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Review

Soil Health and Crop Productivity

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Soil health emphasizes the integration of biological, chemical and physical measures of soil quality that affect farmers profit and the environment. Healthy soil, an essential component of a healthy environment, is the foundation upon which sustainable agriculture is built. Soil quality or soil health can be defined as "the fitness of soil for use" that has both inherent and dynamic components. The indicators of soil quality cover the whole range of soil physical, chemical and biological properties and the key soil quality indicators are soil texture, bulk density, aggregation, available water capacity, pH, EC, available soil nutrient reserves, organic C, microbial biomass, number of earthworms and termites. Major issues of soil health under Indian context include: i) physical degradation caused by compaction, crusting, puddling, water logging and soil erosion, ii) chemical degradation caused by wide nutrient gap between nutrient demand and supply, high nutrient turn over in soil-plant system coupled with low and imbalanced fertilizer use, emerging deficiencies of secondary and micro nutrients, poor nutrient use efficiency, insufficient input of organic sources because of other competitive uses, acidification and aluminium toxicity in acid soils, salinity and alkalinity, iii) biological degradation due to organic matter depletion and loss of soil fauna and flora, and iv) soil pollution from industrial wastes, excessive use of pesticides and heavy metal contamination. Management options to overcome these problems include the amelioration of soil physical environment, enhancing soil chemical and biological qualities through Integrated Plant Nutrition System (IPNS), soil test based fertilizer recommendation, micronutrient fertilization, management of industrial wastes and poor quality waters for agricultural use.

Key words: Soil health, quality indicators, crop productivity

India has to feed almost 17 per cent of the global human and 11 per cent of the livestock population on only 2.3 per cent of the world's land and the entire burden of producing enough depends upon the first few inches of the earth's crust – the SOIL. Soil is the most vital and non renewable resource which provides a very complex life support system and the emergence of major civilizations and the prosperity of the people in a region or a country depend upon the rational use of this basic resource. Therefore, greater attention has been paid throughout the world to study soils, their distribution and extent, behaviour, potential and problems and their suitability for sustained use for different purposes. With the increasing population, there is increasing demand for food, fodder, fuel and fibre. It is estimated that by 2025 A.D., India would require 350 million tonnes of food grains to feed its teeming millions (Singh, 2008). This target has to be met under the constraint of an almost fixed net cultivated area hovering around 140± million ha since the 1970s. The solution lies in improving the soil health by increasing the productivity of existing lands.

Concept of Soil Health

Soil health emphasizes the integration of biological with chemical and physical measures of soil quality that affect farmers profit and the environment. Healthy soil, an essential component of a healthy environment, is the foundation upon which sustainable agriculture is built. Prevalence of one or more unfavourable soil conditions for long periods leads to unsustainability of agricultural system.

The Soil Science Society of America defines soil quality as "the capacity of a specific kind of soil to function within natural or managed

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ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance soil and water quality, and support human health and habitation". Soil health has been defined as the capacity of a soil to function within ecosystem boundaries to sustain biological productivity. In simple terms, soil quality or soil health can be defined as "the fitness of soil for use". In agricultural systems, high quality soil provides for the sustained and productive growth of crops with minimal impacts on the environment.

Components of Soil Quality

There are two components of soil quality *viz.*, inherent and dynamic. Inherent soil quality refers to the characteristics that define a soil's inherent capacity for crop production. These are usually static, changing little over short time frames (years to decades). Soil texture and soil mineralogy are commonly included as properties of inherent soil quality for productivity. Other soil properties such as total soil Carbon, CEC and ESP may also be defined as inherent properties where broad soil type or regional comparisons are of interest at one point of time, even though they may be altered by management over longer time frame. The inherent quality of a soil should be viewed in the light of its intended agricultural use.

Properties of dynamic soil quality are those that change in response to human use and management normally over relatively short time frame (years to decades). Agricultural soils of high dynamic quality maintain high nutrient availability, permit adequate infiltration of water and air, have relatively stable structure and also maintain a functionally diverse community of soil organisms that support a high level of plant productivity. These processes are reflected in specific physical, chemical and biological properties of soils. The term "dynamic soil quality" and "soil health" are often used interchangeably. Two soils may be equally "healthy" but achieve different levels of crop productivity because of differences in their inherent qualities.

In natural ecosystem, soil quality is observed as a base line value or set of values against which future changes in the system can be analyzed and compared. In agricultural systems, soil quality is monitored with the view to manage the system to enhance production while not degrading soils and the environment. Thus soil quality is directly related to agricultural sustainability. In order to make interpretation of the health of a soil, various processes and functions need to be assessed through meaningful indicators.

Indicators of Soil Quality

The indicators of soil quality cover the whole range of soil physical, chemical and biological properties, reflect soil functions and are easy to measure for a variety of users and under various field conditions, and respond to changes in climate and management. Key soil quality indicators are soil texture, bulk density, aggregation, available water capacity, pH, EC, NPK reserves, organic C, microbial biomass, number of earthworms and termites. In specific situations, additional soil properties may be identified as indicators e.g., soil aggregation, ESP, micronutrient status, pesticide residues and heavy metal pollutants.

The term soil health is used to assess the ability of a soil to (i) sustain plant and animal productivity and diversity, (ii) maintain or enhance water and air quality, (iii) support human health and habitation. Soil productivity can certainly be lost through erosion, nutrient mining, salinization, sodification, compaction and waterlogging. The linkage between soil productivity and soil used to assess soil quality are linked to causes of productivity loss. The effects of management practices on productivity can also be assessed using soil quality attributes.

In the post green revolution era, country-wide on-going long term experiments have clearly revealed that the rate of response to added fertilizers and the factor productivity of major crops have been on the decline year after year under intensive cropping systems due to (1) high nutrient turn over in soil-plant system coupled with low and imbalanced fertilizer use, (2) emerging deficiencies of micro and secondary nutrients (S, Zn, B, Fe, Mn, *etc*.) (3) acidification and aluminium toxicity in acid soils, (4) insufficient input of organic resources because of other competitive uses and (5) consequent deterioration in soil physical, biological and chemical health and low fertilizer use efficiency, *etc*. The physical, chemical and biological indicators used for determining soil health are listed in Table 1.

Table 1. Physical, chemical and biological indicators used for determining soil health

S.No.	Indicator	Measurement
1.	Physical	Bulk density, infiltration rates and hydraulic conductivity, water content, water holding capacity, water release curve.
2.	Chemical	pH, EC, CEC, ESP, organic C, macro/micronutrient status
3.	Biological	Direct microscopic counts, chloroform fumigation, substrate induced respiration (SIR), CO_2 production,
	Microbial biomass	Microbial quotient, Fungal estimation, PLFA (Phospholipid fatty acids)
	Microbial activity	Bacterial DNA synthesis, Bacterial protein synthesis, CO_2 production
	Carbon cycling	Soil respiration, metabolic quotient (q CO_2),
	Nitrogen cycling	N mineralization, nitrification, denitrification, N-fixation
	Biodiversity and Microbial resilience	Direct counts, selective isolation plating, carbon and nitrogen utilization pattern, extra cellular enzyme pattern
	Bioavailability of contaminants	Plasmid-containing bacteria, anti biotic resistant bacteria

Source: Arias *et al*. (2005)

Major Problems Related to Soil Health and Crop Productivity

Soil health is affected by land degradation due to desertification, soil salinity, alkalinity, waterlogging, drought or floods, excessive soil erosion and unscientific agricultural practices. Crop productivity – measured in terms of responses to fertilizers – can only be sustained if soil fertility levels (supply of all nutrients in proportions matching with a crop's needs) are maintained. In order to attain this balance, it is essential that the nutrient demand of a crop to produce a target yield and the amount removed from the soil is replaced sooner or later.

Major issues of soil health under Indian context include: i) physical degradation caused by compaction, crusting, excessive cultivation or puddling, water logging and soil erosion, ii) chemical degradation caused by wide nutrient gap between nutrient demand and supply, high nutrient turn over in soil-plant system coupled with low and imbalanced fertilizer use, emerging deficiencies of secondary and micro nutrients, poor nutrient use efficiency, insufficient input of organic sources because of other competitive uses, acidification and aluminium toxicity in acid soils, salinity and alkalinity, iii) biological degradation due to organic matter depletion and loss of soil fauna and flora, and iv) soil pollution from industrial wastes, excessive use of pesticides and heavy metal contamination.

Soil erosion and land degradation are among the serious environmental problems adversely affecting soil productivity and continuously converting productive lands into wastelands. Intensive cultivation, raising more crops from unit area of land, results in rapid depletion of organic matter content of soil and adversely affects the physical condition of soil causing deterioration in soil aggregation. Lighter soils become more vulnerable to erosion by wind and water which gives rise to loss of top soil and aggravates the problem of landscape degradation. It is an irony that while Nature takes some 300 years to form only one centimeter of top soil, as much as 5334 million tonnes of soil gets eroded every year on a national basis accounting for about 16.4 t ha^{-1} $year^{-1}$. Of the soil so eroded, 29% is permanently lost to sea, 10% is deposited in reservoirs resulting in loss of their storage capacity and rest 61% is transported from one place to another. Thus, degradation of land resources poses a big threat to the natural resources resulting in soil and nutrient losses (5.94 mt NPK $year^{-1}$), loss in productivity (Table 2) and destruction of floral and faunal wealth, which ultimately adversely affects human life.

Table 2. Estimated impact of soil degradation on Indian agriculture

Crop	Per cent loss	Loss (million US $)	Crop	Per cent loss	Loss (million US $)
Rice	2.7 – 4.7	189	Jowar	5.7 – 7.6	40
Wheat	3.6 – 6.4	248	Bajra	6.8 – 8.4	25
Barley	4.5 – 7.0	8	Cotton	5.3 – 8.8	140
Groundnut	2.8 – 4.4	110	Maize	3.2 – 4.9	25
Gram	5.6 – 7.8	60	Sugarcane	4.5 – 7.9	200
Rapeseed & Mustard	5.8 – 8.5	155	Other crops	4.0 – 6.3	750

Source: Singh (2008)

Further, negative nutrient balance between crop removal and fertilizer addition has been around 8 to10 mt $year^{-1}$. Imbalanced nutrient application in respect of NPK, induces unsustainability in crop productivity. Out of 17 nutrients, focus has been on nitrogen followed by phosphorus while the secondary and micronutrients have not been given due attention. As a consequence, deficiencies of nitrogen, phosphorus, potassium, sulphur, zinc, boron, iron, manganese and copper have been reported to the extent of 89, 80, 50, 41, 48, 33, 12, 5 and 3%, respectively (Singh, 2008). The deficiencies of sulphur, zinc and boron are becoming more widespread and critical. The use efficiency of applied N, P, K, Zn, Fe and Cu in Indian soils is 30-50, 15-20, 70-80, 2-5, 1-2 and 1-2%, respectively. Thus, problems of nutrient deficiencies are aggravated further because of low use efficiency of applied nutrients, particularly P and micronutrients. Concerns have been expressed over the decline in response per unit NPK from 12 in 1960-69 to 7.70 in 2000-07. However, deterioration in soil is not solely responsible for such declining response. Rather, it appears that this issue has been related more to the principle of diminishing return with quantum increase in NPK use over the years.

Management Options for the Enhancement of Soil Health and Crop Productivity

Amelioration of soil physical quality for crop productivity

The soil physical constraints, such as drying of seed zone prior to planting time of post rainy season crops in rainfed areas, crust formation on seedbed after seeding, limited soil depth, low water retentivity, low water permeability, excessive rains or irrigation, salt content, extremes of soil temperature, and mechanical impedance may limit plant performance at any stage starting from seedling emergence upto final yield. Scientists have made efforts to overcome these problems by devising suitable agrotechnologies including tillage, residue management, soil amendments, erosion control, drainage and irrigation.

Continuous corn for 28 years with no tillage on a Wooster silt loam increased the percentage and mean weight diameter of water stable aggregates compared to chisel and mould board plough-based tillage system (Mahboubi *et al*., 1993). Tillage effects on aggregation, porosity and pore space size distribution also influence hydraulic properties of soil. Vegetative barriers and hedges have been found useful in reducing runoff losses, conserving soil and nutrients,

Table 3. Effect of chiseling on yield of crops and bulk density

S. No.	Treatment	Yield (t/ha)	Bulk density (mg m^{-3})
1. Sorghum			
	Chiseling (0.5 m apart)	4.72	1.42
	Chiseling (1.0 m apart)	4.08	1.45
	Chiseling (1.5 m apart)	3.71	1.58
	Unchiseled	3.42	1.65
	C.D. (P=0.05)	0.64	-
	Groundnut husk (5 t ha^{-1})	4.54	1.45
	Rice-husk (5 t ha^{-1})	3.89	1.55
	Control	3.52	1.62
	C.D. (P=0.05)	0.48	-
2. Tapioca			
	Chisel plough	53.79	1.527
	Disc plough	49.46	1.564
	Country plough	43.97	1.575
	C.D. (P=0.05)	3.91	N.S.
	Groundnut husk (5 t ha^{-1})	48.74	1.568
	Coir dust (10 t ha^{-1})	47.66	1.560
	Press mud (10 t ha^{-1})	52.56	1.491
	Control	47.34	1.604
	C.D. (P=0.05)	3.69	N.S.
3. Groundnut			
	Chisel plough	1.747	1.64
	Disc plough	1.499	1.64
	Country plough	1.458	1.69
	C.D. (P=0.05)	0.194	N.S.
	Groundnut husk (5 t ha^{-1})	1.576	1.66
	Coir dust (10 t ha^{-1})	1.511	1.65
	Press mud (10 t ha^{-1})	1.694	1.62
	Control	1.491	1.60
	C.D. (P=0.05)	0.119	N.S.
4. Cotton			
	Unchiseled	0.78	1.552
	Chiseled (0.5 m apart)	0.95	1.513
	Chiseled + Coir pith composted @ 12.5 t ha^{-1}	1.01	1.459
	C.D. (P=0.05)	0.12	N.S.

Source: Basker *et al*. (1995)

stabilizing earthen bunds in black soil region when one or two rows of grasses are established across the slope at 0.50-0.75 m vertical interval. Grasses such as *Vetiveria zizanoides* (Vetiver), *Cymbopogan martinii* (Rosha grass), *Dichanthium annulatum* (Marvel) and *Panicum maximum* (guinea grass) are the most suitable grass species as vegetative barrier for soil conservation in the black soil region (Ranade *et al*.,1995).

Basker *et al*. (1995) have brought forth the technologies developed for various soil physical constraints existing in Tamil Nadu. Under sub-soil hard pan conditions, chisel ploughing and application of organic amendments registered increased yield of sorghum, tapioca, groundnut and cotton besides reducing the bulk density of soil (Table 3). In the case of excessively permeable soils (sandy soils), adoption of compaction technology, using stone roller had enhanced the yield of groundnut, maize and sorghum. The experiments conducted on fluffy paddy soils with compaction technology using stone roller increased rice grain yield by 35.5 per cent over control. In red laterites of Tamil Nadu, where surface crusting is a major problem, yield of greengram was improved by 20 per cent due to the application of lime @ 2 t ha^{-1} along with FYM 10 t ha^{-1} after ploughing at optimum soil moisture. In slow permeable soils with high clay content the highest grain yield of sorghum was recorded from the raised bed plots followed by sowing on ridges.

Hulugalle and Enstwistle (1997) observed that after nine years of irrigated cotton, subsoil compaction and soil strength were higher in the minimum tilled plots (permanent ridges, soil disturbance limited to furrow deepening only) than in the maximum tilled (disc ploughing or chisel ploughing followed by ridging) plots, and soil water extraction by crops was unaffected. It appears that the effect of compaction was partly nullified by providing bypass channels.

At wheat sowing, soil moisture storage in the 1.8 m deep profile was significantly more by 27-85 mm in the manured plots than control during four of the six years. This increase in water storage was probably caused by improvement in organic carbon content of the soil (Ghuman and Sur, 2001). Application of FYM and green manure increased organic carbon in the top 0.1 m of deep alluvial loamy sand soil. Bulk density and pH of the surface layer decreased with organic manuring, whereas steady-state infiltration rate increased by 25-69 % and soil moisture storage by 27-65 mm per 1.8 m depth over control. Wheat grain yield increased significantly by manuring during four of the six growing seasons. After withholding FYM for two years, the residual effect could produce only 6 and 21% more wheat grain than in control, in the FYM at 6 and 18 t ha^{-1}, respectively.

Yield of rainfed crops is generally low owing to coarse nature of soils low in organic carbon and water retention. If soil organic carbon is enhanced affecting soil properties, productivity of these soils can be improved substantially. There are reports from irrigated agriculture that incorporation of organic residues into soils increased the available water holding capacity, decreased the bulk density, increased the organic carbon and available N status and also infiltration rate (Tolanur and Badanur, 2003).

Root grows best when soils are relatively well supplied with moisture. In a field study on wheat, Bandyopadhyay and Mallick (2003) observed that during the growing season from day 46 to107 as the plants grew and developed, the root length density increased with time and rate of increase was the maximum between 46-78 days. The penetration rate of roots was faster under relatively drier soil water regimes.

On sandy clay loam soil of Andhra Pradesh, by straw residue incorporation, decrease in bulk density and increase in infiltration rate were observed over control or burning (Surekha *et al*., 2004). Offseason deep tillage, particularly in subnormal rainfall years, has been found effective in conserving soil and water resources and enhancing crop yields substantially (Tomar, 2005).

Dhakshinamoorthy *et al.* (2005) reported that continuous application of balanced fertilizers significantly reduced the bulk density of soil than unfertilized plots which could be attributed due to the increased biomass production with consequent increase in organic matter content of soil. Further, combined application of NPK and FYM resulted in significantly higher hydraulic conductivity, porosity, water holding capacity and aggregate stability as compared to either NPK alone or unmanured control in finger millet-maize-cowpea sequence on Inceptisols of Tamil Nadu.

Enhancement of soil chemical quality

Natural waste plant residues form other potential resources to supplement organic sources as soil amendments. These plant residues may be incorporated into soils directly or after composting them to restore degraded soils, increase productivity and improve environmental quality (Bharadwaj, 1999). Singh *et al*. (2000) observed a general build up in soil N with integrated nutrient management under eight years (1988-96) of rice-wheat cropping in a sandy loam soil. Verma and Sharma (2000) also observed higher Olsen's P with organics than without organics at a given level of fertilizer P after 5-6 rice-wheat cropping cycles. Puste *et al*. (2001) reported that organic residues are used to supplement soil plant nutrients only and not to substitute them, because even the additions of best quality FYM or plant residues can hardly substitute 50% of the recommended dose of chemical fertilizers in wet season rice. Lantana biomass could be used as a supplement to fertilizer N in rice soils. Its regular addition to soil @ 15 t ha^{-1} before rice transplanting improved the Soil Organic Carbon (SOC) and available NPK status of soil, with consequent increase in rice yield and water use efficiency.

Productivity of acid soil is generally low due to the toxic levels of Al, Fe and Mn in soil solution, nutrient imbalance, deficiency of P, B and Mo and poor microbial activity leading to low N and S availability. Strongly acid soils may be managed with lime, but moderately acid soils can be managed with sufficient quantity of organic manures. Crops differ in their response to lime application and based on the response to lime application. Mandal *et al.* (1966) grouped crops into high, medium and low lime responsive. Among pigeonpea, maize, cowpea and groundnut, cowpea responded maximum to lime application followed by groundnut, pigeonpea and maize in acid Alfisol of Bhubaneswar (Mishra, 2002).

Table 4. Grain yield of wheat (g pot^{-1}) as affected by levels in relation to chloride (Cl) and sulphate (SO_4) dominated salinities at different ECe levels

Added P levels (mg kg^{-1})	Non-saline	ECe 6 dS m^{-1}		ECe 8 dS m^{-1}		ECe 10 dS m^{-1}	
		Cl	SO_4	Cl	SO_4	Cl	SO_4
0	10.5	3.5	5.1	2.2	3.7	1.9	2.4
30	26.0	21.5	24.4	16.2	18.8	9.2	12.0
60	29.5	27.9	30.0	20.7	22.7	13.7	18.3
90	29.4	28.7	30.7	23.7	26.6	16.9	19.8
Mean	23.9	24.0	22.6	15.7	18.0	10.4	13.2
CD (P=0.05)							
P		1.7	1.4	1.5			
Salinity		1.5	1.2	1.3			
P x salinity		2.9	NS	2.6			

Source: Sharma *et al*. (2007)

On sandy clay loam soils of Andhra Pradesh, under intensive rice mono-cropping conditions significant improvement in rice productivity, nutrient balance and soil health were observed with recycling of 100% straw directly or its ash or straw + green manure over straw removal or 50% straw addition after two crop cycles (Surekha *et al*., 2004). In a long term fertilizer experiment on Inceptisols of Tamil Nadu, Dhakshinamoorthy *et al.* (2005) found that balanced use of NPK fertilizer either maintained or slightly enhanced the SOC level over the initial levels.

In a greenhouse study conducted on a Typic Torripsamment, P requirement of wheat increased with the increase in the EC of soil (Table 4), suggesting that threshold P concentration values in the soil would not only increase with the increase in the ECe of soil, but would also vary with the predominance of Cl or SO_4 salts (Sharma *et al*., 2007).

Significantly higher yields to the tune of 4.3 t ha^{-1} for rice and 4.0 t ha^{-1} for wheat were recorded when rice -wheat were grown after green manuring of dhaincha *in-situ* or application of FYM (10 t ha^{-1}) or vermicompost (5 t ha^{-1}) once in a year during kharif season along with reduced quantity of fertilizers per hectare per crop (30-90 kg N, 13-20 kg P and 37 kg K) accompanied by microbial cultures (*Azotobacter*, PSB and BGA), as compared to the yield (4.0-4.1 t ha^{-1}) with RDF (120-26-50) per ha per crop. Reduction to the tune of 25 % in recommended dose of NPK fertilizers (30 kg N, 6.5 kg P and 13 kg K $ha^{-1}crop^{-1}$) could be made with the application of FYM or vermicompost or green manuring alone without decrease in yield of rice and wheat (Fateh Singh *et al*., 2008).

Enhancement of soil biological quality

A large, diverse, and active population of soil organisms may be the most important indicator of a healthy soil. For a working definition of soil biological quality and ease of analysis, biologically active fractions of Soil Organic Matter (SOM) and biochemical attributes of soil have proven more useful. Low soil microbial diversity indicates stressed conditions in soil while high diversity is an indicator of a healthy soil (Rao, 2007). Dehydrogenase and urease activities were low in alkali soils, which however improved upon addition of gypsum followed by cropping, growing trees or grasses (Rao and Ghai, 1985). Rao and Burns (1990) reported that inoculation with cyanobacteria in submerged soils improved the general health of soils through building up organic matter, stimulating the bacterial and fungal populations, enzyme activities, polysaccharide production and soil aggregation. Amendment with a steadily decomposable carbon source (Sesbania) removed the sodicity stress on microbes and improved their activity dramatically (Rao and Pathak, 1996).

Rao and Gill (2000) showed that in sequential agroforestry with perennial nitrogen fixing *Sesbania sesban* for four years followed by rice-wheat for six years, the residual effects of legume growth resulted in a permanent improvement in soil quality resulting in an additional yield of 1.2 t of rice and 0.5 t ha^{-1} of wheat each year on a sustained basis that was attributed to non-symbiotic N fixation of 30.8 kg $ha^{-1}yr^{-1}$.

On a sandy clay loam soil of Andhra Pradesh, substantial improvement in soil respiration rate was increased over straw removal or burning (Table 5) and with maximum in straw + green manure treatment (Surekha *et al.,* 2004).

Table 5. Influence of crop residue management practices on soil respiration

S. No.	Treatments	Biological indicator Soil respiration (mg CO_2 g^{-1} soil 24 h^{-1})
1.	100% straw incorporation	0.162
2.	50% straw incorporation	0.127
3.	100% straw + GM incorporation	0.172
4.	100% straw burning	0.121
5.	Control (Removal)	0.109
	CD (P = 0.05)	0.011

Source: Surekha *et al*. (2004)

On acid soils of Mizoram, inoculation of rice seedlings with PSB in combination with optimum dose of rock phosphate produced the highest and sustainable crop yield by increasing the efficiency of added P fertilizers besides maintaining soil health and minimized the expenditure on P fertilizer cost to an extent of 30-40% (Laxminarayana, 2005). On acid hill soil of Manipur, inoculation of groundnut with effective rhizobium strain was recommended along with furrow liming to improve groundnut productivity and soil health especially with regard to available N (Raychaudhuri and Raychaudhuri, 2008).

Integrated plant nutrition system (IPNS)

Integrated nutrient supply holds great promise in crop production not only for securing high productivity but also against emergence of multiple nutrient deficiencies and deterioration of soil environment**.** Farmyard manure, one of the components of IPNS which is a good source of carbon and nutrients could contribute considerably to the organic matter status of the soil (Biederdeck *et al*., 1984).

As reported by Nambiar and Ghosh (1994), better water retentivity and favourable environment for root development were established by the addition of organic manures. Inclusion of leguminous green manure crops in the cropping sequence and incorporation of green manures were beneficial in supplying N to the crop (Adiningish, 1988). Benefits of green manuring accrue from substitution of chemically fixed nutrients and enhanced biological activity. Combined application of FYM and BGA also resulted in significantly higher infiltration rate than their individual application (50.0×10^{-7} m s^{-1} in rice –wheat cropping system and 50.0×10^{-7} m s^{-1}. in rice-winter maize cropping system (Mishra and Sharma, 1997).

Sharma and Singh (2000) reported that the targeted yield approach was more balanced, profitable and helpful in checking soil nutrient mining as compared to fertilizer recommendations for economic yield based on regression approach. Pachauri and Vinay Singh (2001) studied the effect of integrated use of chemical fertilizer and FYM on soil fertility using onion as test crop and reported that when manure was applied in conjunction with chemical fertilizers, decline in organic carbon was arrested.

Rangasamy *et al.* (2000) reported that INM through Integrated Farming Systems in wet land/ irrigated dry land/rainfed dry land conditions will certainly pave way for increasing the productivity, profitability and also will help in sustaining the soil health. According to Bhattacharya and Ghosh (2001), combined application of P, S and FYM recorded the highest fruit yield in brinjal coupled with higher available P content in soil.

Muneshwar Singh and Sammi Reddy (2001) observed that the organic matter and total N status decreased with application of fertilizers alone and increased with conjunctive use of fertilizer N and organic manure. The N balance due to the use of fertilizer N alone was negative and integration of organic and biological N resulted in positive N balance (Duraisami *et al.,* 2002).

Santhi *et al.* (2002a) reported that post-harvest soil fertility was maintained due to IPNS for onion on Inceptisols of Tamil Nadu. Smitha John *et al.* (2005) and Saranya (2009) reported that IPNS resulted in low critical soil test values due to less requirement of fertilizer N, P_2O_5 and K_2O over NPK alone and higher yield targets recorded relatively higher critical levels for soil available NPK for cabbage and ashwagandha respectively.

Enriched sugar cane trash mulch consisting of 6 t /ha and industrial glue waste @ 4 t ha^{-1} significantly decreased the surface bulk density and EC by 2.0 and 6.4 per cent, respectively and increased the *in situ* saturated hydraulic conductivity, organic carbon, soil moisture and cane yield by 28.1, 19.6, 16.9 and 11.6 per cent respectively as compared to unmulched (Rita Dahiya *et al*., 2003). Laxminarayana and Patiram (2006) reported that the integrated use of inorganic, organic (green manure/FYM/Poultry manure/pig manure) and biological sources (PSB) of nutrients increased the NUE, ANR and soil fertility in addition to increased rice yields under Ultisols of Mizoram.

Significant enhancement in the activity of dehydrogenase and hydrogenase was observed in the rhizosphere soils of both *Azospirillum brasilense* and *Azotobacter chroococcum* upon inoculam with both N fixers and AM fungi and the enhancement was maximum with dual inoculation (Aseri and Rao, 2005). Saini *et al.* (2005) found that for obtaining maximum crop yield in soybean - winter maize cropping sequence on a clay loam soil, only 50% of the required chemical fertilizers might be supplied along with suitable bioinoculants such as N fixers, P solubilizers and VAM along with FYM.

The findings of long term fertilizer experiment with finger millet-maize-cowpea cropping sequence over 29 annual cropping cycles (Table 6) spectacularly revealed the fact that integrated use of FYM with 100 % NPK had significantly increased the yield of all the three crops in the sequence (Dhakshinamoorthy *et al*., 2005). Continuous exclusion of S from the fertilizer schedule resulted in yield reduction to a tune of 13 per cent over 100 % NPK recommended level.

Table 6. Long term effect of fertilizer application on crop productivity of finger millet-maize-cowpea cropping sequence in Inceptisol of Coimbatore

Treatment	Pooled mean yield, (kg ha^{-1})			
	Fingermillet	Maize	Cowpea (grain)	Cowpea (fodder)
50% NPK	2650	2560	434	2014
100% NPK	3033	3073	467	2354
150% NPK	3197	2384	511	2530
100% NPK + HW	2912	2948	475	2274
100% NPK + Zn	2975	3138	497	2325
100% NP	2935	2877	476	2363
100% N	1322	1172	218	869
100% NPK + FYM	3500	3575	570	2887
100% NPK (S free)	3500	2957	513	2316
Control	2891	912	171	639
CD at 5%	1042	430	157	277

Source: Dhakshinamoorthy *et al*. (2005

Further, the continuous experiment on STCR-IPNS technology for rice-rice sequence on Alfisol (Anonymous, 2009a) clearly brought forth the fact that after 11 years of cropping, the application of fertilizers based on STCR-IPNS has produced the highest grain yield and response ratio while sustaining soil organic carbon, available N and P status. Though depletion of available K was noticed in all the treatments (control, blanket, STCR fertilizers alone and STCR-IPNS), mining was minimum in STCR-IPNS treatment. Natesan *et al*. (2007a) reported that an increase of 23 % in soil organic carbon was recorded in STCR-IPNS treatments over control in carrot growing soils of Ooty.

Application of 100% NPK with 10 t FYM ha^{-1} increased in yield to a tune of 146 and 136 per cent in finger millet and maize, respectively over 100% N alone treatment on Inceptisols of Tamil Nadu (Anonymous, 2009b). Continuous application of FYM or incorporation of 40 to 45 days old GM in rice over a period of eight years could meet 50% NPK requirement of rice in a rice-wheat system besides increasing organic carbon available P and micronutrients (Balwinder Kumar *et al*., 2008).

Soil test based fertilizer recommendation

Soil testing is a scientific tool to evaluate soil fertility by predicting probability of getting profitable crop response to recommended fertilizer application under specific soil-crop condition. It is essentially a simple and rapid chemical analysis of soils with the objectives of recommending fertilizer and liming practices. Soil test based fertilizer recommendation plays a vital role in ensuring balanced nutrition to crops and also in preventing wasteful expenditure on the use of costly mineral fertilizers (Biswas, 2002).

In the Department of Soil Science and Agricultural Chemistry, TNAU, Coimbatore, under the All India Coordinated Research Project for Soil Test Crop Response correlation studies (AICRP-STCR), fertilizer prescription equations were developed under IPNS for cereals, millets, pulses, oilseeds, cotton, sugarcane, and horticultural crops (Selvakumari *et al.,* 2000; Natesan *et al*., 2007b) in different agroclimatic zones. Under intensive cropping sequence, the soils of the farmer's field cannot be tested for every season in time. Under such circumstances, the post-harvest soil test values from the test crop to the experimental field can be calculated from the initial soil test values, the fertilizer doses added, and yield obtained. Studies on this aspect were carried out by many workers for various cropping sequence and soil types (Shanmugam, 1992; Murugesa Boopathi, 1995; Santhi, 1995 and Andi, 1998).

Results of verification trials and front line demonstrations conducted with rice, cotton, groundnut, sunflower, tapioca, onion and bhendi in different agro-climatic zones of Tamil Nadu (Table 7) highlighted the possibility of increasing the productivity, efficiency of added nutrients (response ratio) and profitability of crops (benefit-cost ratio) due to STCR- IPNS over STCR-fertilizers alone, blanket and farmers' practice (Santhi *et al*., 2002b).

Table 7. Productivity, nutrient use efficiency and profitability of crops through integrated use of nutrient sources

Zone & Crop/Treatments	Rice-Cauvery Delta	Cotton-Western Zone	Ground nut-Western Zone	Sun flower-North Zone	Tapioca-North Western	Onion-Western Zone	Bhendi-Western Zone
			Productivity (yield-kg ha^{-1})				
Blanket/farmers practice	6410	2750	1340	980	29700	17350	12750
STCR-NPK alone	7260	2820	2150	1400	38100	17550	15700
STCR-IPNS	7390	3 020	2410	1500	41400	18270	16400
			Nutrient use efficiency (response ratio-kg kg^{-1})				
Blanket/farmers practice	11.9	12.2	4.6	3.0	20.8	18.1	46.0
STCR-NPK alone	14.2	13.0	7.2	5.3	26.3	24.4	47.6
STCR-IPNS	19.4	16.8	11.6	10.5	31.8	27.3	51.4
			Profitability (benefit cost ratio)				
Blanket/farmers practice	6.1	22.7	4.5	3.5	3.5	13.9	20.7
STCR-NPK alone	7.9	27.1	6.8	8.2	8.4	22.6	21.4
STCR-IPNS	10.7	37.1	10.5	14.7	16.5	25.7	30.8

Source: Santhi *et al*. (2002b)

Further, a computer software 'DSSIFER' (Decision Support System for Integrated Fertilizer Recommendation) was developed to generate crop, site and situation specific balanced fertilizer prescriptions in Tamil Nadu (Murugappan *et al.,* 2004).

Micronutrient fertilization

The intensive and exploitive agriculture with high inputs, improved varieties and technologies, which helped to attain self-sufficiency in food production, has led to the depletion of nutrients particularly micronutrients. Front line demonstrations conducted on micronutrients in Tamil Nadu clearly revealed that the application of 12.5 kg $ZnSO_4$ + 15 kg borax enriched with 50 kg FYM ha^{-1} to irrigated maize, 40 kg S through gypsum along with 25 kg $ZnSO_4$ + 15 kg borax + 0.5 kg Mo ha^{-1} to blackgram and greengram, 40 kg S through gypsum along with 25 kg $ZnSO_4$ + 15 kg borax to sunflower and groundnut and Zn @ 7.5 kg as $ZnSO_4$ to rice has recorded higher yield over check (Anonymous, 2008). Stalin *et al.* (2009) reported that continuous monitoring of nutrient depletion in rice-rice system revealed that there was no build up of major nutrients and in general, the magnitude of negative balance was greater for Zn and B indicating its careful monitoring and management.

Intensive cropping sequences of sugarcane – sugarcane with heavy doses of fertilizer inputs and non-addition of micronutrients has caused deficiencies of Fe and Cu (Table 8). Application of recommended dose of NPK along with 100 kg $FeSO_4$ + 37.5 kg $ZnSO_4$ + 5 kg $CuSO_4$ ha^{-1} and 12.5 t FYM ha^{-1} can be followed for maintaining positive nutrient balance and sustainable cane production (Muthumanickam *et al.*, 2008).

Table 8. Soil available nutrient status and Nutrient dynamics in continuous sugarcanecropping system

Nutrients		Available Nutrients status				
		Initial	Main crop	Ratoon I	Ratoon II	Nutrient Status (initial to final)
N	(kg ha^{-1})	140.0-252.0 (180.0)	134.4 – 190.4 (160.2)	144.2 – 238.4 (182.0)	151.2 – 235.2 (186.2)	~ = N
P	(kg ha^{-1})	10.5-15.6 (12.2)	12.8 – 17.9 (14.6)	11.5 – 14.8 (13.2)	12.1 – 15.2 (13.2)	~ = P
K	(kg ha^{-1})	162.0-370.0 (225.0)	198.0 – 520.0 (328.4)	328.0 425.0 (380.2)	256.0 – 464.0 (372.8)	+ K
S	(mg kg^{-1})	9.2-17.0 (11.7)	17.5 – 57.5 (31.9)	14.2 – 21.2 (18.1)	15.0 – 28.4 (20.5)	+ S
Fe	(mg kg^{-1})	32.5-62.5 (50.8)	12.2 - 24.8 (17.9)	11.4 – 19.4 (13.9)	10.0 – 19.8 (13.7)	- Fe
Mn	(mg kg^{-1})	11.2-26.0 (18.9)	9.0 – 21.0 (13.7)	12.4 – 24.2 (17.6)	11.4 – 43.7 (19.3)	~ = Mn
Zn	(mg kg^{-1})	0.8-1.6 (1.20)	0.10 - 4.10 (1.32)	1.12 – 1.94 (1.53)	0.91 – 2.43 (1.47)	+ Zn
Cu	(mg kg^{-1})	2.5-5.8 (4.3)	1.0 – 5.0 (2.55)	0.30 – 2.94 (1.80)	1.24 – 1.95 (1.56)	- Cu
B	(mg kg^{-1})	0.15-0.55 (0.37)	2.0 – 5.2 (3.16)	0.6- 1.8 (1.09)	0.3 – 2.5 (1.03)	+ B
OC	(%)	0.28-0.48 (0.43)	0.16 – 0.28 (0.22)	0.10 - 0.28 (0.19)	0.12 – 0.24 (0.16)	- OC

Source: Muthumanickam *et al*. (2009)

Management of industrial wastes and poor quality waters

To mitigate the concerns of environmental pollution and as a source of nutrients to crops, many scientists have attempted on the effective use of industrial wastes and also poor quality waters for crop production without deteriorating the soil health. In this context, Selvakumari *et al.* (1998) reported that integration of fly ash @ 20 and 40 t ha^{-1} with fertilizer or fertilizer plus compost or fertilizer plus compost plus *Azospirillum* resulted in higher Olsen-P and NH_4OAc–K status of the post-harvest soil.

Malla and Totawat (2006) reported that use of sewage water irrigation either on sandy loam or sandy clay loam soil, had brought an improvement in physico-chemical properties of Haplustepts of sub humid southern plains of Rajasthan and their fertility status.

Jagadeeswaran (1999) reported that the application of ferrogypsum, (a byproduct obtained from effluent treatment plant of Titanium industry) @ 575 kg ha^{-1} (equivalent to 400 kg of agricultural gypsum) was as effective as agricultural gypsum with soil application or foliar spray of $FeSO_4$ in enhancing the yield of groundnut on calcareous soils. Further as a soil amendment for alkali soils, application of ferrogypsum @ 50 per cent of gypsum requirement either alone or along with FYM was as effective as agricultural gypsum in reclamation efficiency, increasing rice yield and improving soil fertility status. On laterite soils of Kerala, use of Phosphogypsum as an amendment significantly increased the yield, yield attributes and uptake by cowpea (Mathew and Manorama Thampatti, 2007).

Sodic water of RSC 12 me L^{-1} along with gypsum can be successfully used in fallow-wheat, pearl millet-wheat, fallow-mustard and Desi cotton-mustard crop rotations in light textured soils of Haryana (Sultan Singh *et al.,* 2005). Based on the critical level of saline tolerance, medicinal plants can be cultivated using different salinity levels of irrigation water with appropriate soil and land management practices (Santhi *et al.,* 2008). Application of biocompost made from sugar industry wastes @ 5 t ha^{-1} plus recommended dose of NPK fertilizers along with gypsum @ 3 t ha^{-1} and Azophos @ 2 kg ha^{-1} was found to be effective in enhancing rice yield and sustaining the soil fertility of salt affected coastal soils of Tamil Nadu (Dhanushkodi, 2008).

Therefore to conclude, enhancing soil physical, chemical and biological environments through various ameliorative or management measures would sustain the soil health which in turn would improve crop productivity over long run.

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