32.32	580.75	65.02
FYM	15	0	0	63.71	684.00	87.72
	15	150	0	59.75	742.75	76.27
	15	150	30	50.48	733.50	71.25
Poultry manure	5	0	0	48.62	704.45	85.20
	5	150	30	40.13	756.00	75.75
Press mud	7.5	0	0	58.14	664.63	97.60
	7.5	75	30	44.86	675.65	83.49
	7.5	150	30	39.44	673.20	71.28
C.D. (P = 0.05)				5.69	17.91	7.88

Source: Sheoran (2015)

Table 3.22 N use efficiency in different crops as affected by long-term nutrient supply with and without FYM

Soil type	Location	Crop	N use efficiency (%) N	NP	NPK	NPK + FYM
Inceptisol	Ludhiana	Maize	16.7	23.5	36.4	40.2
		Wheat	32.0	50.6	63.1	67.8
Alfisol	Palampur	Maize	6.4	34.7	52.6	63.7
		Wheat	1.9	35.6	50.6	72.6
Mollisol	Pantnagar	Rice	37.5	40.7	44.4	61.7
		Wheat	42.4	46.1	48.4	47.9

Source: Singh et al. (2012b)

and 40.2% on integration with P, PK, and FYM, respectively (Table 3.22). Similar trend was noted in Mollisols (Pantnagar) under, and agroecological regions need to be worked out, and nutrient supply packages with optimum application rates of organic manures and fertilizers should be developed.

3.9 Constraints in Adoption of INM Technology

The constraints in the adoption of INM technology are as follows:

- Cost and nonavailability of FYM
- Difficulties in growing green manure crops
- Nonavailability of biofertilizers
- Nonavailability of soil-testing facilities

- High cost of chemical fertilizers
- Nonavailability of water
- Lack of knowledge and poor advisory services
- Nonavailability of quality seeds

3.10 Suggestions for Improving Adoption of INM Technology

The following are the suggestions for improving adoption and implementation of the INM technology:

- Create mass awareness among the farmers for recycling and use of organic resources and for preparation of quality compost and FYM.
- Educate the farmers through media, mass contact and awareness program, and on-farm demonstration about the benefits of INM.
- Educate the farmers about the nature of soil and its importance for mankind and need to preserve it for posterity.
- Loan facilities should be provided to farmers by financial agencies to encourage adoption of INM.
- Develop promotional literatures in local languages and distribute to the farmers.
- Advise the farmers to incorporate crop residues into soil to the extent possible.
- Information on balanced use of fertilizers based on soil test, biofertilizers, green manuring, and information on compost-making techniques should be transferred to farmers.
- Motivate KVKs, fertilizer industry, and NGOs to propagate the usefulness of INM.

3.11 Priorities for Future Research

- Contribution of organic resources during the crop growing season and residual nutrients from their applications to soil nutrient budget should be assessed.
- Efficient management of crop residues in different cropping systems should be investigated under different agroecosystems.
- Role of industrial wastes in improving nutrient use efficiency should be evaluated under different agroecosystems.
- The major component of the system that needs attention is recycling of solid waste and vermicomposting.
- Beneficial effect of inclusion of legume on soil health needs to be quantified under cereal-cereal cropping systems.
- Organics, wastes, residues, and biofertilizers should be identified for various location-specific cropping systems.
- Location-specific INM technology should be developed and effectively transferred to the farmers for sustaining crop productivity of various cropping systems.

- Causes of decline in the rate of growth of total production under various cropping systems associated with the deterioration of soil health and reduction of soil OC stocks should be studied, and possible measures should be found out.
- Dynamics of soil organic matter and C sequestration should be studied regularly under LTEs in different cropping and agroecosystems.

3.12 Conclusions

Based on the results of short and LTEs conducted in different soil-crop environments, it is concluded that INM has a great potential to meet the growing demands of nutrients, to achieve maximum yields, and to sustain the crop productivity on a long-term basis without any adverse effect on the environment. The soil health can be maintained with the use of balanced fertilization along with organic resources, biofertilizers, and green manures besides getting higher yield. The success of INM depends on the different components of INM and how precisely they are used. The INM could play a major role in improving the nutrient use efficiency, crop yields, soil health, and socioeconomic status of small and marginal farmers. About 25% nutrient requirement of Indian agriculture could be met if various sources of organic resources (dung, FYM, crop residues, urban/rural waste, and green manuring) are properly utilized**.**

References

AICRP-CS Annual Reports (1992–93 to 2001–02) AICRP on Cropping Systems, PDCSR, Modipuram, India

AICRP-IFS Reports (2005–2010) AICRP on Integrated Farming Systems, PDFSR, Modipuram, India

Antil RS, Narwal RP (2007) Integrated nutrient management for sustainable soil health and crop productivity. Indian J Fert 3(9):111–112

Antil RS, Narwal RP, Singh B, Singh JP (2011) Long-term effects of FYM and N application on soil health and productivity under pearl millet – wheat cropping system. Indian J Fert 7(7):14–32

Antil RS, DevRaj, Narwal RP, Singh JP (2013) Evaluation of maturity and stability parameters of composts prepared from a wide range of organic wastes and their response to wheat. Waste Biomass Valoriz 4:95–104

Ashoka P, Meena RS, Kumar S, Yadav GS, Layek J (2017) Green nanotechnology is a key for eco-friendly agriculture. J Clean Prod 142:4440–4441

Bandyopadhyay KK, Misra AK, Ghosh PK, Hati KM (2010) Effect of integrated use of farmyard manure and chemical fertilizers on soil physical properties and productivity of soybean. Soil Tillage Res 110:115–125

Bandyopadhyay PK, Saha S, Mallick S (2011) Comparison of soil physical properties between a permanent fallow and a long-term rice–wheat cropping with inorganic and organic inputs in the humid subtropics of eastern India. Commun Soil Sci Plant Anal 42:435–449

Bhattacharya P (2007) Prospect of organic nutrient resources utilization in India. Indian J Fert 3:93–107

Bijay-Singh (2018a) Optimizing fertilizer use to maintain soil health. In: Reicosky D (ed) Managing soil health for sustainable agriculture Vol. 2: monitoring and management. Burleigh Dodds Science Publishing, Cambridge. (ISBN:9781786761927. www.bdspublishing.com)

Bijay-Singh (2018b) Are nitrogen fertilizers deleterious to soil health? Agronomy 8:48. https://doi.org/10.3390/agronomy8040048

Buragohain S, Sharma B, Nath JD, Gogaoi N, Meena RS, Lal R (2017) Impact of ten years of bio-fertilizer use on soil quality and rice yield on an inceptisol in Assam, India. Soil Res. https://doi.org/10.1071/SR17001

Dadhich RK, Meena RS (2014) Performance of Indian mustard (*Brassica juncea* L.) in response to foliar spray of thiourea and thioglycollic acid under different irrigation levels. Indian J Ecol 41(2):376–378

Dadhich RK, Meena RS, Reager ML, Kansotia BC (2015) Response of bio-regulators to yield and quality of Indian mustard (*Brassica juncea* L. Czernj. and Cosson) under different irrigation environments. J App Nat Sci 7(1):52–57

Das B, Chakraborty D, Singh VK, Aggarwal P, Singh R, Dwivedi BS (2014) Effect of integrated nutrient management practice on soil aggregate properties, its stability and aggregate-associated carbon content in an intensive rice-wheat system. Soil Tillage Res 136:9–18

Das D, Dwivedi BS, Meena MC, Singh VK (2015) Integrated nutrient management for improving soil health and crop productivity. Indian J Fert 11(4):64–83

Datta R, Baraniya D, Wang YF, Kelkar A, Moulick A, Meena RS, Yadav GS, Ceccherini MT, Formanek P (2017a) Multi-function role as nutrient and scavenger off reeradical in soil. Sustain MDPI 9:402. https://doi.org/10.3390/su9081402

Datta R, Kelkar A, Baraniya D, Molaei A, Moulick A, Meena RS, Formanek P (2017b) Enzymatic degradation of lignin in soil: a review. Sustain MDPI 9:1163. https://doi.org/10.3390/su9071163, 1–18

Dhakal Y, Meena RS, De N, Verma SK, Singh A (2015) Growth, yield and nutrient content of mungbean (*Vigna radiata* L.) in response to INM in eastern Uttar Pradesh, India. Bangladesh J Bot 44(3):479–482

Dhakal Y, Meena RS, Kumar S (2016) Effect of INM on nodulation, yield, quality and available nutrient status in soil after harvest of green gram. Legum Res 39(4):590–594

Dubey R, Sharma RS, Dubey DP (2014) Effect of organic, inorganic and integrated nutrient management on crop productivity, water productivity and soil properties under various rice-based cropping systems in Madhya Pradesh, India. Int J Curr Microbiol App Sci 3:381–389

Dwivedi BS, Shukla AK, Singh VK (2002) PDCSR Annual Report (2001–02), PDCSR, Modipuram

Dwivedi AK, Singh M, Kauraw DL, Wanjari RH, Chauhan SS (2007) Impact of fertilizer and manure use for three decades on crop productivity and sustainability, and soil quality under soybean-wheat system on vertisols in Central India. IISS, Bhopal, p 51

Dwivedi BS, Singh VK, Meena MC, Dey A, Datta SP (2016) Integrated nutrient management for enhancing nutrient use efficiency. Indian J Fert 12(44):62–71

FAI, Fertilizer Statistics (1974–75, 1992–93, 19997–98, 2002–03, 2007–08) The Fertilizer Association of India, New Delhi

FAO (1998) Guide to efficient plant nutrition management. Land and Water Development Division, FAO, Rome, pp 1–19

Ghosh PK, Ghosh RK, Bandyopadhyay KK, Mishra AK, Manna MC (2005) Role of integrated plant nutrient supply for sustainable production in groundnut based cropping system. Fert News 50:45–53

Gogoi N, Baruah KK, Meena RS (2018) Grain legumes: impact on soil health and agroecosystem. In: Meena et al (eds) Legumes for soil health and sustainable management. Springer, Singapore. https://doi.org/10.1007/978-981-13-0253-4_16

Gong W, Yan X, Wang J, Hu T, Gong Y (2009) Long-term manure and fertilizer effects on soil organic matter fractions and microbes under a wheat–maize cropping system in northern China. Geoderma 149:318–324

Goswami NN (1997) Balanced use of plant nutrients. Fert News 42(4):15–19

Goswami NN (1998) Some thoughts on concept, relevance and feasibility of IPNS under Indian condition. In: Integrated plant nutrient supply system for sustainable productivity bulletin no. 2. IISS, Bhopal, pp 3–9

Goyal S, Chander K, Mundra MC, Kapoor KK (1999) Influence of inorganic fertilizers and organic amendments on soil organic matter and soil microbial properties under tropical conditions. Biol Fertil Soils 29:196–200

Gupta AP, Narwal RP, Antil RS (2003) Influence of soil organic matter on the productivity of pearl millet – wheat cropping sequence. Arch Agron Soil Sci 49:325–332

Hati KM, Swarup A, Singh D, Misra AK, Ghosh PK (2006) Long-term continuous cropping, fertilization and manuring effects on physical properties and organic carbon content of a sandy loam soil. Aus J Soil Res 44:487–495

Jaipaul, Negi MS (2006) In: Sharma et al (eds) Balanced fertilization for sustainable crop production. CSKHPKV/ICAR, Palampur/New Delhi, pp 96–97

Kakraliya SK, Singh U, Bohra A, Choudhary KK, Kumar S, Meena RS, Jat ML (2018) Nitrogen and legumes: a meta-analysis. In: Meena RS et al (eds) Legumes for soil health and sustainable management. Springer, Singapore. https://doi.org/10.1007/978-981-13-0253-4_9

Kumar S, Meena RS, Pandey A, Seema (2017a) Soil acidity management and an economics response of lime and sulfur on sesame in an alley cropping system. Int J Curr Microb Appl Sci 6(3):2566–2573

Kumar S, Meena RS, Yadav GS, Pandey A (2017b) Response of sesame (*Sesamum indicum* L.) to sulphur and lime application under soil acidity. Int J Plant Soil Sci 14(4):1–9

Kumar S, Meena RS, Bohra JS (2018a) Interactive effect of sowing dates and nutrient sources on dry matter accumulation of Indian mustard (*Brassica juncea* L.). J Oilseed Brassica 9(1):72–76

Kumar S, Meena RS, Lal R, Yadav GS, Mitran T, Meena BL, Dotaniya ML, EL-Sabagh A (2018b) Role of legumes in soil carbon sequestration. In: Meena RS et al (eds) Legumes for soil health and sustainable management. Springer, Singapore. https://doi.org/10.1007/978-981-13-0253-4_4

Kumara BH (2013) Long-term effects of organic manures and fertilizers on soil organic carbon pools and nitrogen fractions. Ph.D. thesis, Department of Soil Science, CCS Haryana Agricultural University Hisar, India

Kumara BH, Antil RS, DevRaj (2013) Long-term effects of nutrient management on soil health and crop productivity under pearl millet – wheat cropping system. Indian J Fert 9(12):86–97

Kumara BH, Antil RS, DevRaj (2014) Impact of long-term manures and fertilizer application on carbon sequestration and its efficiency under pearl millet – wheat cropping sequence. Int J Farm Sci 4(1):21–26

Layek J, Das A, Mitran T, Nath C, Meena RS, Singh GS, Shivakumar BG, Kumar S, Lal R (2018) Cereal+Legume intercropping: an option for improving productivity. In: Meena RS et al (eds) Legumes for soil health and sustainable management. Springer, Singapore. https://doi.org/10.1007/978-981-13-0253-4_11

Leroy BLM, Herath HMSK, Sleutel S, De Neve S, Gabriels D, Reheul D, Moens M (2008) The quality of exogenous organic matter: short term effects on soil physical properties and soil organic matter fractions. Soil Use Manag 24:139–147

Mahapatra P, Singh RP, Singh BP, Mishra B, Sarkar AK (2007) SSAC (BAU) technical bulletin no. 4, BAU, pp 1–75

Mandal A, Patra AK, Singh D, Swarup A, Masto RE (2007) Effect of long-term application of manure and fertilizer on biological and biochemical activities in soil during crop development stages. Bioresour Technol 98:3585–3592

Meena RS, Lal R (2018) Legumes and sustainable use of soils. In: Meena RS et al (eds) Legumes for soil health and sustainable management. Springer, Singapore. https://doi.org/10.1007/978-981-13-0253-4_1

Meena H, Meena RS (2017) Assessment of sowing environments and bio-regulators as adaptation choice for clusterbean productivity in response to current climatic scenario. Bangladesh J Bot 46(1):241–244

Meena RS, Yadav RS (2014) Phonological performance of groundnut varieties under sowing environments in hyper arid zone of Rajasthan, India. J App Nat Sci 6(2):344–348

Meena RS, Yadav RS (2015) Yield and profitability of groundnut *(Arachis hypogaea* L) as influenced by sowing dates and nutrient levels with different varieties. Legum Res 38(6):791–797
Meena RS, Yadav RS, Meena VS (2014) Response of groundnut (*Arachis hypogaea* L.) varieties to sowing dates and NP fertilizers under Western Dry Zone of India. Bangladesh J Bot 43(2):169–173
Meena RS, Dhakal Y, Bohra JS, Singh SP, Singh MK, Sanodiya P (2015a) Influence of bioinorganic combinations on yield, quality and economics of mungbean. Am J Exp Agric 8(3):159–166
Meena RS, Meena VS, Meena SK, Verma JP (2015b) The needs of healthy soils for a healthy world. J Clean Prod 102:560–561
Meena RS, Meena VS, Meena SK, Verma JP (2015c) Towards the plant stress mitigate the agricultural productivity: a book review. J Clean Prod 102:552–553
Meena RS, Yadav RS, Meena H, Kumar S, Meena YK, Singh A (2015d) Towards the current need to enhance legume productivity and soil sustainability worldwide: a book review. J Clean Prod 104:513–515
Meena RS, Yadav RS, Reager ML, De N, Meena VS, Verma JP, Verma SK, Kansotia BC (2015e) Temperature use efficiency and yield of groundnut varieties in response to sowing dates and fertility levels in Western Dry Zone of India. Am J Exp Agric 7(3):170–177
Meena H, Meena RS, Singh B, Kumar S (2016a) Response of bio-regulators to morphology and yield of clusterbean [*Cyamopsis tetragonoloba* (L.) Taub.] under different sowing environments. J App Nat Sci 8(2):715–718
Meena RS, Bohra JS, Singh SP, Meena VS, Verma JP, Verma SK, Shiiag SK (2016b) Towards the prime response of manure to enhance nutrient use efficiency and soil sustainability a current need: a book review. J Clean Prod 112:1258–1260
Meena RS, Gogaoi N, Kumar S (2017a) Alarming issues on agricultural crop production and environmental stresses. J Clean Prod 142:3357–3359
Meena RS, Kumar S, Pandey A (2017b) Response of sulfur and lime levels on productivity, nutrient content and uptake of sesame under guava (*Psidium guajava* L.) based agri-horti system in an acidic soil of eastern Uttar Pradesh, India. J Crop Weed 13(2):222–227
Meena RS, Meena PD, Yadav GS, Yadav SS (2017c) Phosphate solubilizing microorganisms, principles and application of microphos technology. J Clean Prod 145:157–158
Meena H, Meena RS, Lal R, Singh GS, Mitran T, Layek J, Patil SB, Kumar S, Verma T (2018a) Response of sowing dates and bio regulators on yield of clusterbean under current climate in alley cropping system in eastern UP. Indian Leg Res 41(4):563–571
Meena RS, Kumar V, Yadav GS, Mitran T (2018b) Response and interaction of *Bradyrhizobium japonicum* and *Arbuscular mycorrhizal* fungi in the soybean rhizosphere: a review. Plant Growth Regul 84:207–223
Meena BL, Fagodiya RK, Prajapat K, Dotaniya ML, Kaledhonkar MJ, Sharma PC, Meena RS, Mitran T, Kumar S (2018c) Legume green manuring: an option for soil sustainability. In: Meena RS et al (eds) Legumes for soil health and sustainable management. Springer, Singapore. https://doi.org/10.1007/978-981-13-0253-4_12
Mitran T, Meena RS, Lal R, Layek J, Kumar S, Datta R (2018) Role of soil phosphorus on legume production. In: Meena RS et al (eds) Legumes for soil health and sustainable management. Springer, Singapore. https://doi.org/10.1007/978-981-13-0253-4_15
Motsara MR (2002) Available N, P and K status of Indian soils as depicted by soil fertility maps. Fert News 47:15–21
Nyamangara J, Gotosa J, Mpofu SE (2001) Cattle manure effects on structural stability and water retention capacity of a granite soil in Zimbabwe. Soil Tillage Res 62:157–162
Ram K, Meena RS (2014) Evaluation of pearl millet and mungbean intercropping systems in arid region of Rajasthan (India). Bangladesh J Bot 43(3):367–370
Roy RN, Ange AL (1991) Integrated Plant Nutrition System (IPNS) and sustainable agriculture. FAI, New Delhi, pp SV/1-1–SV/1-12
Sekhon KS, Singh JP, Mehla DS (2009) Soil organic C pools after seven years of manures and mineral fertilizers application in a rice-wheat rotation. Arch Agron Soil Sci 55:197–206

Sharma SP, Singh MV, Subehia SK, Jain PK, Kaushal V, Verma TS (2005) Research bulletin no. 2. AICRP-LTFE, IISS/Department of Soils, CSK HPKV, Bhopal/Palampur, pp 1–88

Sheoran S (2015) Effects of organic manures and fertilizers on soil properties under pearl millet-wheat cropping system: a long-term study. M.Sc. thesis, Department of Soil Science, CCS Haryana Agricultural University Hisar, India

Sihag SK, Singh MK, Meena RS, Naga S, Bahadur SR, Gaurav YRS (2015) Influences of spacing on growth and yield potential of dry direct seeded rice (*Oryza sativa* L.) cultivars. Ecoscan 9(1–2):517–519

Singh MV (2001) Evaluation of current micronutrient stocks in different agro-ecological zones of India for sustainable crop production. Fert News 46:25–42

Singh M, Wanjari RH (2007) AICRP on Long-term Fertilizer Experiments (LTFE) to study changes in soil quality, crop productivity and sustainability research bulletin. IISS, Bhopal

Singh M, Singh VP, Reddy KS (2001) Effect of integrated use of fertilizer N and FYM or green manure on transformation of NK and S and productivity of rice-wheat system on a vertisols. J Indian Soc Soil Sci 49:430–435

Singh M, Tripathi AK, Reddy DD (2002) Potassium balance and release of kinetics of nonexchangeable K in Typic Haplustert as influenced by cattle manure application under soybean-wheat system. Aus J Soil Res 40:533–541

Singh RK, Ghosh PK, Bandyopadhyay KK, Mishra AK, Mandal KG, Hati KM (2006) Integrated plant nutrient supply for sustainable production in soybean-based cropping system. Indian J Fert 1:25–32

Singh JP, Kaur J, Mehla DS, Narwal RP (2012a) Long-term effects of nutrient management on soil health and crop productivity under rice-wheat cropping system. Indian J Fert 8(8):28–48

Singh M, Dwivedi BS, Datta SP (2012b) Integrated nutrient management for enhancing productivity, nutrient use efficiency and environmental quality. In: Soil science in the service of nation. ISSS, New Delhi, pp 55–67

Sofi PA, Baba ZA, Hamid B, Meena RS (2018) Harnessing soil Rhizobacteria for improving drought resilience in legumes. In: Meena RS et al (eds) Legumes for soil health and sustainable management. Springer, Singapore. https://doi.org/10.1007/978-981-13-0253-4_8

Sudhir K, Singh MV, Jayaprakash SM (2004) Soil quality, crop production and sustainability experiences under long-term finger millet-maize cropping in alfisol. IISS, Bhopal, pp 1–130

Tejada M, Gonzales JL (2008) Influence of two organic amendments on the soil physical properties, soil losses, sediments and runoff water quality. Geoderma 145:325–334

Tiwari KN (2008) Future plant nutrition research in India. J Indian Soc Soil Sci 56:327–336

Varma D, Meena RS, Kumar S (2017a) Response of mungbean to fertility and lime levels under soil acidity in an alley cropping system in Vindhyan Region, India. Int J Chem Stud 5(2):384–389

Varma D, Meena RS, Kumar S, Kumar E (2017b) Response of mungbean to NPK and lime under the conditions of Vindhyan Region of Uttar Pradesh. Legum Res 40(3):542–545

Verma JP, Jaiswal DK, Meena VS, Meena RS (2015a) Current need of organic farming for enhancing sustainable agriculture. J Clean Prod 102:545–547

Verma JP, Meena VS, Kumar A, Meena RS (2015b) Issues and challenges about sustainable agriculture production for management of natural resources to sustain soil fertility and health: a book review. J Clean Prod 107:793–794

Verma SK, Singh SB, Prasad SK, Meena RN, Meena RS (2015c) Influence of irrigation regimes and weed management practices on water use and nutrient uptake in wheat (*Triticum aestivum* L. Emend. Fiori and Paol.). Bangladesh J Bot 44(3):437–442

Walia MK, Walia SS, Dhaliwal SS (2010) Long-term effect of integrated nutrient management on properties of Typic Ustochrept after 23 cycles of an irrigated rice-wheat system. J Sustain Agric 34:724–743

Walia MK, Dhaliwal SS, Walia SS, Shukla AK (2017) Impact of integrated nutrient management on soil health and rice yields in India – a review. Indian J Fert 13(7):28–37

Yadav RL, Singh SR, Prasad K, Dwivedi BS, Batta RK, Singh AK, Patil NG, Chaudhary SK (2000) In: Yadav JSP, Singh GB (eds) Natural resource management for agricultural production in India. ICMNR, New Delhi, pp 775–870

Yadav GS, Babu S, Meena RS, Debnath C, Saha P, Debbaram C, Datta M (2017a) Effects of godawariphosgold and single supper phosphate on groundnut (*Arachis hypogaea*) productivity, phosphorus uptake, phosphorus use efficiency and economics. Indian J Agric Sci 87(9):1165–1169

Yadav GS, Lal R, Meena RS, Babu S, Das A, Bhomik SN, Datta M, Layak J, Saha P (2017b) Conservation tillage and nutrient management effects on productivity and soil carbon sequestration under double cropping of rice in North Eastern Region of India. Ecol Indic. http://www.sciencedirect.com/science/article/pii/S1470160X17305617

Yadav GS, Lal R, Meena RS, Datta M, Babu S, Das LJ, Saha P (2017c) Energy budgeting for designing sustainable and environmentally clean/safer cropping systems for rainfed rice fallow lands in India. J Clean Prod 158:29–37

Yadav GS, Das A, Lal R, Babu S, Meena RS, Saha P, Singh R, Datta M (2018a) Energy budget and carbon footprint in a no-till and mulch based rice–mustard cropping system. J Clean Prod 191:144–157

Yadav GS, Das A, Lal R, Babu S, Meena RS, Patil SB, Saha P, Datta M (2018b) Conservation tillage and mulching effects on the adaptive capacity of direct-seeded upland rice (*Oryza sativa* L.) to alleviate weed and moisture stresses in the North Eastern Himalayan Region of India. Arch Agron Soil Sci. https://doi.org/10.1080/03650340.2018.1423555

Yadvinder-Singh, Bijay S, Ladha JK, Khind CS, Gupta RK, Meelu OP, Pasuquin E (2004) Long-term effects of organic inputs on yield and soil fertility in the rice-wheat rotation. Soil Sci Soc Am J 68:845–853