Journal of the Indian Institute of Science
A Multidisciplinary Reviews Journal
ISSN: 0970-4140 Coden-JIISAD

REVIEWS

Sustainable Soil Nutrient Management

V.R. Ramakrishna Parama and Atheefa Munawery*

Abstract | Productive agriculture is dependent upon sound soil nutrient management practices. Seventeen elements are known to be essential for plants. Over years of intensive cultivation and imbalanced fertilizer use, Indian soils have become deficient in several of these nutrients and are also impoverished in organic matter. Yields of various crops have reached a plateau or are on the decline. This is of serious consequence given increasing population and diminishing per capita land availability. Several methods of nutrient management have been practiced on farms, however, the best option for the farmer is an integration of organic and inorganic approaches to nutrient management. This far a lot of emphasis has been placed on the conservation and management of N-one of the earliest reported scarce plant nutrient. However, current studies across India have shown a gradual and alarming depletion of potassium and increase in P fixation leading to sustainability concerns for these two nutrients. Among other nutrients S, Zn and B are also reaching deficient status in Indian soils. This sustainability crisis needs to be addressed holistically. This paper explains the philosophy, strategies and practices available to various users of sustainable nutrient management.

1 Introduction

This paper features the soil as a biomass producer using the nutrients contained in it and the factors which influence nutrient availability. The paper highlights technologies developed for sustainable nutrient management which support higher yields and biomass production. A significant part of the plant nutrients applied as fertilizer to crops undergo various physico-chemical changes as competitively picked up by other biota creating low efficiencies. Also, not all the nutrients picked by the crop is allowed to recycle back to soil. This shortfall needs to be supplemented through external additions of fertilizers—which cannot be carried out indefinitely. The poor balance between nutrients synthetically added and that recycled

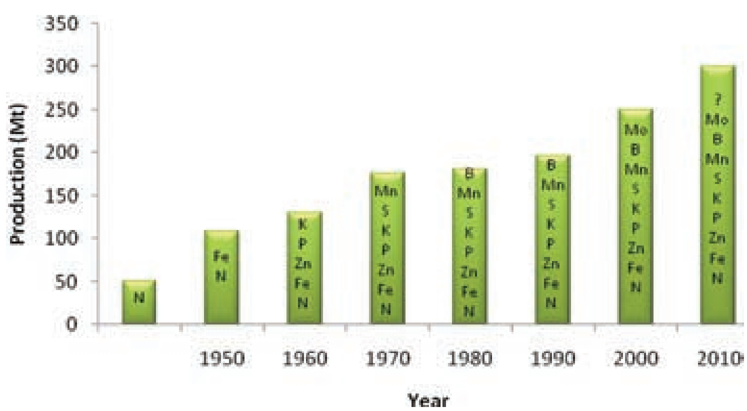

Figure 1: Nutrient deficiency over the years.[2]
Note: (?—indicates many more are likely).

Department of Soil Science and Agricultural Chemistry, University of Agricultural Sciences, G.K.V.K., Bangalore, India.
**vrrparama@yahoo.com*

brings about issues of sustainability and has been the single largest problem for sustainable agriculture.

Plant growth is the result of a complex process involving solar energy, carbon dioxide, water, and nutrients from the soil. The primary nutrients for plant growth are nitrogen, phosphorus, and potassium (known collectively as NPK). In addition to the primary nutrients, less intensively used secondary nutrients (sulfur, calcium, and magnesium) are necessary as well. A number of micronutrients such as iron, manganese, zinc, copper, boron, molybdenum, nickel and chlorine also influence plant growth.

Humans owe their existence to a productive soil which provides for food and biomass. Croplands have been farmed and managed to maintain a nutrient balance at the farm level rather easily with subsistence farming for over 2000 years relying on organic nutrient sources namely manure, crop residues, green manuring, oil cakes etc. The use of inorganics began during the early 1900s with an emphasis on nitrogen and phosphorus. The Green Revolution initiated in the 1960s to feed the increasing population relied on the use of inorganic fertilizers (NPK) and other nutrients to cater to the increased nutrient demand of the high yielding varieties. Forty years later, the All India Fertilizer Nutrient demand projection showed a very unbalanced[1] N:P:K ratio which varied from 8.5:3.1:1 to 37.1:8.9:1, whereas the ideal N:P:K ratio is 4:2:1. As indicated, nitrogen was used more than phosphorus, potassium, secondary and micronutrients. Hence the nutrient imbalance leading to poor soil fertility and productivity. This also brought about nutrient depletion[2] as explained below

The added problems were low fertilizer use efficiency and yield stagnation, which was a threat to food security. For example, during the last 25 years, Indian soils have been experiencing on an average a net negative balance of 8–10 million tones of nutrients per annum.[3] A classic example of the effect of imbalanced fertilizer use on the fertility decline in an intensive cropping area for over 25 years has been reported.[4] This is indicated by poor growth trends in agriculture as indicated in the Figure 2.

This is a serious situation given the fact that a 4% growth in agriculture is essential to provide food security.[5] By 2025, it is estimated[6] that the population of India would be 1690 million requiring a food grain supply of 338 million tonnes, which would need 45 million tonnes of nutrients (NPK) as compared to the 17.5 million tonnes currently being used to produce 253 million tonnes of food grains.

Agriculture is soil-based and crops extract nutrients from it. The ability of the soil to produce biomass can be enhanced by effective and efficient nutrient management approaches which optimize the removal and return of nutrients to the soil and thus attain sustainability in agriculture.

2 Biomass and Nutrient Dynamics

Biomass accumulation through agricultural cropping and other vegetation is indeed important for proper nutrient distribution and recycling. Whenever accompanied with nutrient deficits, the biomass and grain yield potentials are reduced by 49–58 per cent. Proportionate reductions in nutrient turnover are to be expected. The effect of cropping on nutrient losses from the system needs consideration. Cropping enhances the rate of organic matter decomposition. For example, a 44-year evaluation of virgin prairie, cultivated soil in North America revealed that organic N, total N and organic P losses due to cultivation were 61, 58 and 57 respectively.

Cropping systems involving different sequences, mono-crops or inter-crops have their unique effects on nutrient dynamics in soils.

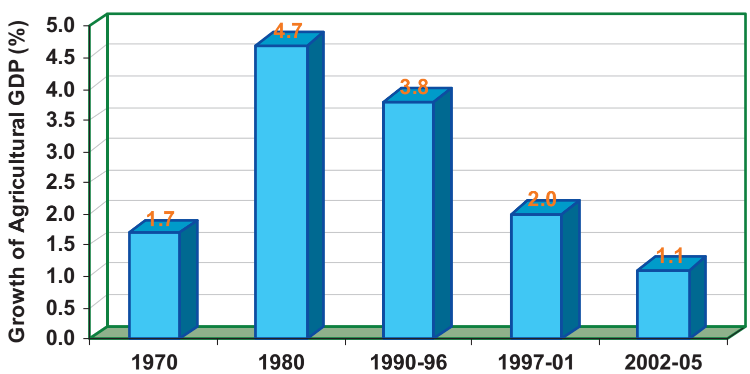

Figure 2: Growth trend in Indian agriculture.[2]

Table 1: Influence of soil fertility and agronomic practices on crop produce in a dry land ecosystem.

Crop	Average yield[1] (30-year average) (kg/ha)	Yield obtained at ICRISAT, Hyderabad, India	
		Low fertility and average soil management (kg/ha)	High fertility and average soil management (kg/ha)
Sorghum	842	2627	4900
Pearl millet	509	1636	3452
Chickpea	745	1400	3000
Pigeonpea	600	1000	2000
Groundnut	794	1712	2572

[1]Average yield recorded in the Indian subcontinent.[10]
Low fertility = 20–43 kg N/ha and 20 kg P_2O_5; High fertility = 86 kg N/ha and 46–60 kg P_2O_5.

Table 2: Nutrient balance recorded in semi-arid regions during the crop year 1990–91 (in million tonnes).

Nutrient	Fertilizer nutrients added (A)	Effective nutrients added (A × Efficiency factor = B)	Nutrient removal by crop (C)	Balance C-B
N	4.75	2.14	2.98	–0.84
P_2O_5	1.97	0.79	1.36	–0.86
K_2O	0.80	0.56	4.35	–3.79
Total	7.52	3.19	8.69	–5.49

Efficiency factor: N = 0.45; P_2O_5 = 0.25; K_2O = 0.071.[11]

A forage legume crop may leave nearly 50% organic N in the soil. A cereal mono-crop, on the other hand, which absorbs and translocates a major fraction of nutrients into seeds will leave only a small proportion of nutrients in the soil. Crop rotations involving legumes add significantly to soil organic N.[8,9]

Cultivation practices adopted by farmers in arid and semi-arid regions also affect the biomass production, grain yield, nutrient recovery, the use efficiency of soil nutrients and recycling. Obviously, a poor crop stand and a meager plant population retard biomass accumulation. Lowered rates of chemical fertilizer accentuate this situation. Biomass and grain yield formation immensely depends on soil fertility management procedures (Table 1), which ultimately affects nutrient cycling.

Another example is about N application rates in semi-arid India that hover around 20 kg N/ha and P dosages around 5–15 kg P/ha. These rates are nearly 3–4 fold lower than in humid tropics or wetland zones. Since crop harvests achieved in dry lands are low, the residue returned to the soil is meager, leading to lower rates of nutrient cycling (Table 2).

3 Need for Wise Use of Nutrients

To achieve healthy growth and optimal yield levels, nutrients must be available not only in the correct quantity and proportion, but in a usable form and at the right time. For the farmer an economic optimum may differ from a physical optimum, depending on the added cost of inputs and the value of benefits derived from any increased output.

Nutrient availability has traditionally been equated with biomass production and crop yields. A soil which had a poor yield was considered less fertile. However, the farmers overlooked the fact that the nutrient availability from the soil to crops is dictated by several soil and crop factors.

Soil nutrient availability changes over time. The continuous recycling of nutrients into and out of the soil is referred to as the nutrient cycle.[12] The cycle[13] has two parts; "inputs" that add plant nutrients to the soil and "outputs" that export them from the soil largely in the form of agricultural products. Important input sources include inorganic fertilizers; organic fertilizers such as manure, plant residues, and cover crops; nitrogen generated by leguminous plants; and atmospheric nitrogen deposition. Nutrients are exported from the field through harvested crops and crop residues, as well as through leaching, atmospheric volatilization, and erosion.

The difference between the volume of inputs and outputs constitutes the nutrient balance. Deficit nutrient balances in the soil could indicate that farming systems are inefficient; on the other hand, negative balances could well indicate that the soil is being mined and that farming systems are unsustainable over the long term. Strategies of optimization of nutrient use aim at a positive balance; however, the positive is kept to the barest minimum so that the plants do not suffer deficits of any kind, Even if there were leaks or mismatch between what is provided and what was taken up, it was considered a occupational evil.

Despite the continued development of new and improved modern varieties and greater use of chemical fertilizers, yield growth began to slow in recent years (Table 3).

The major factor contributing to declining crop response is the continuous nutrient mining from the soil caused by imbalanced nutrient use.

This slowdown has raised concerns that yield growth may have reached a plateau or begun to decline in most fertile areas. The cumulative effect of negative nutrient balances on crop yields is often seen in the form of a decline in soil productivity. The reasons for the same have been indicated earlier, but the main reason is a nutrient imbalance with a skewed dependence on N, rather than P and K and other nutrients triggering nutrient mining and several related issues. The contrasting pattern of nutrient addition and nutrient consumption in Indian agriculture is indicated below (Figure 3).

The figures clearly indicate the addition of more nitrogen and less of potassium. Research data further provide concrete evidence of the same. For example, the fate of the soil nutrient

Table 3: Decrease in nutrient response over the years.

Period	Increase in nutrient consumption (Mt)	Increase in food production (Mt)	Nutrient response (kg grain/kg nutrients applied)
1960–1970	1.47	26.4	17.9
1971–1980	2.44	31.09	12.7
1981–1990	5.28	46.8	8.9
1991–2000	3.18	19.53	6.3

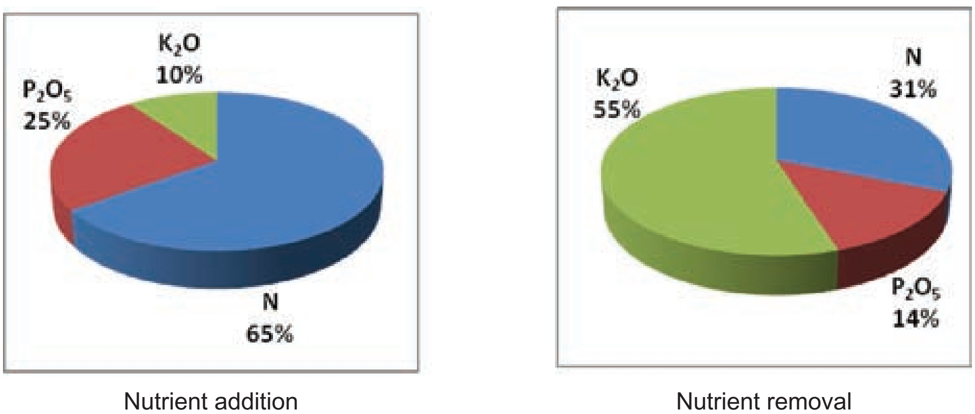

Figure 3: Nutrient addition and removal in Indian agriculture.

Table 4: Nutrient balance after a sugarcane-wheat system in western Uttar Pradesh (productivity 120 mt cane/ha/2 crops + 3 tonnes wheat grain/ha).[14]

Details of inputs	N	P_2O_5	K_2O
Initial soil nutrient capital	280	40	336
Capital after sugarcane crop	315	103	215
Capital after sugarcane ratoon (the residual crop)	238	107	70
Capital after wheat	217	121	–14
Capital after the system	217	121	–14
Change after 2 years (one crop cycle) in per cent	–63 (–23%)	81 (102%)	–350 (–104%)

capital and balance in the two most important cropping systems of Uttar Pradesh is illustrated below.[14] The initial soil nutrient capital is taken to reflect the soil's low status in nitrogen, medium in phosphorus, and high in potassium in the plough layer. Fertilizer inputs for the sugarcane-wheat system are typical of the practice. The analysis shows that after one cycle of the sugarcane-wheat system, the initial soil nutrient capital decreased by 23 per cent in the case of N, increased by 1.2 per cent in the case of P but decreased by 1.04 per cent in the case of K. The improvement in P status was attributed to its application to both the main crops and the input of FYM and press mud, that less was removed by the crop than was added, and the ability of P (unlike N) to accumulate in the soil. The large depletion in K was due to its low additions as fertilizer and crop removal exceeded the K input.

Another important study on the long-term fertilizer experiment under maize-wheat-cowpea during 27 years of cropping showed that the mining of soil K occurred even under NPK and NPK + FYM treatments, i.e. application of 15t FYM/ha along with the recommended rates of NPK.[15] The overall nitrogen and potassium balances are indicated in the figures below.

These results call for better nutrient management. The overall strategy for increasing crop yields and sustaining them at a high level must include an integrated approach to the management of soil nutrients, along with other complementary measures, such as integrated nutrient management (INM). INM aims to supply plant

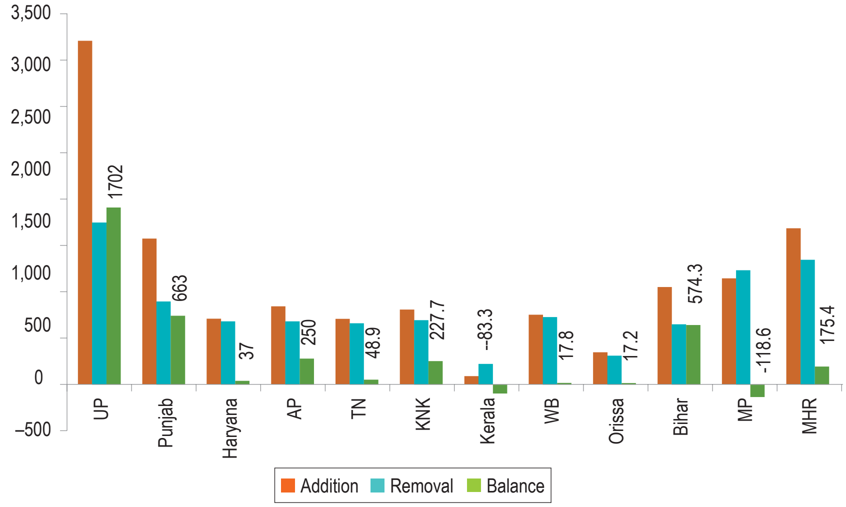

Figure 4: N balance (000 t) in some agriculturally important states of India.

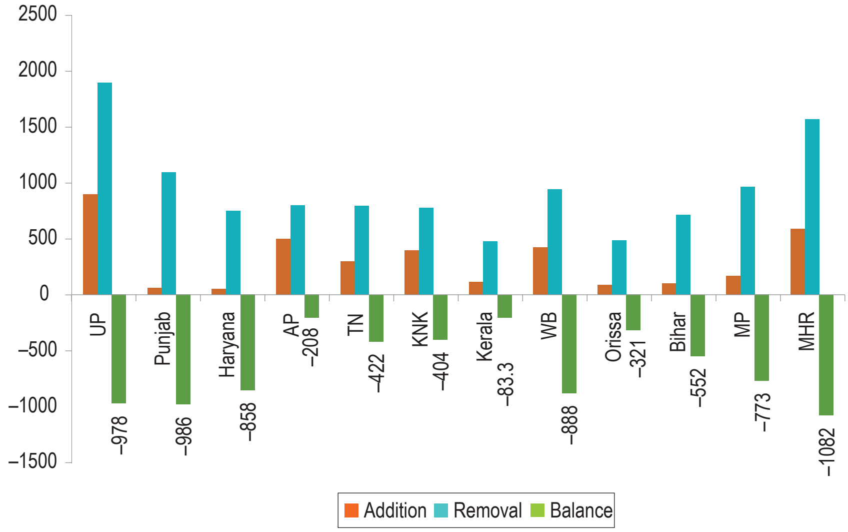

Figure 5: K balance (000 t) in some agriculturally important states of India.

nutrients through different sources at the right time, and in the right combination and right proportion to sustain soil quality and productivity. Though several other approaches have been tried, INM has proved to be the most viable and sustainable method of nutrient management.

4 Sustainable Nutrient Management Technologies

4.1 *Macronutrient management*

4.1.1 Nitrogen: Nitrogen is the principal element required by all crops and is taken up in the NO_3 and NH_4 form. The nitrogen use efficiency varies between 40–50% (dryland crops) and 20–30% (flooded paddy) because NO_3–N is hardly adsorbed on clay surfaces and hence is lost through several pathways such as leaching and denitrification. Low N use efficiency may be attributed to improper N use management, imbalanced fertilization and losses through leaching, volatilization, immobilization and erosion. Various techniques have been adopted to improve the use efficiency.

Nitrification inhibitors: Since nitrates are easily leached and lost by denitrification, the retardation of the nitrification of ammonium-containing or ammonium producing fertilizers by using nitrification inhibitors in rice fields subjected to intermittent flooding helped improve the efficiency of the nitrogen use. Chemical nitrification inhibitors as well as indigenous materials such as *neem* (*Azadirachta indica*) and *karanj* (*Pongamia glabra*) cakes have been successfully used. Also some slow release nitrogen materials like urea-form, isobutylidene diurea as well as coated fertilizers such as sulphur coated urea, lac-coated urea etc., have been used to reduce nitrogen losses.[16]

Coating of nitrogenous fertilizers: Coating urea with selected materials offers the possibility of controlling the transformation of applied N in the soil thereby reducing N loss and increasing its utilization by rice.

Neemcake—coated urea applied at the time of transplanting (basal) performed much better than split-applied urea in diverse soil types. Neem cake possesses both urease and nitrification inhibition properties and a 10–15% higher N efficiency was realized using neem cake coated urea compared to urea.[17] Neem cake also appears to be an efficient source of N for rain-fed lowland rice where water control is poor. By ensuring slow N release, crop growth and yields increased.

Time of N application: The time of fertilizer application is important for particularly those nitrogenous fertilizers which tend to leach with irrigation, water or rainfall.[18,19] The split application of nitrogen is the most common and widely accepted practice for almost all the crops. The basic concept is to apply nitrogen in two or more splits to coincide with the peak period of the nitrogen requirements of the crop. Nitrogen application in split doses is particularly beneficial on light-textured soils in increasing the efficiency of applied nitrogen. Its application occurs in three split doses at transplanting, tillering and panicle initiation in rice; at planting. Its application at the knee high stage and tasselling stage in the case of maize, is usually recommended.

The application of N in 2–3 splits increases N–use efficiency significantly as compared to a single basal application at planting.[20] The yield advantage brought about by the application of 100 kg N/ha in three splits compared to N at planting was 372 kg paddy/ha in Kharif and 476 kg/ha in Rabi. In general, crops grown in the rainy season were applied with nitrogen fertilizers in split doses so that the leaching of the nutrient during heavy rains was avoided and an adequate supply of the nutrient at critical stages was ensured. The highest efficiency of fertilizer N in direct seeded rice was obtained by the application of 25% of total N at seeding, 50% at 3 weeks after germination and 25% at panicle initiation.[21]

Nitrogen management in cropping systems: A cropping system refers to a sequence of crops usually grown in a given agro-ecological situation. These systems have been tried and tested and ensure better nutrient use and biomass yields. Although many rice-based cropping systems are practiced in different agro-climatic regions, the most common ones in India are rice-rice, rice-wheat, rice-wheat-jute, rice-potato-jute, rice-pulse (gram/lentil/pea/bean etc.) and rice-oilseed (mustard/groundnut/linseed/sesame etc.).[22]

The fertilizer need of a crop in a system is strongly influenced by the preceding crops and the amount of fertilizer applied to them. Therefore, for efficient nutrient management in cropping systems, a quantitative evaluation of the role of the preceding crops and the residual effect of nutrients applied assumes great importance.

All field crops significantly respond to fertilizer N. While the direct effect of N on the crops is most important, the carry-over residual effect is generally negligible because of its loss through various pathways and incorporation in the slowly-available soil organic fraction. The inclusion of legumes in crop sequences have been identified as important agro-techniques to increase the efficiency of directly

Table 5: Relative efficiency of urea forms in rice and their residual effect on succeeding wheat.

	Banswara (deep black soil)		Faizabad (alluvial soil)	
	Rice	Wheat	Rice	Wheat
N source	Grain yield, (t/ha)			
Urea	2.62	2.08	5.53	2.34
Neem cake coated urea	2.92	2.27	5.12	2.30
Gypsum coated urea	2.92	2.53	5.20	2.29
Rock phosphate coated urea	2.87	2.25	5.14	2.41
Urea super granules	3.05	2.41	5.65	2.32
C.D (5%)	1.04	0.10	0.32	NS

Data source: **24**.

applied N and also the productivity of the succeeding crops.[22]

A short-duration leguminous green manure crop like Sesbania raised during intervals between two main crops can assimilate N and thereby conserve it in the soil. The green manure crop may be incorporated into the soil for recycling the conserved N to the succeeding crop. This practice often benefits the succeeding crop by saving at least 30–35 kg of its total fertilizer N requirement. The use of modified urea materials generally help in reducing the loss of fertilizer N from soil characteristics.[23] The use of gypsum-coated urea, neem-cake-coated urea, rock phosphate coated urea and urea super granules (USG) applied to Kharif rice produced a significant residual effect on the yield of the succeeding Rabi crop of wheat in deep black soils but not in alluvial soils (Table 5).

4.1.2 Phosphorus management: Phosphorus is as equally important as nitrogen. It is taken up by the plant in the form of H_2PO_4, and HPO_4. However, it is the most difficult element to be managed. The use efficiency of phosphorus is as low as 8–20 per cent which is low. The main reason for the low use efficiency is due to its fixation in the soil. The chemistry of the soil decides P availability. The process of fixation is pH dependent and occurs in acid soils where Fe and Al complex with P as Fe-P and Al-P, in calcareous soils as Ca-P and in alkaline soil as Na-P.[25] Therefore maintaining an optimum soil pH of near neutral would ensure the best P availability. Alternatively, suitable P fertilizers could be used. Fixation results in a temporary unavailability of phosphorus; however, in the long run, the cumulative effects of fixation could result in soils recording very high total phosphorus. This locked up phosphorus needs to be solubilized and made available to the plant and this can be achieved by using phosphate solubilizing microorganisms. The response to applied P depends on soil properties, the initial available P, the level of N applied and management practices.[26] Yield increases brought about by the application of P have been significant.

Types of P fertilizers: Phosphatic fertilizers containing phosphorus in a water soluble form like diammonium phosphate, and single superphosphate have been found superior for most of the crops in neutral or alkaline soils as compared to the citrate soluble or citrate insoluble form. Both single superphosphate and diammonium phosphate proved equally efficient on the basis of an equivalent phosphate content but single superphosphate has the advantage in soils that are low in available sulphur and particularly for sulphur-loving crops like oilseeds and pulses. Rock phosphate which has phosphate in a water insoluble form has proved useful in acid soils, rice soils or in long duration legumes.[27]

Time of P application: Phosphorus application at the time of seeding/planting or just prior to that, is the most widely recommended practice for crops. There have been some trials on the split/delayed application of P but generally the results of such trials have been inconsistent.[27] This is because these have not been related to the initial level of available P in the soil. Although the best results are obtained when all P is applied as a basal dressing to crops, a split/delayed application is better than not applying P at all and could be a suitable practice in the following situations: (i) If P-fertilizer is in short supply at planting, (ii) If the soils are medium in available P, and (iii) if seasonal conditions are in favour of the release of soil P in the early periods of crop growth.

On a highly P deficient clay soil, the delayed application of P to rice produced 85% of the maximum yield in Kharif but 37% of the maximum yield in Rabi.[28] On "medium P" soils, the application of P could be delayed up to 30–40 days without an appreciable loss in yield.[29] In several cases, a split application of P, half at transplanting and the rest at tillering was more efficient than the use of all P as basal.[30,31] These practices have resulted in increased P use and yields.

Method of P application: The placement of water soluble phosphatic fertilizers adjacent to crop plants is better than its broadcast (hand application of fertilizer to the land) as it reduces the fixation processes. However, phosphates of low water solubility react slowly in soil and are usually more effective as a source of phosphorus when broadcast.[31] When rock phosphate is used in rice culture, it should be mixed with soil a fortnight or a month before rice planting.

For higher P-use efficiency in upland crops, the results are overwhelmingly in favour of drilling/placement the broadcast of P is an inefficient practice and is not advocated except for flooded rice.

The highest efficiency was obtained when 50% of the soil area was in contact with SSP in contrast to 70–90% soil area in contact with rock phosphate.[32]

Phosphorus in cropping systems: The recovery of P by rice is usually 8–20%.[33] The P that remains in the soil can benefit succeeding crops.[31] Phosphorus application, unlike N, is known to benefit the growth and productivity of more than one crop in rotation. The residues of fertilizer P remain in the soil after a directly fertilized crop has been harvested. Such residues in the soil are formed as a result of an array of fertilizer reactions and their products. These can be expected to be in the proportion based on their contribution to available P pools and the ability of the crops to utilize it. Since the availability of P increases under wetland rice culture, P applied to upland crops such as wheat, chickpea etc., can have a greater residual effect for the succeeding crop. Therefore, the prior application of P fertilizer to the crops preceding rice will help increase the production and productivity of both the crops, as observed in the rice-wheat cropping system in Punjab.[34] The application of the recommended dose of P to only one crop, preferably the dry season crop, could adequately meet the P requirement of both the crops.[35]

4.1.3 Potassium management: The third most important element for plant growth is potassium and its content in the soil varies from low to high. It is referred to as a quality nutrient. The use efficiency of potassium varies from 20–30 per cent and is dictated by the process of erosion, leaching and fixation in the soil. The addition of potassium has always been overlooked and hence there has been potassium mining from the soil by plants. Deficiency is potassium is on the increase and hence potassium management is of importance specifically because potassium influences the uptake of other major nutrients and influences crop quality.[36] Most of the fertilizer K used in Indian agriculture is imported largely in the form of muriate of potash (KCl) and only about 1% as sulphate of potash.

Method of application: A split application of potassium is expected to increase its efficiency in situations where leaching losses are considerable either because of the light texture of the soil or the long duration of the crop. The beneficial effects of split application have been observed in sugarcane and rice. For fruit crops, 2–6 splits have been recommended depending upon the crop.[37]

Potassium in cropping system: In eastern India, jute-rice-potato is a system in which potato requires a high dose of soluble K. Considering the relatively high K needs of potato, it is generally recommended that potato receive K fertilizer on priority, the other crops in sequence, including rice, may benefit from K residues in the following season.[38] The requirement of potassium in crops such as banana, sugarcane, grapes and others are high. This is specifically because K has a role in influencing sugar metabolism and quality of the fruit. Therefore, in these crops K is added as several split applications and consequently can be expected to withdraw a large quantity of K from the soil, making the soil K deficient.

5 Management of Secondary Nutrients

5.1 *Management of calcium and magnesium*

The important secondary nutrients are calcium, magnesium and sulphur. The distribution of these in the soil depends upon the nature of the soil, the parent material and the environmental conditions. For example, calcium and magnesium are found to be deficient in soils where there is high rainfall resulting in the leaching and the weathering of the soil. These soils are referred to as laterites or acidic soils. They are also known as base unsaturated soils (poor in bases such as Ca, Mg, Na and K). In normal soil, calcium dominates the exchange surface followed by magnesium and others cations. This equilibrium, if altered due to management or weather conditions, results in the soil becoming acidic or alkaline. Acid soils record a pH of less than 6 which influences the availability of calcium and magnesium. Such soils

Table 6: Average removal of secondary nutrients by some crops.[41]

Crop	Economic yield (tonne/ha)	Nutrient removal (kg/ha)		
		Ca	Mg	S
Rice	3.0	21	9	9
Wheat	3.0	16	14	14
Sugarcane	8.8	132	–	26
Coffee	2.2	143	33	27
Soybean	2.5	35	19	22
Groundnut	2.0	39	20	15
Sunflower	0.6	41	16	7

need amending with agricultural lime ($CaCO_3$) or dolomitic limestone ($CaCO_3 + Mg_2CO_3$) to restore calcium and magnesium levels.[39,40] The yields of crops as a result of secondary nutrient application is indicated in Table 6.

5.2 *Management of sulphur*

Sulphur is an important secondary nutrient. Its deficiency has been reported in most parts of India. S is also deficient in soils that are sandy and those having low organic matter. Its main function is related to influencing the quantity and quality of oil in oil seed crops. Besides it is important for sulphur-containing amino acids. Sulphur is managed to some extent because sulphur is contained in small quantities in complex fertilizers.

The application of sulphur in neutral to calcareous soils is equally efficient in correcting its deficiency whether it is broadcast, drilled or applied in split doses. In a standing crop of wheat, a top dressing of ammonium sulphate is beneficial.[42]

Sulphur application in general benefits more than one crop grown in sequence and produces a significant residual response. Among cereals, the response to applied S is more in rice than in wheat or other upland crops, since the prolonged anaerobic conditions brought about by submergence significantly reduce the availability of S in the soil. In a rice-wheat system, rice contributed 77% and wheat 23% to the total rotational response when S was applied to the rice crop only.[42] Sulphur is usually supplied as sulphate fertilizers and through organic manures. Increases in yield and oil content have been recorded in several oilseed crops.[43]

6 Management of Micronutrients in Soil

The third group of nutrients known as micronutrients consist of zinc, iron, manganese, copper, molybdenum, boron, chlorine and nickel. These influence enzyme reactions and oxidation reactions, which in turn affect biomass production.

Table 7: Micronutrient response in different crops (kg/ha) of India.

Micronutrient	Cereals	Pulses	Oilseeds
Zinc	<200–7500	200–500	200–500
Molybdenum	200–900	Nil–190	Nil–220
Manganese	Traces–1070	20–200	110–550
Iron	300–1880	450–670	230–470
Copper	Nil–1780	–	Nil–800
Boron	10–1670	40–900	10–430

Source: **44**.

Though, these micronutrients are required in small quantities, they play an important role. The application of micronutrients has been neglected and leads to soil deficiencies. Of these micronutrients, deficiency of zinc has been reported throughout India. The simplest way of managing micronutrient deficiencies is to add them to the soil along with NPK fertilizers in alternate years. In cases of severe deficiency, foliar application is recommended. Several factors influence micronutrient availability such as pH, Organic mater, chemical interaction of nutrients and chemical transformations in soil. The application of micronutrients has resulted in increased yields as indicated in the table.

6.1 *Management of zinc*

For the efficient utilization of applied zinc, the best time of its application for wheat and rice is at seeding or at the transplanting of the crop.[45] Among the different methods, broadcasting and mixing zinc is more efficient than its drilling or band placing and top dressing 60 days after seeding.The application of zinc sulphate @ 25–50 kg/ha to the soil is superior to foliar sprays of 0.5% zinc sulphate solution neutralized with lime.

In rice-rice cropping on the Zn-deficient red sandy loam of Tamil Nadu, the application of 5 kg Zn/ha to every crop or 15 kg Zn/ha only to the first crop in the sequence of 3–4 rice crops gave almost the same response. The Zn requirement of a cropping system therefore can be met through a single application, if the dose is adequate.[45] In medium-deep black soils (DTPA-extractable Zn 0.70 ppm), the application of 4 kg Zn/ha to rice increased grain yield as well as Zn uptake by the crop that followed chickpea.[46]

6.2 *Management of manganese and iron*

Foliar sprays of 0.5 to 1.0% of manganese sulphate solution have been found more effective and economical than the soil application (20 kg Mn/ha) of manganese in manganese deficient sandy loams of Punjab.[44]

The soil application of ferrous sulphate in coarse-textured soils for rice is less efficient than foliar sprays. However, for upland crops, the soil applied iron has been found to be as effective as foliar sprays. Straight micronutrient carriers like zinc sulphate, manganese sulphate and copper sulphate have been found to be superior and more economical than other sources of micronutrient cations.[45]

7 Nutrient Recycling Techniques

Land is the generator of biomass and hence is the nearest and most rightful place for the return of excess biomass. This return to the soil ensures organic matter and nutrient recycling. Organic matter is considered the life of the soil and Indian soils record low organic matter levels. Hence, addition in any form must be explored. The addition of organic matter ensures a wholesome improvement in the soil. It brings about positive changes in physical, chemical and biological properties.

7.1 *Strategies and practices for soil organic matter management includes*

- Returning organic materials to the soil to replenish soil organic carbon lost through decomposition (recycling of plant and animal residues, green manuring cover crops rotation)
- Ensuring minimum disturbance of the soil surface (residue mulch, conservation tillage) to reduce the rate of decomposition
- Reducing soil temperature and water evaporation by mulching the soil surface with plant residues and
- Integrating multipurpose trees and perennials into cropping systems to increase the production of organic materials.

7.2 *Organic manures*

Several long-term fertilizer studies on organic matter decomposition have indicated the advantage of recycling organic matter and nutrients from farmyard manure, vermicompost, agro-industrial waste, urban waste and other sources. Though the nutrients contained in these are small, the organic matter contained in them influence the physical, chemical and biological properties of the soil. These studies clearly indicate that a part of the inorganics can be substituted, thus substantially cutting the cost of cultivation. These sources need to be tapped in future as alternatives for deriving nutrients and improving soil health.[47]

7.3 *Crop rotation*

Cereals grown in rotation with leguminous plants can absorb the nitrates released from the decaying roots and nodules of the leguminous plants. Experiments have shown that rice-legume rotations can result in a 30 percent reduction in chemical fertilizer use.[48] As with leguminous plants, plant nitrogen needs could be partially met by the plant itself, so that farmers would then simply need to top-up crops with inorganic nitrogen fertilizers.[40]

Crop rotation results in 5 to 15% greater yield than continuous monoculture of the same crop. Growing a variety of crops in sequence has many positive effects on soil fertility. In a diverse rotation, deep rooted crops alternate with shallower, fibrous- rooted species to bring up nutrients from the deeper layers of the soil. This captures nutrients that might otherwise be lost from the system.

Differences in plant rooting patterns, including root density and root branching at different soil depths, also result in a more efficient extraction of nutrients from all soil layers when a series of different crops is grown. Including sod forming crops in a rotation with row crops decreases soil and nutrient losses from runoff and erosion, and increases organic matter. Growing legumes to fix atmospheric nitrogen reduces the need for purchased fertilizers and increases the supply of N stored in organic matter for future crops.

Biologically fixed N is used most efficiently in rotations where legumes are followed by crops with high N requirements. Rotating crops also increases soil biodiversity and nutrient cycling capacity by supplying different residue types and food sources. It also reduces the buildup and carrying over of soil borne disease organisms.

Farmers traditionally prefer to grow pearl millet—legume rotation as the monoculture of pearl millet causes a reduction in yield due to the depletion of nutrients and the production of allelochemicals. Legumes increase soil fertility.[50]

7.4 *Inter cropping and mixed cropping*

Growing sorghum along with pigeon pea (3:3)[51] in strip and changing strip arrangement every year significantly improved the chemical properties, fertility index and micronutrient availability of the soil as compared to other cropping systems. The mixed cropping of legumes with paddy has a synergistic effect on nutrient availability and soil properties.[52]

7.5 *Alley cropping*

It was developed by researchers at the International Institute of Tropical agriculture (IITA) in Nigeria. In this system, food crops such as maize and cowpea are grown in alleys along the contours formed by hedgerows planted three to four meters apart of fast growing, leguminous shrubs and trees such as *Leucaena leucocephala*.

The hedge rows are periodically pruned during the cropping season to prevent shading. The prunings are used as mulch and green manure for the associated food crop.[53] When trees and shrubs with their deep root systems are planted along the contours on sloping land, they are not only able to recycle soil nutrients but also minimize water runoff and soil erosion.[54] One beneficial effect of alley cropping on acidic soils is that the use of prunings as leguminous green manure can reduce soluble and exchangeable Al in the soil by forming less soluble organo-Al complexes.[55]

7.6 *Cover crops*

Growing cover crops and green manure crops can be viewed as a type of crop rotation, in which adding a non revenue generating crop between annual cash crops extends the growing season. The main difference between the two is that the soil surface is protected from raindrop impact, runoff, and erosion. Rapidly growing summer annuals like buckwheat and sorghum are planted between short season vegetable crops as green manure to add organic matter to the soil, but they also protect the soil from erosion. Growing legume cover crops adds biologically fixed N. The additional plant diversity with cover crops stimulates a greater variety of soil microorganisms, enhances carbon and nutrient cycling and promotes root health.[56]

The soil surface is covered for a long period of time during the year, so nutrient losses from runoff and erosion are reduced. This longer period of plant growth substantially increases organic matter additions to the soil. The extended growth period obtained with cover crops also extends the duration of root activity and the ability of root exuded compounds to release insoluble soil nutrients.

A winter cover crop that makes good fall growth traps excess soluble nutrients not used by the previous crop, prevents them from leaching, and stores them for release during the next growing season. Complimentary cover crop mixtures produce root exudates with varying compositions and effects, and have different zones of nutrient uptake because they differ in amount, depth, and patterns of root branching. Deep rooting cover crops, like sorghum- sudan grass and sweet clover, can break up some types of compacted soil layers and improve the rooting depth for the next crop. Both summer and fall cover crops absorb residual nutrients in addition to increasing the time and amount of surface cover.

7.7 *Green manuring and crop residues*

Returning manure to crop fields recycles a large portion of the plant nutrients removed from the harvested crops. Nutrients are often lost during storage and handling of manures. Sometimes it can cause environmental problems. Nutrient losses from manure also occur when it is applied at rates exceeding crop nutrient requirements. This reduces nutrient losses. Organic matter not only adds organic matter it also improves the soil structure and increases CEC.

The management of crop residues is through one of the following three methods: removal, burning or incorporation into soil. It was reported that *in situ* recycling of crop residues in rice-wheat rotation reduced the grain yield of rice and wheat. Therefore, most of the farmers recycle the crop residues not by choice, but because of combined harvesting, and burn the residue causing loss of precious organic matter, plant nutrients and environmental pollution. Experiments conducted in Punjab have shown that co-incorporation of green manure and crop residues of wheat and rice helped alleviate the adverse effects of unburned crop residues on crop yields (Table 8).

Crop residues are important sources of plant nutrients and also improve the physical and biological properties of the soil.[57] In arid regions they have special significance as they add organic matter.[58] The Incorporation of powdered groundnut

Table 8: Effects of incorporation of green manure (G.M.) and crop residue on grain yield of rice (t/ha).[57]

Treatment	1988	1989	1990	1991	1992	1993
Control (No N)	4.0	4.6	3.7	4.3	4.1	3.4
150 kgN/ha	6.3	6.6	6.2	6.5	5.7	5.6
180 kg N/ha	6.6	6.9	5.8	6.7	NT	5.3
G.M.	6.6	6.5	6.2	6.5	5.8	5.5
G.M. + wheat straw	6.9	6.9	6.4	6.8	5.6	5.5
G.M. + rice straw	6.9	6.9	6.7	7.0	5.9	5.3
L.S.D (P = 0.05)	0.53	0.59	0.46	0.45	0.32	0.37

G.M. = Green manure.

shells @ 5 t/ha in the top 10 cm red soil, 20–25 days before the sowing of the crop improved yields of sorghum and wheat by 34 and 24%, respectively[59] and that of groundnut by 34%.[60]

7.8 *Straw mulching*

The favourable effects of straw mulching in sugarcane increased the yield by 14% and saved 18 to 34 cm irrigation water during the pre monsoon summer period. Similar gains of mulching on crop yields and saving water were also observed in the case of Maize and Sorghum.[60] Similar gains due to mulching were observed in maize[61] and sorghum.[62]

8 Integrated Nutrient Management

Sustainable soil nutrient enhancing strategies involve the wise use and management of inorganic and organic nutrient sources in ecologically sound production systems.[63] The primary goal of integrated nutrient management (INM) is to combine old and new methods of nutrient management into ecologically sound and economically viable farming systems that utilize available organic and inorganic sources of nutrients in a judicious and efficient way. Integrated nutrient management optimizes all aspects of nutrient cycling. It attempts to achieve the best nutrient cycling with synchrony between nutrient demand by the crop and nutrient release in the soil, while minimizing losses through leaching, runoff, volatilization and immobilization, enhanced nutrient use efficiency and recovery by crops, and improvements in soil health and productivity, and hence could sustain high crop yields in various cropping systems ensuring long-term sustainability of the system.[64]

INM uses five major sub-concepts namely:

- Plant nutrients stored in the soil
- Plant nutrients, those present in crop residues, organic manure and domestic wastes
- Plant nutrients purchased or obtained from outside the farm
- Plant nutrients loss e.g. those removed from the field in crop harvests and lost from the soil through volatilization (ammonia and nitrogen oxide gases and leaching (nitrate, sulphate etc)
- Plant nutrient outputs e.g. nutrient uptake by the crops at harvest time.

The combined application of organic manures and fertilizers improve the C:N and C:P ratios and organic carbon status. Hence, the soil exchange capacity is improved leading to better adsorption and reduced losses. The synergistic and complimentary effects of the conjoint application of fertilizers and manures increase the efficiencies of added nutrients.[65]

Organic recycling is especially promoted through INM for facilitating nutrient recycling to improve soil fertility and productivity at a low cost. The beneficial effects of organic matter are well known. The labile soil organic matter pool, which is important for nutrient release during the growing season can be manipulated through various soil management practices.[66] In general more than 95% of the total N and S and upto 75% of the P in surface soils are in organic forms.[67]

The studies on integrated nutrient management for sustainable crop production in rice and wheat cropping systems show that INM could reduce N and P losses and enhance nutrient use efficiency as indicated in the table.[68]

These studies (Tables 9 and 10) clearly demonstrated that the excessive application of N reduces crop yields and results in the leaching of NO_3—to deeper soil layers. Enhanced nitrate accumulation (70 to 74%) in the 90 to 150 cm depth indicated the possibility of nitrate leaching below 150 cm and into groundwater. While the leaching of nitrate beyond the plant rooting zone could be substantial in rice fields fertilized with FN in porous soils, INM could minimize potential nitrate leaching as organics act as slow release fertilizers synchronizing N supply with plant need. It is further established that long-term applications of fertilizer P could cause an enormous movement of P to deeper layers in a coarse-textured soil having low adsorption and retention capacity for nutrients

Table 9: Effect of INM on rice yield, denitrification losses, N_2O emissions and soil organic C.[68]

Treatment	Rice yield (q/ha)	Denitrification losses (kg/ha)	N_2O emissions (kg/ha)	Soil organic C (%)
Control	34	18	6.9	0.37
120 kg FN/ha	56	58	12.4	0.37
GM_{20} + 32 kg FN/ha	59	50	11.8	0.41
CR_6 + GM_{20} + 32 kg N/ha	59	52	11.8	0.49
LSD (0.05)	2	6	3.4	0.04

FN = 88 kg N/ha 20 t/ha sesbania green manure; CR = 6 t/ha crop residues.

Table 10: Effect of INM on soil organic C, potentially mineralizable N (PMN) and microbial biomass N (MBN) in soybean-wheat rotation under conventional till (CT) and no-till (NT) systems.[68]

	TOC (mg C/ha)		PMN (mg N/kg)		MBN (mg N/kg)	
Treatment	CT	NT	CT	NT	CT	NT
Control	2.9	3.5	2.7	3.6	5.9	6.4
$N_{20} + P_{60}$	3.2	3.6	2.9	3.9	9.5	10.4
$N_{20} + P_{60}$ + 10 t FYM/ha	3.4	3.8	5.1	6.5	16.0	16.8
$N_{25} + P_{75}$	3.3	3.6	3.9	5.1	12.7	15.6
Control + CR	3.0	3.7	3.3	4.2	7.0	7.2
$N_{20} + P_{60}$ + CR	3.4	3.8	6.9	8.9	12.9	15.4
$N_{20} + P_{60}$ + 10 t FYM/ha + CR	4.4	4.8	9.7	12.1	24.3	27.3
$N_{25} + P_{75}$ + CR	3.7	3.8	8.4	10.3	17.6	20.5

Table 11: INM for major cropping systems.[3]

Cropping system	INM strategy
Rice-wheat	Green manuring of rice with sun hemp equivalent to 90 kg fertilizer N along with 40 kg N/ha produces yield equivalent to 120 kg N/ha. In an acid Alfisol soil, incorporation of lantana camera 10–15 days before transplanting of rice helps to increase the N use efficiency. Apply 75% NPK + 25% NPK through green manure or FYM at 6 t/ha to rice and 75% NPK to wheat. Inoculation of BGA @ 10 kg/ha provides about 20–30 kg N/ha.
Rice-rice	Use of organic sources, such as FYM, compost, green manure, azolla etc. meet 25–50% of N needs in *kharif rice* and can help curtailing NPK fertilizers by 25–50%. Apply 75% NPK + 25% NPK through green manure or FYM at 6 t/ha to *kharif* rice and 75% NPK to *rabi* rice. A successful inoculation of blue green algae @ 10 kg/ha provides about 20–30 kg N/ha.
Rice-potato-groundnut	Use 75% NPK with 10 t FYM/ha in rice and potato.
Sugarcane based cropping systems	Combined use of 10 t FYM/ha and recommended NPK increases the cane productivity by 8–12 t/ha over chemical fertilizer alone.
Maize-based cropping systems	Apply 50% recommended NPK as fertilizer and 50% of N as FYM in maize and 100% of recommended NPK as fertilizer in wheat.
Soybean-wheat	To get 2 t soybean and 3.5 t wheat, apply 8 t FYM/ha to soybean and 60 kg N + 11 kg P/ha to wheat or apply 4t FYM + 10 kg N + 11 kg P/ha to soybean and 90 kg N + 22 kg P/ha to wheat.
Pulses	Integrated use of FYM at 2.5 t/ha and 50% recommended NPK fertilizers plus rhizobium inoculation helps in saving of 50% chemical fertilizers.
Sorghum based cropping system	Substitute 60 kg N through FYM or green *leuceana leaucocephala* loppings to get higher yields and FUE.
Cotton	50% of recommended NPK can be replaced by 5 t FYM/ha.
Oilseeds (Mustard, Sunflower etc.)	Substitute 25–50% of chemical fertilizer through 10 t FYM/ha to get higher yield and FUE.

whereas INM reduces the accumulation of labile P in soils as well as the downward movement to deeper soil layers.

8.1 *INM in cropping systems*

In a sustainable nutrient management approach, the nutrient management strategy is based primarily on the assessment of the ability of the soil to provide nutrients as also the physical and biological characteristics of soil that modify this ability. Accordingly the INM strategies are designed to realize higher crop yields and sustain soil quality. The INM strategies developed for different cropping systems all over the country are compiled and presented in Table 11.

9 Conclusion

The Green Revolution achieved through high yielding varieties coupled with chemical fertilizers and irrigation, was a success in increasing food production. However, it left behind a challenge in terms of combating the threat of nutrient mining, imbalanced fertilization, and the use of poor organics, which are the primary causes of soil degradation and poor soil health. The real challenge is to keep up production under conditions of decreasing per capita arable land without losing productivity. Sustainable and successful agriculture in India envisages the adoption of various technologies which have been time tested over years of painstaking research conducted all over India. These technologies have been developed keeping in mind the average Indian farmer, who with the resources at his disposal, is the main architect of soil fertility management, *vis a vis*, sustainable agriculture. The best options of managing soil fertility clearly points to an integration of inorganic fertilizers and organic residues. Long term manurial studies indicate that addition of organic manures improves soil quality index—by bringing about a wholesome improvement in the physical, chemical and biological attributes. Thus soil organic matter is referred to as the "life of soil"—especially in impoverished Indian soils. Integrating the organic base with optimal inorganic supplements has been the route to sustainable nutrient management thus far and now needs to be revisited. The single message conveyed through this paper is that soil health needs to be cared for by adopting the sustainable soil nutrient management practices outlined in this paper for the sustenance of human life.

Received 09 March 2012.

References

1. *Fertilizer Statistics*.: The Fertiliser Association of India, New Delhi. (2003).
2. A. Subba Rao and S. Srivastava.: 'Soil test based fertilizer recommendations for targeted yields of crops'. *Proc. National Sem on soil testing for balanced and integrated use of fertilizers and manures*. Indian Institute of Soil Science, Bhopal. (2001).
3. A. Subba Rao and Sammi Reddy.: 'Integrated Nutrient Management vis-a-visCrop Production/Productivity, Nutrient balance, farmer livelihood and environment: India', (2010), (Unpublished report).
4. Anand, Swarup.; A.N. Ganeshmurthy: 'Emerging nutrient deficiencies under intensive cropping systems and remedial measures for sustainable high productivity', *Fert. News*, 43, 7, pp. 43–50, (1998).
5. P. Kumar.: 'Food demand and supply position for India', *Agric. Econ. Policy Paper*, 98–101, IARI, New Delhi, (1998).
6. G.S. Sekhon.: In 'Plant nutrient needs, supply, efficiency and policy issues: 2000–2025', *(J.S. Kanwar and J.C. Katyal eds.),* NAAS, New Delhi, pp. 78–90, (1997).
7. J.F. Power.: 'Fertility Management and Nutrient Cycling', *Adv. Soil Sci.*, 13. pp. 131–147, (1990).
8. A.K. Latha; Saxena and K.V.B.R. Tilak.: "Biofertilizers to augment soil fertility and crop production", *Soil Fertility and Crop Production*, K.R. Krishna (Ed.), Science Publishers Inc., Enfield, USA. pp. 279–312 (2002).
9. H.P. Singh.: "Nutrient management strategies for dryland farming", *Fert. News*. 45:59–64, (2000).
10. B.C. Biswas.: "Soil fertility and fertilizer management in semi-arid tropics", International Crop Research Institute for Semi-Arid Tropics, Hyderabad, India. pp. 15–22, (1988).
11. N.P. Singh; R.S. Sachan; P.C. Pandey and P.S. Bisht.: "Effect of a decade long fertilizer and manure application on soil fertility and productivity of rice-wheat system in mollisol", *J. Indian Soc.f Soil Sci,* 47: 72–80, (1999).
12. NRC (National Research Council). *Alternative Agriculture*, National Academy Press, Washington D.C., (1989).
13. E.M.A. Smaling.: "Soil nutrient depletion in Sub-Saharan Africa", *The role of plant nutrients for sustainable food crop production in Sub-Saharan Africa*, (Ed. H. Van Reuler and W.H. Prims), Leidschendan, the Netherlands: VKP. (1993).
14. H.L.S. Tandon.: *Sulphur Fertilizer for Indian Agriculture—A Guide Book*, FDCO, New Delhi (1995).
15. A. Swaroop.: "Lessons from long term fertilizer experiments in improving fertilizer use efficiency and crop yields". *Fert. News*, 47(12): 59–66 & 71–73 (2002).
16. Directorate of Rice Research, Research Highlights, Hyderabad (1985).
17. M.N. Reddy and J.E. Shinde.: "Neem cake blended urea for efficient use of fertilizer N by flooded rice under poor water management", *Fert. News*, 26(2): 21 (1981).
18. P. Padmaja and M.M. Koshy.: "A note on the run off losses of nutrients in water logged rice soils", *J. Indian Soc. Soil Sci.*, 26: 74–75 (1978).
19. U.C. Sharma.: "Studies on nitrogen leaching due to precipitation in Alfisols". *J Indian Soc Soil Sci.*, 33: 213–230 (1990).
20. M.V. Rao and I.C. Mahapatra.: "Fertiliser use in rice production", *ICAR Manual*, 96–109 (1978).
21. K.G. Pillai.: "An integrated approach to nutrient management in rice", *Indian Farming*, 40 (9): 15–18 (1990).
22. K.N. Tiwari.: "Fertilizer management in cropping systems for increasing efficiency", *Fert. News*, 25(3): 3–20 (1980).
23. K.D. Singh and H.L.S. Tandon.: *Fertilizer management in food crops (Ed. H.L.S. Tandon)*, FDCO, New Delhi, (1993).
24. R.K. Pandey and B.S. Dwivedi.: "Nutrient management in cropping systems", *Soil Fertility and Fertilizer Use (Ed. Kumar et al)*. 4: 221–238 (1990).
25. L.N. Mandal and S.K. Khan.: "Transformation of fixed P in soils under waterlogged condition", *J. Indian Soc. Sci.*, 25: 122–128 (1977).
26. N.N. Goswami and M.B. Kamath.: "Fertilizer use research on P in relation to its utilization by crops and cropping system", *Fert. News*. 29(2): 22–26 (1984).
27. N.N. Goswami and M.B. Kamath.: "Phosphate management in soil-crop system in India", *Proc. Fert. Assn. of India Sem.*, 11(11): 1–23 (1981).
28. J.C. Katyal.: "Management of P in lowland rice", *Phosphorus in Agriculture*, 73: 21–34 (1978).
29. S.P. Chakravarthi.: "Time of application of SSP to rice", *J. Indian Soil Sci.*, 30: 232–234 (1982).

30. A.P. Gupta.: "Effect of split application of P on the yield and uptake of paddy", *RISO*, 24(4): 329–334 (1975).
31. H.L.S Tandon.: "Phosphorus research and agricultural production in India". Fertilizer development and consultation organization (FDCO), New Delhi (1987).
32. I.C. Mahapatra and S. Patnaik.: "Management of upland rice soils. In vertisols and rice soils of the tropics", *Proc. 12th Intl. Cong. Soil Sci.*, New Delhi, 212–228 (1982).
33. N.N. Goswami and N.K. Banerjee.: "Phosphorus, potassium and other macro elements in soils and rice", IRRI, Los Banos, Philippines, 561–580 (1978).
34. H.S. Gill and O.P. Meelu.: "Studies on the substitution of inorganic fertilizers with organic manure and their effect on soil fertility in rice-wheat rotation", *Fert. Research*, 3, 304–314 (1982).
35. D.K. Kundu and S.K. De Dutta.: "Integrated nutrient management in irrigated rice", *Paper presented at the International Rice Res. Conference IRRI*, Las Banos, Philippines, 110 (1988).
36. A. Subba Rao and Srinivasa Rao.: "Potassium in status and crop response to potassium on the soils of agro-ecological regions of India". *IPI Res. Topics No. 20*. International Potash Institute, Basil, Switzerland, 1–57 (1996).
37. H.L.S. Tandon and G.S. Sekhon.: "Potassium research and agricultural production in India". FDCO, New Delhi (1988).
38. J.S. Grewal and R.C. Sharma.: "Responses of potato to potassic fertilisers in India". *Proc. Sym. Potassium in Soil and Crops. PRII,* Gurgaon, 309–326 (1978).
39. S.C. Mandal; H. Sinha; C.R. Prasad and M.H. Ali.: "Studies on liming of acidic red loam soils", *J. Indian Soc. Soil Sci.*, 14: 127 (1966).
40. B.S. Mathur; H. Sinha; N.K. Rana and S. Lal.: "Use of calcium as a nutrient for legume crops in acidic red loam soils of Ranchi", *J. Indian Soc. Soil Sci*, 31, 334 (1983).
41. J.S. Kanwar.: *Soil Fertility—Theory and Practice*, ICAR, New Delhi, 202 (1976).
42. H.L.S. Tandon.: *Soil Research and Agricultural Production in India*. 3rd Ed. The Sulphur Institute, Washington DC, USA, 140 (1991).
43. D.K. Kundan and K.G. Pillai.: "For sustained rice yields use organic measures too". *Int. Agric.*, 29(18): 4–7 (1991).
44. H.L.S. Tandon.: Micronutrient Research and Agricultural Production, FDCO, New Delhi (1995).
45. I.N. Takkar.: "Micronutrient research and sustainable agricultural productivity in India", *J. Indian Soc. Soil Sci.*, 44: 562–581 (1996).
46. B.S. Indulkar and G.O. Malewar.: "Response of rice to different sources of Zn and their residual effect on succeeding chickpea", *Ind. J. Agron.*, 36: 5–9 (1991).
47. All India coordinated research project report—On organic matter decomposition (1995).
48. P.L. Pingali and M.W. Rosegrant.: "Confronting the environmental consequences of the Green Revolution in Asia". *EPTD Discussion Paper No. 2,* Washington, DC: IFPRI (1994).
49. N.S.S. Rao.: *Biofertilizers in Agriculture and Forestry*, 3rd Ed. New York: International Science Publishers (1993).
50. Purushothaman and Padmavathy.: "Performance on Inter Cropped green manure and their effect in rice", *Nat. Sym. Internal Input Mngt. Eff. Crop Prodn.*, p. 115 (1994).
51. M.H. Lomte; Syed Ismail and A.S. Deshmukh.: "Nutrient Dynamics as Influenced by nutrient management practices in sorghum based cropping system on vertisols". *Sem. Adv. Soil Sci. Res. in Maharashtra*, Marathwada Agricultural University, Parbhani (1999).
52. S. Sankaran and S. Mudaliar.: "Manures and Fertilizers", *Principles of Agronomy*, 245–246 (1991).
53. B.T. Kang; G.F. Wilson and L. Sipkens.: "Alley cropping maize and *peucaena* in southern Nigeria", *Plant and Soil*, 63: 165–179 (1981).
54. R. Lal.: "Agroforestry system and surface management of a tropical alfisol", *Agrofor. Sys.*, 8: 97–111 (1989).
55. M.T.F. Wong; E. Akyeampong; S. Nortcliff; M.R. Rao and R.S. Swift.: "Initial response of maize and beans to decreased concentration of monomeric inorganic aluminium with application of manure or tree pruning to an oxisol in Burundi", *Plant and Soil*, 171: 275–282 (1995).
56. G.F. Wilson; R. Lal and N.Okigbo.: "Effects of cover crops on soil structure and on yield of subsequent arable crops grown under strip tillage on an eroded alfisol", *Soil Tillage Research*, 2: 223–250 (1982).
57. J. Venkateswaralu and B.R. Hegde.: "Nutrient management for sustainable production in coarse textured soils". *Proc. Int. Sym. on Nut. Mngt. Sus. Prod.,* Punjab Agricultural University (1992).
58. G.R. Reddy.: Management of swell shrub soils through tillage, inter-cropping and crop residue. PhD thesis. Marathwada Agril Univ, Parbhani (1997).
59. All India Co-ordinated Research Project on Improvement of Soil Physical Condition, (1967–94).
60. S.S. Sandhu; Prithar and K.L. Khera.: "Sugarcane response to irrigation and straw mulch in a sub tropical region". *Agric. Water Mngt.*, 3: 35–44 (1980).
61. K.L. Kher; R. Khera; S.S. Prihar; B.S. Sandhu and K.S. Sandhu.: "Mulch nitrogen and irrigation effects on growth, yield and nutrient uptake of forage corn". *Agron. J.*, 68: 937–941 (1976).
62. B.S. Sandhu; B. Singh and T.S. Aujla.: "Effect of irrigation, nitrogen and rice straw mulch on idaphic environment and growth of summer forage sorghum", *J. Indian Soc. Soil Sci.*, 53: 603–611 (1987).
63. B.H. Janssen.: "Integrated Nutrient Management: The use of organic and mineral fertilizers", *The role of Plant Nutrients for Sustainable Crop Production in sub-Saharan Africa*. H. van Reuler and W.H. Pruns (eds.) Parsen and Looyen, The Netherlands, 89–105 (1993).
64. M.S. Aulakh and C.A. Grant.: Integrated Nutrient Management for Sustainable Crop Production. The Haworth Press. Taylor and Francis Group, New York (2008).
65. S. Saktivel and E. Thinivarasan.: "Effect of combined use of organic material and nitrogen in transplanted rice",

Nat. Sym. Integrated Input Management for Eff. Crop Prodn. p. 92 (1994).

66. H.G. van Faassen and K.W. Smilde.: "Organic matter and nitrogen turnover in soils", In *Proc. Sym., Nitrogen Mngt. Fmg. Sys. in humid and sub-humid tropics.* B.T. Kang and J. van der Heide (eds.). International Institute of tropical Agriculture, Ibadan, Nigeria and Institute of Soil Fertility, Haren, the Netherlands, p. 39–55 (1985).
67. E.C.M. Fernandez and P.A. Sanchez.: "The role of organic inputs and soil organic matter for nutrient cycling in tropical soils." *Organic Management and tillage in humid and sub-humid Africa,* E. Pushparajah and M. Latham (Eds.). Bangkok, Thailand. IBSRAM. Proc. No. 10, 169–212 (1990).
68. M.S. Aulakh.: "Integrated Nutrient management for sustainable crop production, temporary crop quality and soil health and minimizing environmental pollution", *19th World Congress of Soil Science*, 1–6 August (2010).

Dr. V.R. Ramakrishna Parama is a Professor of Soil Science at the University of Agricultural Sciences, Bangalore, with 26 years of teaching, research and extension experience. Areas of research interest include—soil fertility, organic residue recycling, carbon sequestration and soil pollution management. Served as Principal Investigator of several national and international research projects. Guided 9 PhD and 20 Masters students, credited with over 100 publications. Conferred Indian Society of Soil Science Zonal Award for Best Doctoral Research in 1986 and the ICAR. … Best Teacher Award in 2011.

Ms. Atheefa Munawery is a senior research fellow at the Department of Soil Science and Agricultural Chemistry, University of Agricultural Science, Bangalore. Her areas of interest are soil fertility, and nutrient management. She is conducting research on revalidating the criteria for classifying soils based on nutrient status. The findings of her studies would be useful in making fertilizer recommendations. This would result in fertilizer saving and increased productivity and higher sustainability.