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Integrated Nutrient Management: Theory and Practice

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ABSTRACT

Integrated nutrient management (INM) has been a popular area of investigation in crop production research, with varied concepts and applications. Better responsiveness of soil microbial biomass over a chemically available nutrient pool to nutrient input has led to an increased interest in measuring the quantum of nutrients held microbially. This has advocated the possibility of using changes in microbial biomass and soil enzymes (phosphatase, catalase, and urease) as potential diagnostic tools to measure soil fertility. The differential efficacy of two conventional methods of fertilization (soil versus foliar application) has undoubtedly helped in improving the yield and quality of both, although of late, continuous fertilization has failed to maintain the same yield expectancy on a long-term basis due to the depletion of soil carbon stock. Consequently, the occurrence of multiple nutrient deficiencies raised serious concerns about sustained crop production, irrespective of soil type. The gradual shift from purely inorganic to organic fertilization started to gain wide-scale use for enhanced biogeochemical nutrient cycling. These later formed the basis for INM involving three basic components viz., microbial inoculants (biofertilizers), inorganic and organic fertilizers. The approach involving multiple microbial inoculation along with enrichment of organic manures or crop residues by loading with inorganic fertilizers, the substrate, is increasingly been shown to modulate nutrient dynamics within the rhizosphere. The present review highlights the research work on various issues of INM-based production management, targeting several popular annual and perennial crops.

Keywords: citrus, INM, inorganic fertilizers, manures, microbial inoculants, substrate

Abbreviations: AB, *Azotobacter brasilense*; **Alum**, aluminum potassium sulphate; **AM**, arbuscular mycorrhiza; **C**, carbon; **CEC**, cation exchange capacity; **CEC**, cation exchange capacity; **C$_{mic}$**, microbial carbon; **DW**, *Drwida wilsii*; **EA**, enzyme activity; **EE**, *Eudrilus eugineae*; **EF**, *Eisenia foetida*; **FFP**, farmers' fertilizer practice; **FYM**, farmyard manure; **HA**, humic acid; **INM**, integrated nutrient management; **IPNS**, integrated plant nutrient system; **K**, potassium; **LM**, *Lampito mauritil*; **MAD**, maximum allowable depletion; **MBC**, microbial biomass carbon; **MRR**, microbial respiration rate; **N**, nitrogen; **NM**, nutrient mining; **N$_{mic}$**, microbial nitrogen; **NUE**, nitrogen use efficiency; **Om**, organic manure; **OM**, organic matter; **P**, phosphorus; **PE**, *Perionyx excavatus*; **PGPR**, plant growth-promoting rhizobacteria; **PM**, poultry manure; **P$_{mic}$** microbial phosphorus; **PRE**, phosphorus recovery efficiency; **PSM**, phosphate-solubilising microorganisms; **RMCS**, rhizosphere microbial community structure; **SIC**, soil inorganic carbon; **SMB**, soil microbial biomass; **SMRR**, specific maintenance respiration rates; **SOC**, soil organic carbon; **SOM**, soil organic matter; **SSNM**, site specific nutrient management; **VC**, vermicompost

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INTRODUCTION

Demographic pressure of a burgeoning population has kept researchers on their toes to find possible alternatives of raising productivity per unit land area and time. On the other hand, achieving a balance between crop nutrient requirements and nutrient reserves in the soil is essential for maintaining high yield and soil fertility, besides safeguarding environmental degradation. Such an objective becomes further difficult to accomplish due to shrinking *per capita*

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land availability, more so in the developing world. Globally, soil nutrient deficits are estimated at an average of 18.7 N, 5.1 P, and 38.8 (kg ha^{-1} $year^{-1}$) with an annual total nutrient deficit of 5.5 Tg (1 Tg = 10^{12} g) N, 2.3 Tg P and 12.2 Tg K coupled with a total potential global production loss of 1136 Tg $year^{-1}$ considering four major (rice, wheat, maize, and barley) cereal crops (Tan *et al*. 2005).

Integrated nutrient management (INM) is an approach that seeks to both increase quality of production and protect the environment for posterity. It relies on nutrient application and conservation, new technologies to increase nutrient availability to plants, and the dissemination of knowledge between farmers and researchers (Palm *et al.* 2001). In the past, nutrient management had been driven by the need for maximizing production. But now, nutrient management that is sustainable involves maximizing production, preventing on-site soil degradation, and minimizing off-site involvement of applied nutrients (Tagaliavini and Marangoni 2002).

There are three concepts of nutrient management often used in relation to each other (Raychaudhuri 1977; Roy and Ange 1991): i) IPNS (integrated plant nutrient supply system) is a concept which aims to maintain or adjust supply to an optimum level for sustaining desired crop productivity by optimizing benefit from all possible sources of plant nutrients in an integrated manner, ii) IPNS is a method to achieve the objective of 'IPNS'. In the latter is embedded a philosophy with social, economic, and technological components, while the former provides a strategy to achieve the said objective, and iii) INM, the actual technical and managerial component of achieving the objective of IPNS under a farm situation. It takes into account all the factors of soil and crop management including the management of all other inputs such as water, agrochemicals, etc. besides nutrients. In the light of above three concepts, in order to address present or future nutritional problems, only two strategies, a strategic or diagnostic approach is chosen. In strategic INM, potential problems on farms are characterized that fit into particular category, and recommendations are then accordingly made for each category. In the diagnostic approach, the problem of each soil type is diagnosed separately, and the remedies are then tailored as per soil type (Srivastava and Singh 2006; Srivastava *et al*. 2008).

According to Angers (1997), a simplified mode of INM uses five major concepts: i) immobilized capital of plant nutrients, ii) working capital of plant nutrients, iii) annual investments in plant nutrients, iv) plant nutrient losses, and v) plant nutrient outputs. The most important hurdle is how to integrate the various components of the INM decision.

External agricultural inputs such as mineral fertilizers, organic amendments, microbial inoculants, and pesticides are applied with the ultimate goal of maximizing productivity and economic returns, while side effects on soil organisms are often neglected (Katyal 2003). Mineral fertilizers have limited direct effects, but their application can enhance soil biological activity via increases in system productivity, crop residue return, and soil organic matter (Hartz *et al.* 2000; Sankar *et al*. 2009). Another important indirect effect especially of nitrogen (N) fertilization is soil acidification, with considerable negative effects on soil organisms (Chhonkar 2003). The outcome of a long-term fertilizer experiment in rice established that a balanced application of N, phosphorus (P) and potassium (K) promoted microbial biomass through improved diversity of the microbial community (Zhang and Wang 2005).

Inoculant application research, on the other hand, is increasing with a focus on co-inoculation with several strains or mixed cultures enabling combined niche exploitation, cross feeding, complementary effects, and enhancement of one organism's colonization ability when co-inoculated with a rhizosphere competent strain (Goddard *et al.* 2001). The outcome of studies like population diversity analysis of fluorescent *Pseudomonas* within the plant's rhizosphere, which helped to discriminate flax (*Linum usitatissinum* L.) and tomato (*Lycoperscion esculentum* Mill.) isolates (Lemanceau *et al.* 1995), could be befittingly exploited to synthesize a rhizo-competent dynamic substrate suiting diverse requirements of a specific crop. Later studies (Johnson 2009; Siasou *et al.* 2009) established that AM inoculation in wheat increased the biocontrol efficiency of *Pseudomonas fluorescens* on account of increased synthesis of 2,4-diacetylphloroglucinol by the latter in the presence of soluble C in the soil. In another study, Rengel *et al.* (1996) observed that the total number of bacterial colony forming units were greater in the rhizosphere of Zn-efficient genotypes of wheat under Zn-deficiency and in Mn-efficient genotypes under conditions of Mn-deficiency. In contrast, a Zn-deficiency treatment acted synergistically with the number of fluorescent *Pseudomonas* in the rhizosphere.

Organic amendments such as manure, compost biosolids, and humic substances provide a direct source of C for soil organisms as well as an indirect source via increased plant growth and plant residue return (Bunemann *et al*. 2006). Organic and integrated production systems offer alternatives to conventional production systems (Curl *et al.* 2002; Peck *et al.* 2005). However, integrated production methods have yet to attain the same widespread farmers' acceptance as organic production methods. In this review, efforts have been made to review various components of INM in relation to biological soil fertility management, besides quality production of crops.

SOIL C AND NUTRIENT DYNAMICS

Restoring soil fertility with inorganic fertilizers and maintaining farm productivity with ever increasing inputs have been successful, but continued to result in a decline in soil organic C, a common feature especially under tropical or subtropical conditions (Watson *et al*. 2002). Organic C (carbon) in soil plays a key role in the C cycle, and has a potentially large impact on the greenhouse effect (Lal and Kimble 2000). The world soil total C reserve is estimated as 1500 pg organic C pool and 750 pg as inorganic C pool to a 1-m depth; the present rate of annual enrichment of atmospheric concentration of CO_2 is 3.3 pg (Kimble *et al*. 2002). With the knowledge that such an increase in atmospheric CO_2 is affecting the global climate, and eventually the loss of organic C from farm lands in warm, humid, tropical countries at 40° either side of equator, a paradigm shift is needed in not only which improved farm productivity and monetary profit are looked at, but also the net profit, including the environmental benefit of sustainable farming system finds a place of due consideration. Organic C retained in soils is a function of soil N content (r = 0.98, p = 0.001) and the soil carbohydrate concentration (r = 0.96, p = 0.001), according to Dean *et al*. (2007). The occurrence of nutrient constraints explains the low C conversion efficiencies (Angers 1997).

Soil C as a quality index

Soil tests have long been used as a diagnostic tool to determine the available nutrients in soil (Srivastava and Singh 2001; Esilaba *et al*. 2005). But, quite often, they are challenged in terms of: i) soil nutrients measured by a specific extraction method that fails to relate to plant availability of nutrients; ii) the critical levels of soil-available nutrients thus determined are affected by other soil properties such as clay content, mineral composition, and biological characteristics; and iii) critical levels of soil-available nutrients vary greatly from year to year and between different crops (Srivastava and Singh 2001, 2002).

Soil organic matter (SOM), nutrients, and biological activity are important for productivity through soil structural, and fertility improvement (Palm *et al*. 2001). In recent years, the application of organic amendments with high SOM content, such as fresh and composted urban wastes, to fertility-depleted soils has become a common environmental practice for maintaining SOM, reclaiming degraded soil, and supplying plant nutrients (García *et al.* 1997; Ros *et al.* 2003). However, the influence of SOM on soil properties depends on the amount, type, and size of added organic materials (Nelson and Oades 1988). The quality of soil is rather dynamic, and can affect sustainability in production. A minimum data set was proposed to measure soil quality and changes due to current soil management practices by a selection of key indicators such as soil texture, OM, pH, nutrient status, bulk density, electrical conductivity, and rooting depth (Mishra 2005). These properties were later expanded with a few biological aspects of soil quality, namely microbial biomass C and N, and soil respiration (Doran and Parkin 1994), because soil quality is strongly influenced by microbially-mediated processes (nutrient cycling, nutrient capacity, aggregate stability), whereby the key is to identify those components that rapidly respond to changes in soil quality (Scholes *et al*. 1994). Indicators, however, will vary according to the site geography and sophistication level of measurements.

Within this context, two terms, indicator and threshold, are frequently referred to (Symth and Dumanski 1995). Indicators are the attributes that measure or reflect the environmental status or conditions of sustainability, whereas threshold is the level of indicator beyond which a system undergoes significant change, e.g., points at which stimuli provoke a significant response. In terms of sustainable land management, the threshold value may be considered as the level of a specific indicator beyond which the particular system of land management is no longer sustainable (Syers and Craswell 1995). According to these authors, the understanding of likely thresholds is not well developed, except for a limited number of environmental indicators such as soil acidity and nutrient status for P and K for a given soil type or some biophysical indicators such as bulk density. It would be difficult for a single threshold value to represent the boundary between sustainable and unsustainable. Consequently, a range of threshold values and temporal trends for particular indicators is required.

Total C, including both SOC and SIC pools in the active soil layer of 1 m depth, contributes about 2227 pg. The soil C pool of 2227 pg is 3.0 times the atmospheric pool estimated as 760 pg and 3.6 times the biotic pool estimated at 620 pg. Such a large and active C pool cannot be ignored (**Table 1**). Of late, the triggering effect of greenhouse gases (global warming) on depletion of the soil C stock has been considered pivotal for declining soil health that strongly warranted the restoration of menacing depletion in total C stock of soils.

The quasi-equilibrium values (stage after accumulation of dry matter and loss of OC over time) of SOC in the shrink-swell soils decreased with intensive cropping. Addition external sources of farmyard manure or other green manure may raise the quasi equilibrium value of SOC from 0.44-0.51 to 0.70-0.80% in soils of a horticulture-based farming system (Naitam and Bhattacharya 2004). Out of different soil orders, Vertisols (7.90 kg C m^{-2}) showed the highest SOC storage (Dutta *et al*. 2000) followed by Inceptisols (6.60 kg C m^{-2}), Alfisol (5.26 kg C m^{-2}), and Entisols (3.31 kg C m^{-2}) up to 1 m in soil depth.

The voluminous rhizosphere size of annual as well as perennial crops could be a perspective to maintain the soil nutrient supply system, since roots contribute to a significant amount of C in soil more than the above-ground residue (Bohm *et al*. 2002). C-sequestration implies removing atmospheric C and storing it in natural reservoirs for extended periods. Strategies of C-sequestration are grouped under two categories: biotic and abiotic. The underlying principle for the biotic option is converting atmospheric CO_2 into biomass and transforming a fraction in the SOC pool through microbial reactions (Goh 2004). Three biotic processes exist, two of which involve compression of CO_2 emitted by industrial complexes and injection into geologic strata and the deep ocean. The third is a soil process that involves dissolution of atmospheric CO_2 leading to the formation of carbonates following reaction with Ca^{2+} or Mg^{2+} cations brought in from outside the ecosystem (Bloodworth and Uri 2002). In this regard, there is a paucity of information on changes in SOC and microbial abundance that accrue from different management practices globally.

To differentiate the changes under different farming management systems, the most important factor is the microbial communities and activities inputting the amount of C into the system because C is always a limiting factor (Gunapala and Scow 1998). Parameters such as microbial biomass carbon (MBC), microbial respiration rate (MRR), and enzyme activity (EA) all could differentiate between a manured system and a non-manured system, suggesting their sensitivity to compost input. But, phosphatase and urease activity had significant differences between a chemical fertilizer farming system and a control system ($p < 0.05$), suggesting their sensitivity to chemical fertilizer input. The biological index responded differently to diverse amounts of compost and MBC, and phosphatase activity had significant differences amongst different levels of compost treatment (Hu and Cao 2007). Therefore, it would be difficult to establish a single biological or chemical criterion that could adequately reflect soil quality because of the multitude of microbiological components and biochemical pathways (Schloter *et al*. 2003). Parameters such as MBC, MRR, and EA are important bioindicators of soil fertility assessment (Spedding *et al*. 2004).

Soil enzymes activity and fertility dynamics

Studies on soil enzymes became attractive since certain information pointed to the connection of EA with soil fertility. A great amount of research has been conducted on the systems of soil enzymes, on the determination, generation, state, and function of EA in soil. Measurement of the soil EA can be effectively utilized as an indicator of the re-establishment of connections between the biota and restoration of function in degraded soils, since enzymes respond immediately to changes in soil fertility status (García *et al*. 1994; Aon and Colaneri 2001). Many researchers have studied the effect of fertilization on soil fertility by investigating soil EA (Jia *et al*. 2001; Liu 2004a). Various studies (Bandick and Dick 1999; Masciandrao *et al*. 2004; Tejada *et al*. 2006) suggested that enzymes may react to a change in soil management more quickly than other variables and therefore, may be useful as early indicator of biological changes since soil enzymes were more positively correlated with yield than soil fertility.

Different fertilizers may affect soil EA and fertility dynamics. Soil enzymes are derived primarily from soil fungi, bacteria, plant roots, microbial cells, plant, and animal residues (Cao *et al*. 2003) and play a significant role in mediating biochemical transformations involving organic residue decomposition and nutrient cycling in soil (McLat-

Table 1 Carbon stock (Pg = 10^{15} g)* of tropical region soils vis-à-vis global stock.

Carbon source	Soil depth (cm)		
	0-30	0-100	0-150
Tropical region			
* Soil organic carbon	207	395	628
* Soil inorganic carbon	76	211	-
* Total carbon	283	606	-
World			
* Soil organic carbon	704	1505	2416
* Soil inorganic carbon	234	722	-
* Total carbon	938	2227	-
India			
* Soil organic carbon	9.77	25.04	29.97
* Soil inorganic carbon	4.06	22.37	34.03
* Total carbon	13.83	47.41	64.00

Sources: Batjes 1996 ; Bhattacharya *et al*. 2000.

* Total carbon stock is computed by first calculation of organic carbon by multiplying organic carbon content (gg^{-1}), bulk density (Mg^{-1}), and thickness of horizon (cm) for individual soil profile with different thickness varying from 0-30, 0-50,0-100, and 0-150 cm. In the second step, the total organic carbon content per unit area is multiplied by the area (ha) of the soil unit identified in an area. Total soil organic carbon content is calculated in terms of Pg (1 Pg = 10^{15} g) and soil inorganic carbon using 12% carbon value in $CaCO_3$.

chey and Reddy 1998). Yang *et al*. (2005) indicated that soil EA was lower in increasing soil depth, e.g., soil enzymatic activity in the 0-10 cm layer was significantly higher than that in the 10-20 cm layer. Martens *et al*. (1992) earlier in a field experiment indicated that phosphatase activity increased when the compost manure was added at rates between 90 and 270 Mg ha^{-1}. Soil EA, measured as phosphatase, catalase, invertase, and urease activities, decreased in the early growth stages of cucumber (*Cucumis sativas* L.), but increased at later stages, when plants were supplied with partially decomposed horse manure. Chemical N fertilizer inhibited soil EA, but P and K fertilizers enhanced it. Activity of different soil enzymes viz., urease and phosphatase, was positively correlated with soil NH_4^+-N and available P concentration, but negatively correlated with leaf N and P concentration. Cucumber yield was also positively correlated with the soil EA (Yang *et al*. 2008). These studies demonstrated that rhizosphere enzymes can act as an index to detect changes in the microbial functioning in soil treated with microbial inoculants (Aseri *et al*. 2005).

Zhang and Wang (2006) demonstrated that soil enzyme activities had significant responses to irrigation scheduling on the basis MAD in soil during the period of subsurface irrigation. The neutral phosphatase activity and catalase activity were found to increase with more frequent irrigation at MAD of -10 and -16 kPa in tomato. The results further suggested that a higher level of water content favoured an increase in activity of these two enzymes. In contrast, urease activity decreased under irrigation, with less effect for MAD of -40 and -63 kPa. This implied that relatively wet soil conditions were conducive to retention of urea-N, but relatively dry soil conditions could result in increasing loss of urea-N. It was further observed that soil EA could be an alternative natural bio-sensor for the effect of irrigation on soil biochemical reactions, and could help optimize irrigation management of tomato for improved production (Zhang and Wang 2006), which can be expanded to other vegetables under greenhouse conditions.

Studies by Hu and Cao (2007) suggested that soil enzymes viz., alkaline phosphatase and urease activity in different soil management practices were minimum in the control followed by chemical fertilizer treatment and compost, suggesting that these enzymes could reflect the condition of soil fertility as bioindicators of changes in soil quality.

BIOFERTILIZATION AND INM

Renewed and intensified efforts are being made to grow different crops using various microbial inoculations, ever since depleting soil fertility attained serious dimensions, more so, with increased cropping intensity coupled with heavy use of chemical fertilizers (Kohli *et al*. 1998; Srivastava and Singh 1999) triggering the menace of nutrient mining (NM) defined as the quantum of nutrient added – quantum of nutrients removed (if obtained on negative side, it denotes the NM). The concept of biofertilizers using microorganisms began in 1834 when Boussingault, the French agricultural chemist, put forward a classical idea of biological N fixation, later established by Hellriegel and Wilfarth in 1886. Microbial fertilizers are biofertilizers or microbial inoculants defined as preparations containing live or latent cells of efficient strains of N-fixing, phosphate-solubilising or cellulotytic microorganisms to augment the nutrient availability in an assimilable form (Srivastava and Singh 2003a). Use of biofertilizers is often considered one of the most sustainable agricultural practices and if used appropriately, it promises to offer rich dividends on a long-term basis. Opinions vary greatly about the use of bifertilizers as a part of sustainable agriculture.

Benefits from microbial biofertilizers (Motsara *et al*. 1995; Bhattacharya *et al*. 1999) focus on the fertiliser supplement in mitigating the crop nutrient requirement, enriching soil with the addition of 25-40 kg N ha^{-1}, in some cases more than 200 kg N ha^{-1} under optimum conditions, and solubilising/mobilising 30-50 kg P_2O_5 ha^{-1}; liberating growth-promoting substances and vitamins to maintain soil tilth and fertility; suppressing the incidence of pathogens, thereby, leading to increased growth and yield.

Great claims are made for microbial soil inoculants as natural product. A small quantity of inoculant or other material brings about an enormous increase in numbers and activities of soil organisms, releases inorganic plant nutrients from soil minerals, improves the structure of both the subsoil and top soil, increases water penetration into the soil, improves the quality of crops growing on the soil, makes the plants resistant to various plant pests and disease organisms, restores the proper nutritional balance in the soil, and/or exerts many other similar effects on the soil. With respect to the microbial inoculants, it should be pointed out that the soil is teeming with countless millions of microbes. The types present are there because they are best able to cope with the environmental conditions. When microbial inoculants are applied to the soil, they rapidly decrease in numbers. They either die or are destroyed by the existing population. If some do survive, it is very probable that the same forms are already present. To establish a new type, the soil environment has to be made favourable by changing the acidity or alkalinity of the soil, applying essential nutrients in required amounts, or by applying a favorable source of organic food material (Hazarika and Ansari 2007).

Potdukhe and Somani (1997) suggested that sterilized degraded pulverized agricultural wastes may be used immediately after degradation for bioinoculants. Despite contributing significantly towards bioavailability of nutrients directly by mobilizing the insoluble fractions, the microorganisms can also act indirectly in producing quality compost at the shortest possible time from organic residues. One possible way of increasing nutrient content of the final product is a microbial enrichment technique with cellulose decomposers, N_2 fixers, and P solubilizers. The beneficial effects of such organisms on dairy farm wastes, crop residues, and city wastes (Gaur 1987) have been reported. Such procedures are collectively known as compost enrichment using bioinoculants (Manna *et al*. 1997; Marschner *et al*. 2004; Selvakumar *et al*. 2008).

Nutrient enrichment of fresh cowdung can be accomplished by adding fresh cowdung and farm residues (soybean, wheat, chickpea, and mustard straw) in a 1: 1 ratio with an initial C: N ratio maintained at 31: 48 (to stimulate microbial activity at this range) by adding urea-N. Moisture initially adjusted after five days, bioinoculum viz., cellulose decomposer (*Paecilomyces fusisporus*, *Aspergillus awamorie* 500 mg mycelium kg^{-1} material), P-solubilizing bacteria (*Bacillus polymyxa* and *Pseduomonas striata* for 10^7 viable cells ml^{-1} at a rate of 50 ml kg^{-1} material on a dry weight basis), and free-living N_2 fixer (*Azotobacter chroococcum*) were added and allowed to decompose for 120 days. The cowdung which initially had total OC and N of 35.1 and 0.47%, respectively, improved to 50.0 and 1.12% with soybean followed by 49.7 and 0.91% with chickpea, 48.9 and 0.52% with wheat, and 46.8 and 0.56% with mustard straw (Manna *et al*. 2000).

Biological significance of SMB

SMB serves as: i) a labile source or an immediate sink of C, N, P, and S (Dalal 1998) and ii) a driving force of nutrient transformation in soil (Gunapala and Scow 1998). A significant relationship between microbial biomass and crop yield was reported by Srivastava *et al*. (2002). Therefore, microbial-C, -N, and -P may have great potential as diagnostic indices of soil quality, especially nutrient availability changes. The annual fluxes of N and P through microbial biomass turnover are comparable with the amounts of N and P removed by harvested crops annually (Srivastava *et al*. 2006), and therefore, may provide an estimate of dynamic available pool of nutrients like N and P in soils. More studies are needed to understand the significance of microbial biomass turnover in the supply of N, P, K, and other nutrients.

SMB is a living component of SOM, and it comprises 1-5% of SOM (Zhang and Zhang 2003; Spedding *et al.* 2004). The size and activity of the microbial biomass is regulated by the SOM quantity, and quality and has been related to climatic conditions (Insam 1990), soil moisture content (Villar *et al.* 2004), soil temperature (Waldrop and Firestone 2004), soil pH (Roper and Gupta 1995), soil structure and texture (Amato and Ladd 1992), cropping system (Moore *et al.* 2000), and to soil and crop management practices (Nsabimana *et al.* 2004; Gil-Stores *et al.* 2005). SMB contributes immensely to the maintenance of soil fertility by controlling major key functions in soil (Bohme *et al.* 2005) and nearly all mineral nutrient transformations in soil are related to plant nutrition and soil fertility (Balota *et al.* 2004; Zhang *et al.* 2004).

The microbial biomass is part of the SOM that plays a major role in any ecosystem development and functioning. In cultivated orchard systems, potential productivity is directly related to the SOM concentration and turnover (Chen *et al.* 2002). The living SOM pool, or the SMB, is considered to be a part of the active SOM. The quality and quantity of the Om of soils normally changes at slow rates which are difficult to detect in the short term because of the large pool-size of Om and the spatial variability of soils. However, SMB is an active fraction of the Om that responds more rapidly than SOM to assess long-term effects of changes in soil resulting from management practices (Schloter *et al.* 2003; Chen *et al.* 2004). Accordingly, SMB either alone or as ratio between SMB and SOM has been proposed as an indicator of the state and changes of total SOM (Pankhurst *et al.* 1995; Dick 1997). Spatial variability of RMCS was influenced by the amount and composition of root exudates, e.g., RMCS of root tips of alfalfa plants was different from those in the mature root zone, and as plants mature, different cluster root age classes (young, mature, old) had distinct rhizosphere communities (Marchner *et al.* 2004). Hence changes in microbial biomass are considered as an early indication for changes in SOM.

SMB (C_{mic}/C_{org}) as microbial – C content per unit soil C serves as: i) a labile source or an immediate sink of C, N, P, and S (Chen *et al.* 1997; Dalal 1998) and ii) a driving force of nutrient transformation in soils (He *et al.* 1997). The C_{mic}, N_{mic}, and P_{mic} are often reported to be interrelated and highly correlated with key soil fertility indices including OM, soil availability indexes of N and P (McCarty and Meisinger 1997; Devi and Yadava 2006). Therefore, C_{mic}, N_{mic}, and P_{mic} may be great potential diagnostic indices of soil fertility, especially nutrient availability changes (Moore *et al.* 2000). In addition, C_{mic}, N_{mic}, and P_{mic} are sensitive enough to measure early changes due to different land use, management, and restoration of fertility-depleted soils (Ghoshal and Singh 1995; Aslam *et al.* 1999). The annual fluxes of N and P through microbial biomass turnover have been reported to be comparable with the amounts of N and P removed by harvested crops per year (Tripathi and Singh 2009), and therefore, may provide an estimate of dynamic available nutrient pools in soils. Changes in C_{mic}, P_{mic} and the turnover period of SMB C are governed by soil pH (Chen *et al.* 2002) which further suggests the shorter turnover period (just 139 days) on sandy red soil responsible for occurrence of frequent nutritional disorders.

Different genera of bacteria and fungi were isolated by Yadav *et al.* (1989) from soils treated with poultry manure (PM) and sewage sludge. *Pseudomonas* dominated in Calcifluvent soil type and *Flavobacterium* in Haplustalfs. *Escherichia* was only detected in sewage sludge-treated soil. The other microbial species viz., *Aspergillus candidus*, *A. terreus*, *Alterneria alternata*, *Curvularia* spp., *C. lunata*, *Fusarium oxysporum*, *Mucor plumbeus*, *Penicillium digitatum*, *P. funiculosa*, and *Trichoderma* spp. were also identified irrespective of treatment.

Abundance of microbial diversity

The size of the soil microbial pool is often expressed in terms of microbial biomass (Powlson *et al.* 1987; Powlson 1994). Vigour and yield of orange crop are affected by soil types due to variation in microbial population (Zou *et al.* 1994), cultivar type (Singh *et al.* 2002), and soil fertility (Yao *et al.* 2000). Rhizosphere soils of 19 fruit plants from a horticultural farm of Bangladesh Agricultural Research (BARI), Joydebpur, Gazipur were assessed for AM spore population and determining colonization in their roots. The spore numbers (100 g^{-1} soil) ranged from 48 in lemon (*Citrus limon*) to 1,050 in custard apple (*Annona reticulata*) in 2004, which later increased from 41 in pummelo (*Citrus grandis*) to 962 in gooseberry (*Phyllanthus embica*) in 2005, and from 44 in pummelo (*Citrus grandis*) to 575 in wax apple (*Syzygium samarangense*) in 2006 (Khanam 2007). Other studies reported that using a trap culture technique 26 species (Gai *et al.* 2006) and as many as 60 species (Tchabi *et al.* 2008; Brundrett 2009) of AM were isolated belonging to six genera, *Glomus*, *Acaulospora*, *Paraglomus*, *Archaespora*, *Pacispora*, and *Scutellospora*.

Despite soil being low or high in root colonizing population of AM propagules, a definite relationship exists between AM population and soil properties. The population of AM propugules in soil shows a positive correlation with soil properties such as N, organic C, available K, sand content, pH, and per cent AM root infection capacity, but a negative correlation with CEC, available P, silt, and clay content (Joshi and Singh 1995).

Studies on factors affecting the distribution of *Azotobacter* in acid soils of south India revealed the presence of *Azotobacter* in 35.2% of soils tested (Nair 1984). The SOM content showed no marked effect on the presence of these organisms, except at high levels when a universal correlation existed. A progressive increase in *Azotobacter* population was observed with increase in level of P due to lime application.

Dehydrogenase and urease activity, microbial population (fungi and bacteria), and Om content of the soils increased with an increase in altitude up to 1100 m in Arunachal Pradesh, India (Tiwari and Sharma 1998). Gandotra *et al.* (1998) observed the presence of *Azotobacter* in 55 out of 66 soils studied in Himachal Pradesh (India) representing soil orders viz., Mollisols, Alfisols, Ultisols, Inceptisols, and Entisols. The soils of Paleudalfs and Dystrochrepts were devoid of *Azotobacter*. Its population varied widely, constituting less than 1% of total bacteria. Haplustalfs and Hapludalfs had higher counts than other soil orders. Of the various soil properties positively correlated with *Azotobacter* population, a significant correlation was observed only with pH, available P, and exchangeable Mg^{2+}. Three species viz., *A. chroococcum*, *A. beijerinckii*, and *A. vinelandi* were identified in these soils.

The occurrence of *Azospirillum* in the roots of a wide range of crops like cotton, plantation crops, and orchard crops has been reported under varying growing conditions (Bashan 1999). Subsequently, acid- and salt-tolerant strains have also been reported (Magalhães *et al.* 1983). So far taxonomists have identified many species in the genus *Azospirillum viz.*, *A. lipoferum*, *A. brasilense*, *A. amazonense*, *A. halopraeferens*, and *A. irakense* (Okon and Gonzales 1994; Bhattacharya 2001); *A. doebereinrae* (Eckert *et al.* 2001); *A. melinis* (Peng *et al.* 2006); *A. canadense* (Mehnaz *et al.* 2007a); *A. zeae* (Mehnaz *et al.* 2007b); *A. rugosum* (Young *et al.* 2008); and *A. picis* (Lin *et al.* 2009). Among the free-living N-fixing bacteria, *Azospirillum* is considered to have more efficient nitrogenase properties than other N fixers. It has been well demonstrated that *Azospirillum*-inoculated plants were able to absorb nutrients from solution at faster rates than uninoculated plants resulting in accumulation of more dry matter, N, P, and K in the foliage (Okon 1985).

1. Nitrogenous biofertilizers

Even though *Azospirillum* was previously known as *Spirillum lipoferum*, it was only after its rediscovery by Dobereiner and her associates during the 1970s that the bacterium gained the reputation of being the most studied plant-associated bacterium. *Azospirillum* spp. are ubiquitously distributed in many parts of the world with tropical, sub-tropical, and temperate climate conditions (Tilak *et al*. 2005).

The rhizosphere supports large and active microbial populations capable of exerting beneficial, neutral, or detrimental effects of plant growth (Orhan *et al*. 2006). PGPR was first described by Kloepper *et al*. (1989), as soil bacteria that colonize the roots of plants following inoculation onto seeds and that enhance plant growth. Later, Bashan and Holguin (1998) proposed two new terms, biocontrol plant growth promoting bacteria and plant growth promoting bacteria. *Azospirillum* and *Pantoea* are defined as free-living, plant-growth-promoting bacteria, capable of affecting the growth and yield in numerous plant species, many of agronomic and ecological significance (Bashan *et al*. 2004). Later, Herman *et al*. (2008) suggested *Bacillus* (*B. subtilis* and *B. amyloliquefaciens*)-based PGPR for simultaneously improved production in bell pepper and reduced aphid infestation in peach. These PGPR have no preference for crop plants or weeds, or for annual or perennial plants, and can be successfully applied to plants that have no previous history of PGPR in their roots (Dobbelaere *et al.* 2003). PGPR have been reported to enhance plant growth directly by a variety of mechanisms; fixation of atmospheric N that is transferred to the plant, production of siderophores that chelate Fe and make it available to the plant root, solubilization of minerals such as P, and synthesis of phytohormones (Dobbelaere *et al*. 2001). Direct enhancement of mineral uptake due to increases in specific ion fluxes at the root surface in the presence of PGPR has also been reported (Bertrand *et al*. 2000).

Azospirillum spp. are known mainly for their ability to produce plant hormones as well as polyamines and amino acids in culture (Thuler *et al*. 2003), but they are also involved in the biological fixation of N and the increased activity of glutamate dehydrogenase and glutamine synthetase (Ribaudo *et al*. 2001). *A. brasilense* produces high quantities of extracellular indole-3-acetic acid (IAA), increasing root elongation, root surface area, and root dry matter (Molla *et al*. 2001). The effects of these microorganisms are influenced greatly by the species and genotype (Sensoy *et al*. 2007), soil type, and cultural practices such as fertilizer application (Gryndler *et al*. 2001), while the growth and fruit quality response of sweet pepper are also affected by the cultivation method (del Amor 2006, 2007). Basu *et al*. (2006) suggested that a small amount of chemical fertilizer like Co (0.2 kg ha^{-1}) showed a triggering effect on the efficacy of *Rhizobium* in groundnut (*Arachis hypogaea* L.).

There is a general consensus that *Azospirillum* and plant roots can be described as a mere colonization of the rhizosphere, rhizoplane, and root interior (Govindarajan and Thangaraju 2001). The colonization is the result of a selective enrichment of the organism best adapted to the ecological niche formed by the root environment (showing both chemotaxis and chemokinesis), whose beneficial effects have been postulated to be partially due to the production of phytohormones including GA_3, gibberellic acid (Cassan *et al*. 2001). The majority of bacteria are root colonizers, for example, *Azospirillum* has the ability to colonize at least 64 plant species (Bashan and Holguin 1995). Therefore, most of the studies demonstrated no host specificity in the *Azospirillum*-root association (Aseri *et al*. 2005; Tilak *et al*. 2005; Scheludko *et al*. 2009).

Response of microbial biofertilization showed highly unpredictable results due to their biological origin and susceptibility to various abiotic stresses (Okon and Labandera-Gonzalez 1994; Bashan and Holguin 1997), besides difficulty in adjusting the inoculated microorganisms into new soil environment. However, considering the vital role of microbes in the maintenance and buildup of soil fertility, their utility is indispensable (Badiyala *et al*. 1990). Okon and Gonzalez (1994) evaluated worldwide data accumulated over the previous 20 years on field inoculation with *Azospirillum* and concluded that these bacteria are capable of promoting the yield of crops in different soils and climatic area. Other results suggested that *Azospirillum* inoculation benefited plant growth and increased yield by improving root development, mineral uptake, and the plant-water relationship (Michiels *et al.* 1989; Govindarajan and Thangaraju 2001). In addition to N fixation, *Azospirillum* also produces growth-promoting substances like IAA and GA_3 and these phytohormones go a long way in enhancing crop growth.

Patel *et al*. (1995) observed that the order of efficacy of different nitrification retarders in conserving NH_4-N was observed as: nitrapyrin (NP) > neem oil (NO) > acetone extract of neem oil (ANO) > neem cake (NC) > ether extract of neem oil (ENO) > petroleum ether extract of neem oil (PNO) up to 30 days of incubation. However, after 45 days of incubation the order changed to: NP = NO > ANO > NC > ENO = PNO. In terms of production of NO_3-N under *Nitrosomonas* + *Nitrobacter* culture, the nitrification retarders could be classified under three effective groups as: NP > NO = ANO = NC = ENO ≥ PNO up to 30 days of incubation. But at the end of 45 days of incubation, their efficacy decreased and thus they could be classified under two groups viz., NC = NO = ANO > NC = ENO = PNO (Patel *et al*. 1995). This could be due to the loss in the effectiveness of the retarder on the nitrifying organisms with time span (Vyas *et al*. 1991).

Nitrogen-fixing bacteria and AM fungi were found to enhance the growth and production of various fruit plants significantly (Khanizadeh *et al*. 1995; Ghazi 2006) besides improving the microbial activity in the rhizosphere (Kohler *et al.* 2007). Aseri *et al.* (2008) observed that the combined treatment of *Azotobacter chrococcum* and *Glomus mosseae* was found to be the most effective since, besides enhancing the rhizosphere microbial activity and concentration of various metabolites and nutrients, these bioinoculants helped in better establishment of pomegranate plants under field conditions.

2. Phosphatic biofertilizers

In 1903, Stalatrom first reported microbial involvement in the solubilisation of inorganic phosphate (Panda 1990). During 1907-1908, Sacket, along with other scientists confirmed the solubilising capacity of different microorganisms (Gaur 1990). Now a number of microorganisms (**Table 2**) have been isolated, and they can solubilise insoluble phosphate substantially. These phosphate-solubilising microorganisms popularly known as PSM involve phosphate sour-

Table 2 Important phosphorus-solubilising microorganisms.

Phosphorus-solubilising bacteria	
	Bacillus megaterium; *Bacillus polymyxa*; *Bacillus firmus*; *Bacillus circulan*; *Pseudomonas striata*; *Bacillus subtilis*; *Bacillus mycoides*; *Bacillus mesentericus*; *Bacillus fluorescence*; *Bacillus pulvifaciens*; *Pseudomonas putida*; *Pseudomonas liquifaciens*; *Pesudomoas calcis*; *Pseudomonas rathonia*; *Xanthomonas* spp.; *Flavobacterium* spp.; *Brevibacterium* spp.; *Serratia* spp.; *Alcaligenes* spp.; *Achromobacter* spp.; *Aerobacter* spp.; *Aerobacter aerogenes*; *Erwinia* spp.; *Nitrosomonas* spp.; *Thiobacillus thiooxidans.*
Phosphate-solubilising fungi	
	A. candidus; *A. fumigatus*; *A. niger*; *Aerothecium* sp.; *Aspergillus awamori*; *Aspergillus terreus*; *Candida* sp.; *Cunninghamella* sp.; *Curvularia lunata*; *Fusarium oxysproum*; *Fusarium* sp.; *Humicola* sp.; *Mortierella* sp.; *Penicillium lilacinum*; *Penicillum digitatum*; *Phoma* sp.; *Puccilomyces* sp.; *Pythium* sp.; *Rhodotorula* sp.; *Schwanniomyceas occidentalin*; *Sclerothium rolfii*
Phosphorus-solubilising actinomycetes	
	Streptomyces sp.

Sources: Subbarao 1982 ; Kohli *et al.* 1998 ; Bhattacharya and Jain 2000 ces, mainly of two types i.e. i) mineral (fluorapatite, hydroxyapatite, tircalcium phosphate, mono- and dicalcium phosphate, rock phosphate, and iron phosphate) and ii) organic nature (phytin, lecithin, hexose monophosphatic ester, phenyl phosphate, and calcium glycerophosphate).

The highly populated PSM produce significant quantities of organic acids as metabolic by-products (Bhattacharya and Jain 2000) namely formic, citric, acetic, propionic, malic, succinic, fumaric, glycolic, gluconic acid, etc. (Dubey and Gupta 1996; Dubey *et al*. 1999) depending on various C substrates. These organic acids are sources of biologically generated H^+ ion, dissolve mineral phosphate, and make it available to plants. The degree of phosphate solubilisation is further influenced by pH, Eh, O_2, CO_2 concentration, and by the presence of organic material in the growing media. Sometimes these acids form a unionised association with meal (chelation) and increase the concentration of soluble phosphate (Gyaneshwar *et al*. 2002).

Many heterotrophic microorganisms are known to have some ability to solubilize inorganic P from insoluble sources (Gaur 1990; Badiyala *et al*. 1990; Gaur and Gaind 1992). Microbial solubilization of insoluble phosphates has also been reported through acidification, chelation, ion exchange reactions and external and internal accumulation of Ca^{2+} besides cell death lysis (Kucey 1983).

Incidentally, another study by Gaur and Gaind (1992) revealed that all these microorganisms have the potential to solubilise insoluble phosphate reserves of soil. A large number of commercially available P-based biofertilizers utilizing PSM are known by different trade names. These include: Nutra Phos™, Goredia Mekon Agri. Ltd., Maharashtra; Ecophos™, Green Fields Agrotech, Maharashtra; Agrophos™, Bio Science Laboratories, Karnataka; Phospho culture™, Tejashree Biofert, Maharashtra; Sphuranu™, Indore Biotech Inputs, Madhya Pradesh; Amrut Biofert-P™, New Maharashtra Chakar Oil Mill, Maharashtra; Phospho Mag™, Magnum Associates Madras, Tamil Nadu; Bacto-Phos™, K-Fert. Lab., Maharashtra; Phos-Fert™, Eco Max Agro System, Mumbai, Maharashtra; Krishi-Phos™, Maharashtra Krishi Udyog Vikas Mahamandal, Mumbai, Maharashtra; Phospho-Soil (P)™, Nomin Agro Bio Pot. Ltd., Maharashtra; Poshfert™, Kumar Krishi Mitra Bio Product, Pune, Maharashtra; Microphos™, BAIF Lab Ltd., Maharashtra; Superphos™, Nafed Biofert, Indore, Madhya Pradesh; Biophos™, Ajay Biotech Lab Ltd., Maharashtra; Phosphate culture™, Gujarat State Fert. Comp. Ltd., Baroda, Gujarat; Symbion-P™, 'T. Stanes & Co. Ltd., Coimbatore, Tamil Nadu; Phosphoteeka™, Nat. Biofert. Ltd., New Delhi etc. having shelf-life, extending from 4 months to 2 years (Bhattacharya and Jain 2000).

Dubey *et al*. (1999) showed P solubilizing efficiency equivalent to 30 kg P_2O_5 ha^{-1} as SP (superphosphate) on Vertisols. Studies by Gao *et al*. (2009) on the change in PRE in response to soil types showed that PRE in wheat in the isotrophic fluvo-aquic soil, fluvo-aquic soil, manurial loess soil and yellow brown soil were increased by 0.80, 0.60, 1.30 and 0.44% with NPK, respectively. PRE increased with NPK plus manure application in black-soil, red soil and yellow brown soil. PRE was unchanged during the long term application of NPK, while that is released annually by 0.50% with NPK plus OM. PRE in red soil decreased annually by 0.86% with long term application of NPK plus manure. These results indicated that the application of OM is helpful to increase PRE in upland soils. In isotropic fluvo-aquic soil, fluvo-aquic soil, and manurial loess soil, the main fraction of soil phosphorus as Ca-P, the PRE change rates of these soils were higher than those of black soil with the main fraction of occluded P. There were significant positive correlations between PRE and total P and soil pH, respectively.

Various species of *Trichoderma* as dual purpose microbe (phosphate solubilizer as well as microbial antagonist) were also effective in the promotion of growth and yield in various crops (Bal and Altintas 2006a). Both the species of *Trichoderma* viz., *T. harzianum* and *T. virens* promoted growth of cucumber and cotton seedlings (Yedidia *et al*. 2001), sweet corn (Bjorkman *et al*. 1998), cucumber, bell pepper, and strawberry (Altintas and Bal 2005; Bal and Altintas 2006b; Elad *et al*. 2006). On the other hand, application of *Trichoderma* was not conducive to increased yields of tomato (Bal and Altintas 2006c), lettuce (Bal and Altintas 2008), and onion (Poldma *et al*. 2001), suggesting some kind of inconsistency in response. Previous studies obtained significant yield increase in cucumber and bell pepper using a much higher dosage of P as 40 kg ha^{-1} (Altintas and Bal 2008).

The various classes of PSM bacteria involve the following reaction mechanisms (**Fig. 1**).

3. Potassic biofertilizers

Unfortunately, many studies carried out in the past have not been given due consideration due to the changes in soil K equilibrium or the K nutritional status of foliage. A critical review by Mishustin *et al*. (1981) stated that although K is released from silicates by microorganisms, the process is not active enough to complete provision of the plants with this element. In K-deficiency, the increased root exudation accompanied by accelerated microbial proliferation and respiration may lead to O_2 depletion in the rhizosphere, thus favouring denitrification specifically (Merckx *et al*. 1987; Van Veen *et al*. 1989). Denitrification is furthermore supported non-specifically by longer conservation of higher soil moisture due to more restricted growth of K-deficient plants and thus ensures better K availability in the vicinity of roots.

Some microorganisms in soil environment contain enzymes that function in ways analogous to chitinase and celluloses, i.e. they specifically break down mineral structure (Barker *et al*. 1997). Laboratory studies have shown that microbes can increase the dissolution rate of silicate and aluminum silicate minerals, primarily by generating organic and inorganic acids (Barker *et al*. 1997). Although some of these organisms are free-living (plank tonic) in solution, most of these bacteria are attacked to mineral surfaces (Hazen *et al*. 1991; Holm *et al*. 1992), where they can impact water-rock interaction, mineral surface chemistry, dissolution and precipitation of minerals, the evolution of ground water geochemistry and soil formation (Chapelle and Lovely 1990; Hiebert *et al*. 1992; McMohan *et al*. 1992; Barker and Banfield 1996, 1998; Neslson and Stahl 1997). Complete microbial respiration and degradation of particulate and dissolved organic C can elevate carbonic acid concentration at mineral surfaces, in soils and in ground water (Barker *et al*. 1998), which can lead to an increase in the rates of mineral weathering by a proton-promoted dissolution mechanism. In addition to carbonic acid, microbes can produce and excrete organic ligands by a variety of processes such as fermentation and degradation of organic macromoleules, or as a response to nutrient stress (Tempest and Neijssel 1992; Paris *et al*. 1996). The reports showed that silicates dissolving bacteria could activate soil P, K, Si reserves and promote plant growth (Xue *et al*. 2000; Sheng *et al*. 2003). Styriakova *et al*. (2003) reported that the activity of silicate dissolving bacteria played a pronounced role in the release of Si, Fe and K from feldspar and Fe oxyhydroxides. Badr *et al*. (2006) reported that bacterial inoculation combined with K and P bearing minerals gave 49 and 58% increase in dry matter yield of sorghum plants on clay, sandy and calcareous soil, respectively, compared to non-inoculated soils. The uptake of K by sorghum plants also increased by 71 and 116%, while the uptake of P increased by 42 and 79% in the same soils, respectively.

Plant-mycorrhiza association

AM are a symbiotic association between fungi and roots of higher plants, in which both members normally benefit from the association. Two types of mycorrhizal associations viz., ecto- and endomycorrhizae are commonly observed.

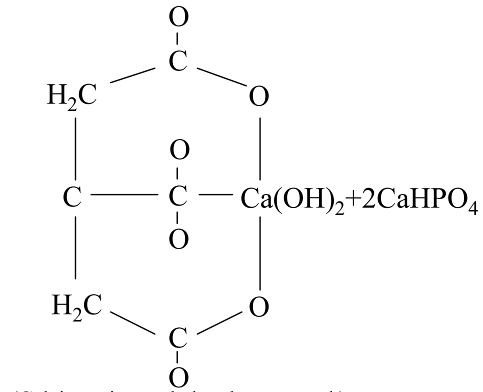
a. Through organic acid production

i. $Ca_3(PO_4)_2$ + CO_2+H_2O $\longrightarrow$ $2CaHPO_4$ + $CaCO_3$
(Insoluble) (Oxidative product of organic acid produced by PSM) (Soluble)

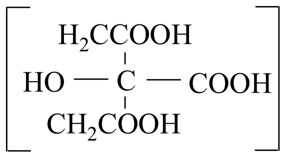
ii. $Ca_3(PO_4)_2$+ $2CO_2$+$2H_2O$ $\longrightarrow$ (CaH_2PO_4) + $CaCO_3$
(Insoluble) (Soluble)

b. By chelating with organic acid

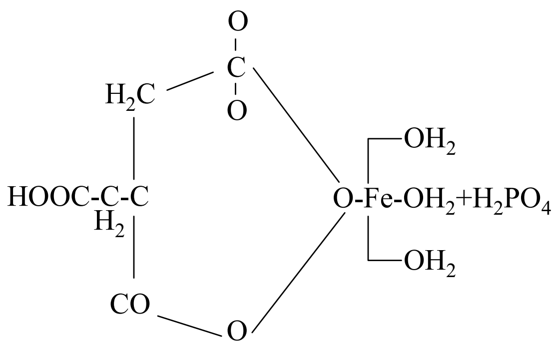
i. $Ca_3(PO_4)_2$ + Citric acid $\longrightarrow$
(Insoluble) (Produced by PSM)



(Calcium citrate chelated compound)



ii. $FePO_4$ + Citric acid $\longrightarrow$
(Produced by PSM)



(Fe-citrate chelated compound)

c. Through production of mineral acid by specific organism

i. By nitrifying bacteria
$Ca_3(PO_4)_2$+ $2HNO_3$ $\longrightarrow$ $2CaHPO_4$ + $Ca(NO_3)_2$
(Insoluble) (Produced by action of nitrifying bacteria) (Soluble)

ii. By *Thiobacillus sp.*
$Ca_3(PO_4)_2$+ $2CO_2$+$2H_2O$ $\longrightarrow$ $2CaH_2PO_4$ + $CaSO_4$
(Soluble)

d. Through H_2S formation by *Disulfovibrio*

i. $FePO_4$ + H_2S $\longrightarrow$ FeS + H_2PO_4
(Insoluble) (Soluble)

Fig. 1 Chemical reaction describing microbial solubilisation of phosphates.

Ectomycorrhizae are those fungi which enclose every feeder rootlet in a sheath or mantle of fungal hyphae and hyphal branches penetrate the intercellular space within root cortex (Uided Maaze *et al.* 2001; Khanam 2007) while endomycorrhizae are the fungi whose fungal hyphae enter the intracellular space, and often disintegrate to enrich soil fertility (Subbarao 1988). AM are intracellular obligate endosymbionts. These are classified on the basis of spore morphology into five genera, namely *Glomus*, *Gigaspora*, *Acaulospora*, *Archaeospora* and *Endogone* (Janos 2007).

Known effects of AM fungi, a symbiotic microorganism are: i) promotion in adsorption of minerals, especially P, ii) stimulation in growth and improvement in fruit quality, and iii) enhancement in resistance against environmental stresses (Whipps 2004). Response of AM inoculation was demonstrated by a large number of crops such as pomegranate, cowpea, chickpea, mungbean, cabbage, banana, tomato, cucumber, raspberry, etc. dependent upon mycorrhiza (Taylor and Harrier 2000; Bahadur *et al*. 2004; Singh and Singh 2004; Subramanian *et al*. 2006; Aseri *et al*. 2008; Wang *et al*. 2008; Molla and Solaiman 2009), by improving growth, yield, quality, and plant nutrition that can be fitted well into INM package.

1. Response on growth and yield

Varied responses on growth and yield of wide range of crops have been reported. AM fungi release an unidentified diffusion factor, known as the myc factor, which activates the nodulation factor's inducible gene mtENODII. This is the same gene involved in establishing symbiosis with nitrogen fixing bacteria *Rhizobium* (Kosuta *et al*. 2003). Mycorrhizal infection (*Glomus etunicatum* Becker & Gerd) decreased the time taken to initiate flowering, increased the total duration of flowering, and increased seed production by increasing number of flowerings produced, the proportion of flowers producing fruits, and the number of seeds per fruit in tomato (Marx *et al*. 2002). Seeds produced by mycorrhizal plants were also heavier and contained more N and P than those produced by non-mycorrhizal plants of velvet leaf (*Abutilon theophrasi* Medic) (Lu and Koide 2006). AM inoculation (*G. intraradices*) in tomato significantly increased shoot dry matter and the number of flowers and fruits. The fruit yields of AM plants under severe, moderate, and mild drought stressed conditions were higher than uninoculated plants by 24.7, 16.2, and 12.3%, respectively (Subramanian *et al*. 2006).

Inoculation of the seedlings of *Vangueria infausta*, a Kalahari tree with AM fungi, increased the dry mass and mineral acquisition, particularly P, Ca, and N (Bohrer *et al*. 2003). Studies by Wang *et al*. (2008) showed that growth of cucumber seedlings were significantly enhanced by inoculation with *G. mosseae*, inhibited by *G. versiforme*, and not significantly influenced by *G. intraradices*. The dry weight of seedlings inoculated with *G. mosseae* was 1.2 times its counterpart. The growth, NPK content, and yield of cucumber (*Cucumis sativus* L. cv. 'Bitostar') and cantaloupe (*Cucumis melo* L. cv. 'Vicar F') were higher in mycorrhizal plants treated with mixed inoculum of AM viz., *G. etunicatum*, *G. intraradices*, and *G. monosparum* grown under an 85% water regime than those of superphosphate-amended plants grown with a 100% water regime (Abdelhafez Ahmed and Monsief Abdel 2006).

2. Response on crop quality changes

A variety of crops has been observed to display response of AM inoculation on different fruit quality parameters. Tomato plants inoculated with *G. intraradices* produced tomato fruits that contain significantly higher quantities of ascorbic acid and total soluble solids than M-plants (Subramanian *et al*. 2006).

Mena-Violante *et al.* (2006) observed that fruits of chile ancho (*Capsicum annum* L. cv. 'San Luis') in the AM treatments subjected to drought and the AM treatments not exposed to drought reached the same size. The former treatment increased the concentration of carotenes (1.4 times) under non-drought conditions and the concentration of xanthophylls (1.5 times) under drought when compared to the non-drought treatment. The weights of a single fruit of cucumber preinoculated with *G. mosseae* and *G. versiforme* were, respectively, 1.4 and 1.3 times higher than those from the uninoculated treatment (Wang *et al*. 2008). Other work on pepper infected with mycorrhizal fungus *G. intraradices* showed 12-47% increase in P, dry matter content, sucrose, and total sugar content (Semra 2004).

3. Response on plant nutrition

Soil microbial processes are important in organic production because these systems rely exclusively on organic sources of nutrients. AM may be especially important for nutrient uptake in an organic production system because they increase the 'foraging' capacity of the root system. Improved nutrition, especially P nutrition of mycorrhiza-inoculated crops has been reported due to increased phosphatase activity (Neelima *et al*. 2002).

Uided Maaze *et al.* (2001) suggested that passion fruit (*Passiflora edulis f. flavicarpa*) plants were 'facultatively mycotrophic' when associated with AMF and fertilized with 30 mg P × dm^{-3} soil. Seedlings in unfertilized soil with 4 mg P × dm^{-3} soil were excessively dependent on the mycorrhizal association. In soil with 11 mg P × dm^{-3} soil, seedlings were marginally to moderately dependent, depending upon the AMF species used. All inoculated seedlings, without considering soil sterilization, were marginally dependent in soil with 30 mg P × dm^{-3} soil. In sterilized soil, independently of P, they were moderately dependent. However, in the same soil, with 30 mg P × dm^{-3} soil, the seedlings were marginally dependent. Mycorrhizal tomato plants had significantly higher uptake of N and P in both roots and shoots regardless of intensities of drought stress (Subramanian *et al*. 2006). The concentrations of N and P in roots and Mg, Cu, and Zn concentration in shoots of cucumber plants were increased by inoculation with AM (Wang *et al*. 2008).

INORGANIC FERTILIZER USE

Soil fertility problems associated with human-induced nutrient depletion are widespread worldwide (Tan *et al*. 2005). The use of man-made inorganic fertilizers is a fundamental component of INM, yet it is often either under-used or over-used in the absence of information on soil test-based fertilization assessment. There is a multiplicity of methods and techniques currently available for determining nutrient requirement, emphasizing the importance attributed to an awareness of fertilizer requirements. The fertilizer requirement of annual or perennial crops depends upon the objectives of fertilization, whether the purpose is to grow the crop or feed the crop.

There are two approaches which can be taken to fertilizer use in perennial fruit crops (Robinson 1989). First, corrective, where the absence of, or chemical availability of a nutrient in the soil, or positional inaccessibility, can be corrected by proper placement of an immobile nutrient in sufficient quantity to remain available to the plants for some years. Second, maintenance, where the time the nutrient will remain available is short, as a result of immobilization or leaching. Annual or more frequent applications are needed. The properties of soil and its interaction with each nutrient will determine which is the appropriate approach. Often the corrective approach is suited to P and the maintenance strategy to nitrogen and micronutrients. Timing is important for some nutrients (e.g. N), which can affect fruitfulness or fruit quality directly, or indirectly via effects on vigour or canopy density. Method of soil management (e.g. tillage, herbicide strips) will influence the fertilizer requirement and the appropriate method of application.

Fertilizer experiments have not generally provided calibrated soil or leaf test data because of their short-term nature, the biennial or variable production of many tree crops, their narrow focus and the difficulty in demonstrating yield responses because tree crops have relatively low rates of nutrient removal over long periods of time. Nutrient balance is basically a sound approach in the development of fertilizer recommendation, and can be easily estimated from crop nutrient removal data. Macronutrient removal by 20 Mg ha^{-1}, passion fruit crop was (kg ha^{-1}): 55 N, 78 K, 6 P, 6 S, 5 Ca, and 4 Mg. For a mango crop, it was (kg ha^{-1}): 11 N, 15 K, 2 P, 15 1 S, 2 Ca, and 2 Mg. For a 10 Mg ha^{-1} avocado crop it was (kg ha^{-1}): 41 N, 61 K, 8 P, 4S, 7 Ca, and 8 Mg. Passion fruit, in contrast to tree crops, is a 3-year crop, and nutrient uptake by developing leaves, vines, and roots inflated nutrient uptake by a factor of 2-3 (Huett and Dirou 2000).

Soil fertilization

Soil provides nearly all the nutrients essential to complete the life cycle of a plant. Different soil properties primarily determine the extent of a fertilizer response (Bronick and Lal 2005) and the crop rotation on the changes in physico-chemical (Lehoczky *et al*. 2005) and biological properties of soil (Manna *et al*. 2005).

1. Macronurient application

There are varied fertilization schedules followed across a variety of crops. Some fertilization plans recommend N application since the beginning of bud break until 6 weeks after full bloom for bearing pear trees (Neto *et al*. 2008), whereas others defend that N must be applied during the whole growth cycle considering that after harvest, trees can still improve their reserves through N uptake from soil. Some authors have studied the fertilizer N use efficiency in pears and apples (Cheng *et al*. 2001; Neilsen *et al*. 2001; Cheng *et al*. 2004). Most studies were performed in pots in sand culture, comprising its applicability to field conditions. The re-cycling of N as a result of the decomposition of senescent leaves in soils was only addressed in one study with apple trees (Tagaliavini *et al*. 2004, 2007). Fertilizer N use efficiency by trees increased from the first to the third year, but was generally small (6, 14, and 33%), and estimated N losses were large (89, 46, and 53%, respectively, in the first, second, and third year). Irrigation water and soil provided more N to the trees than fertilizer N (Neto *et al.* 2008).

For many years, several authors have tested the response of different crops to application of different nutrients, especially K, with respect to yield and quality, and reported the effectiveness of this technique in coffee, *Coffea arabica* L. (Silva *et al*. 2001); almond, *Amygdalus communis* L. (Reídel *et al*. 2004); pistachio, *Pistacio vera* L. (Zeng *et al*. 2001); pecan, *Carya illinoinensis* Koch (Worley 1994); and olive, *Olea europaea* (Jasrotia *et al.* 1999). However, this technique is greatly conditioned by different soil properties, particularly soil moisture, which affects the mobility of the supplied nutrients (Mengel and Kirkby 2000). This is mainly attributed to large variation in fertilizer doses to be really effective (**Table 3**) in different crops, annual versus perennial. Such variation in optimum doses is dictated by climate, soil types, crops, and farming practices in such a way that the correct balance of nutrients necessary for one farm, may be quite different from that necessary for a farm somewhere else in the world. Therefore, determining the appropriate balance of nutrients to increase crop yield and soil fertility will require localized research.

2. Micronutrient application

Soil application of micronutrients, especially inorganic salts, is often not so effective due to immediate reaction of added micronutrient cations with the mineral portion of soil through various processes like adsorption, fixation, chemical precipitation, etc. (Srivastava and Singh 2004, 2008a). Researchers even today are not unanimous about the efficacy of soil versus foliar fertilization with reference to micronutrients (Srivastava and Singh 2008b). Elevating Zn concentration only in the tops of Zn-deficient sour orange (*Citrus aurantium* L.) plants with foliar sprays partially restored normal root growth but clearly was not as effective as the roots absorbing Zn directly from high Zn concentration solutions (Swietlik and Zhang 1994). Johnson *et al.* (2005) observed better response of micronutrient (Fe and Mn) seed priming on chickpea (*C. arietinum*), lentil (*Lens culinaris*), rice (*O. sativa*), and wheat (*T. aestivum*) over soil fertilization with respect to growth and yield while another study by Duxbury *et al.* (2006) suggested that micronutrient-enriched seed successfully addressed Zn and Mo deficiencies in rice and wheat, and increased yields beyond those achieved by soil fertilization due to difference in root health activating early seedling emergence.

Interestingly, some recommendations have advocated soil application of micronutrients as one of the means to realize good yield of a crop, e.g., combination of $ZnSO_4$ (20 kg ha^{-1}) – $Na_2B_4O_7$ (5 kg ha^{-1}) – 180 N – 90 P – 90 K (kg ha^{-1}) in sugarcane on alkaline calcareous soil (Sharma *et al.* 2002) or $ZnSO_4$ (300 g $tree^{-1}$) – $FeSO_4$ (300 g $tree^{-1}$) – 600 N – 200 P – 100 K (g $tree^{-1}$) in citrus (Srivastava and Singh 2008b). The micronutrient-based Zn chelater complexes on the other hand are poorly or not at all absorbed by plant roots, as demonstrated through water culture studies (Chaney 1988; Swietlik and Zhang 1994). Under field conditions, however, the addition of Zn micronutrient-chelate elevated

Table 3 Optimum requirement of inorganic fertilizers for different crops.

Crop	N	P_2O_5	K_2O
Field crops (kg ha^{-1})			
Rice (*Oryza sativa* L.)	90-125	30-60	30-60
Maize (*Zea mays* L.)	120-125	60	30
Wheat (*Triticum aestivum* L)	80-120	40-60	0-60
Pigeonpea (*Cajanus cajan* L.)	20-30	40-80	0
Chickpea (*Cicer arietinum* L.)	18-20	40-50	0
Jute (*Corchorus capsularis* L.)	30-45	20	20
Groundnut (*Arachis hypogaea* L.)*	20	40	50
Vegetables (kg ha^{-1})			
Cabbage (*Brassica oleracea L.*)	150	80	40
Potato (*Solanum tuberosum* L.)	160	80	40
Cotton (*Gossypium hirusutum* L.)	100-180	50-120	60-120
Sugarcane (*Saccharum officinarum* L.)	100-300	60-120	80-120
Onion (*Allium cepa* L.)	120	90	90
Corinder (*Coriandrum sativum* L.)	60	40	30
Plantation crops (kg ha^{-1})			
Rubber (*Hevea brasiliensis* Willd.)**	260	220	104
Coffee (*Coffea arabica* L.)	120	90	120
Tea (*Camellia sinensis* L. Kuntze)	135	370	120
Coconut (*Cocus nucifera* L.)	1.0	0.6	2.4
Cassava (*Manihot esculenta* L.)	100	25	100
Fruits (g $tree^{-1}$)			
Mango (*Mangifera indica* L.)	775	500	700
Acid lime (*Citrus aurantifolia* Swingle L.)	900	250	500
Guava (*Psidium guava* L.)	360	180	180
Grape (*Vitis vinifera* L.)	270	450	900
Pomegranate (*Punica granatum* L.)	700	200	200
Ber (*Zyzyphus mauritiana* Lank)	500	200	300
Aonla (*Emblica officinalis* Gaertn)	1500	750	1000
Sapota (*Achras zapota* Mill.)	1000	500	500
Date palm (*Phoenix dactylifera* L.)	1000	500	500
Fig (*Ficus carica* L.)***	430	200	430
Phalsa (*Grewia subinaeuqualis* DC)	200	75	100
Litchi (*Litchi chinensis* L.)****	600	350	140
Pear (*Pyrus communis*)	1000	2000	1500

* Addition of 200 kg ha^{-1} gypsum
** Addition of 21 kg ha^{-1} MgO in 6 years
*** Addition of 280 g $tree^{-1}$ Ca
**** Addition of 7 g $plant^{-1}$ B
Sources: Sharma *et al.* 2003; Tiwari 2003; Lal *et al*. 2003; Arora and Singh 2006; Nasreen *et al.* 2007; Datta *et al* 2008; Irget *et al*. 2008; Pathak and Mitra 2008; Sharma *et al*. 2008

the amount of free nutrients in the soil solution due to adsorption and exchange properties of minerals present in soil (Chaney 1988). Soil application of a micronutrient, e.g., Zn from $ZnSO_4$ is fixed in the surface soil, while the chelated-Zn remains soluble and becomes distributed evenly throughout the soil, as evident from 46-times higher uptake of Zn by a perennial fruit crop like citrus from Zn-EDTA than $ZnSO_4$ on sandy soils (Parker *et al.* 1995). In non-citrus crops like wheat (Modaihsha 1997), banana (Mostafa *et al.* 2007), pear, apple, grapevine (Sohlegel *et al.* 2006) etc. similar results have been reported.

Nutrient depletion through soil mining is more or less a common problem in the absence of regular testing and monitoring systems. In addition to above most conventional method of fertilization, precision-based management strategy, like SSNM (site-specific nutrient management) has proved very effective in rationalizing fertilizer use in vegetables (Huang *et al.* 2007) and fruits (Srivastava *et al.* 2006). The SSNM aims to apply nutrients at optimal rates and times to achieve high yield and yield efficiency of nutrient use leading to high economic return per unit of fertilizer invested (Dobermann *et al.* 2003a, 2003b). The SSNM adjusts the fertilizer use to optimally fill the deficit between the nutrient needs of a crop and the nutrient supply from naturally occurring indigenous sources such as soil, organic amendment, crop residues, manures, and irrigation water (de la Cruz 2008). There are five step through which the SSNM is accomplished. These are: i.) establishment of yield target; ii.) estimation of actual yield responses to fertilizer N, P, and K; iii.) selection of fertilizer N, P, and K rates based on expected yield responses to fertilizer application considering agronomic efficiencies and nutrient balances; iv.) application of fertilizer to meet the crop demand for nutrients at critical growth stages; and v.) optimization nutrient use efficiencies (Hach and Tan 2007).

The performance of SSNM was tested for four successive rice crops. Compared with the current FFP, average grain yield increased from 5.9 to 6.4 Mg ha^{-1} while plant N, P, and K uptake increased by 8 to 14%. The gross return over fertilizer cost was 10% greater with SSNM than with FFP. Yields were about 20% greater in late rice (hybrid cultivars) than in early rice (inbred cultivar), but SSNM performed equally better than FFP in both seasons. Improved timing and splitting of fertilizer N increased N recovery efficiency from 0.18 kg kg^{-1} in FFP plots to 0.29 kg kg^{-1} in SSNM plots. The agronomic NUE (grain yield increase per kilogram fertilizer applied) was 80% greater with SSNM than with FFP (Wang *et al.* 2001). Similar kinds of responses were observed in rice in subsequent studies (Khurana *et al.* 2007; Liang *et al.* 2008). In rice, wheat, and chickpea, studies by Biradar *et al.* (2006) showed that wheat yield ranged from 3.5 to 3.8 Mg ha^{-1} under SSNM, 2.8 to 3.2 Mg ha^{-1} under RDF, and 2.6 to 2.7 Mg ha^{-1} in FFP. Average wheat yield was 3.66, 2.98 and 2.64 Mg ha^{-1} in the respective practices, signifying 23% higher productivity due to SSNM over RDF and 39% over FFP. Rice yield ranged from 5 to 6 Mg ha^{-1} (SSNM), 3.7 to 4.5 Mg ha^{-1} (RDF), and 3.4 to 3.9 Mg ha^{-1} (FFP), with average yield of 5.5, 4.1, and 3.7 Mg ha^{-1}, respectively, increasing average yield due to SSNM over RDF by 35 and 50% over FFP. In chickpea, yield ranged from 1.18-1.38 Mg $ha^{-}1$ (SSNM), 1.03-1.14 Mg ha^{-1} (RDF), and 1.01-1.13 Mg ha^{-1} (FFP), with average yield of 1.20, 1.08, and 1.06 Mg ha^{-1}, respectively, increasing the average yield due to SSNM by 17-18% over RDF or FFP. Patil *et al.* (2009) reported that cotton supplied with a fertilizer dose of 218N – 59P – 148 K (Kg ha^{-1}) for a targeted yield 3.0 Mg ha^{-1} as economical in the northern transition zone of Karnataka (India). SSNM has also proved very effective under different cropping systems. For example, Bokhtiar *et al.* (2003) observed much higher economic return in sugarcane intercropped with potato and onion than with onion crop only through multi-location trials. Similar studies have shown good results in blackgram (Gupta *et al.* 2007) and coconut with intercropped fodder (Lakshmi *et al.* 2007).

These SSNM studies in fact warrant that fertilizer recommendations should be fine tuned to spatial domains with relatively uniform agroecological characteristics, cropping practices, and socioeconomic conditions. Within such domains, season specific management of the variability in indigenous nutrient supply can accommodate the field specific approaches. However, the major challenges are: i) to retain the demonstrated potential of the SSNM approach and ii) to build upon what has already been achieved while reducing the complexity of the technology as it is disseminated to farmers (Johnston *et al.* 2009).

Of late, fertigation through a microirrigation system gained popularity for raising the productivity through regulated nutrient supply maintained during the entire growth period of annual (Bangar and Chaudhari 2004) and perennial crops (Reddy *et al.* 2002; Shirgure *et al.* 2003; Srivastava *et al.* 2003). Amid continuing concerns over irrigation water shortages fertigation (application of fertilizers through irrigation) is now considered as a time tested technology where water soluble fertilizers are dispensed into irrigation system, thereby channelised through distributaries upto point of disposal into plants's rhizosphere (Mmolawa and Or 2000). Completed broadcast method of fertilization, fertigation has shown a definite edge with regard to NUE. Thomson *et al.* (2003) reported the NUE of 90 to 81% with 250 and 350 kg N ha^{-1}, respectively in broccoli. In tomato, Bradr *et al.* (2007) observed an NUE of 60 and 54% with an N application rate of 221 and 194 kg ha^{-1}, respectively corresponding to fruit yield of 67.7 and 63.3 Mg ha^{-1}. Fertigation has further shown improved response on yield and recovery of applied nutrients in a wide range of crops like squash (Ertek *et al.* 2004; Mohammad *et al.* 2004), onion (Patel and Rajput 2005), tomato (Bradr *et al.* 2007) broccoli (Thomson *et al.* 2003), garlic (Castellanos *et al.* 2001; Castellanos 2002), corn (Asadi *et al.* 2002), grapevine (Reynolds *et al.* 2005), and bell pepper (Silber *et al.* 2005). Use of organic fertilizers (Nakanu *et al.* 2003) and bromide ion as tracer to stimulate movement of nitrate (Zerihum *et al.* 2003) has added better success to fertigation. Later, Gutiérrey *et al.* (2007) proposed the use of an electronic nose for the first time for supervision of the nutrient solution composition produced by a fertigation system. Such approach appeared to be a feasible method for the in-line assessment of nutrients concentration and presence of undesired compounds in fertigation solution.

Foliar fertilization

Foliar fertilization means the epigean application of a plant nutrient, which a plant needs for its nutrition and growth i.e. the non-root feeding or extra radical feeding (Mengel 2002). Historically, a problem of absorption of water by leaves was described in 1676, but was disputed until demonstrated this possibility experimentally in the 1930s. Different aspects of foliar nutrition have been reviewed previously (Srivastava *et al.* 2008).

Foliar fertilizer applications are considered a valid alternative to provide nutrients to plants when soil conditions may limit root uptake or during periods of fast growth when needs may exceed root supply (Toscano *et al.* 2002). The health of the plant is important in any form of fertilization. Foliar fertilizers can perform their action through foliar sprays with utmost efficiency only when they are sprayed at an optimal time (phenological phase), right site, and in correct application rate with uniformity in distribution (Srivastava *et al.* 2007; Fernández-Escobar *et al.* 2009).

Foliar fertilization is better than conventional soil fertilization under certain conditions (Srivastava and Singh 2003b; Fernández and Ebert 2005), e.g., i) acute shortage of nutrient supply, ii) nutrients either due to their total absence or due to trace elements are immobilized on account of unfavorable soil conditions, iii) nutrient imbalances, i.e. having an unfavorable influence on root absorption for optimal growth, and iv) restricted nutrient uptake through the plant roots. The other advantages of foliar application are: high effectiveness, rapid plant response, convenience in application, and elimination of toxicity symptoms induced by excessive accumulation of a given element in soil (Fernández *et al*. 2005; Fernández and Ebert 2005). For example, earlier studies on foliar spray supplying a high concentration of Fe (Fe-DTPA 100 mg L^{-1}) prevented most of the detrimental effects of toxic Zn in soybean (Fontes and Cox 1998) or Zn supply (69 mg L^{-1} Zn-DTPA) mitigated B toxicity in sour orange (Swietlik 1995). On the other hand, the common disadvantage of foliar application is associated with its temporary response, necessitating repeated applications without any residual effect into the next cropping season (Srivastava and Singh 2003a).

Foliar spray provides not only a means to apply nutrients at a particular stage in the growth cycle, but it also permits remedial action to be taken soon after establishing the diagnosis of a deficiency. According to Swietlik and Faust (1984), foliar fertilization causes a plant to pump more sugars and other exudates from its roots into the rhizosphere. Beneficial microbial populations in the root zone are stimulated by the increased availability of these exudates (Eichert *et al*. 2006). In turn, this enhanced biological activity, and increased the availability of nutrients. Some of the advanced foliar fertilization technologies like use of electrostatic sprayers (impart a charge to the spray particles and cause them to adhere more readily to plants) and sonic bloom (uses sound to increase the leaves' absorption capacity of nutrients) have recently come into practice, although they are yet to gain commercial acceptability (Srivastava and Singh 2008b). Such developments have the potential to improve the effectiveness of INM strategy by addressing nutritional deficits through foliar fertilization on one hand, and treating the rhizosphere through enriched substrate on the other.

Many growers are using postharvest foliar urea applications as a way to ensure that the bud reserves of N are high, even when added fertilizer N is being reduced with the goal of increasing crop quality (Sánchez *et al*. 1995). There is also some evidence that a postharvest urea application increases leaf decay rate and reduces the incidence of disease in the following year (Beresford *et al*. 2000; Weinbaum *et al*. 2002). Previous experiments in olive showed that absorption of foliar applied K by leaves is restricted by water stress or K deficiency, and concluded that foliar K spray should be carried out in spring under rain-fed conditions, when trees present a good water status, and there are many younger leaves (Restrepo-Diaz *et al*. 2008a, 2008b).

On the other hand, foliar fertilization with micronutrients is generally successful because deliverable amounts are enough to meet most trees' requirement. For example, because a transitory low B status of plant may limit fruit set, the goal of foliar B programs is, therefore, to increase B in flower buds (Wojcik *et al*. 2008). B sprays are often applied in early fall after harvest or during the pre-pink blossom stage of apple (Peryea 1994; Sánchez and Righetti 2005). Timing of B maintenance sprays is not critical for apple trees if the trees already contain adequate amounts of B, and do not show visual evidence of B insufficiency (Peryea *et al*. 2003).

Foliar spray of both macro- and micronutrients in a wide range of crops has been reported effective with respect to growth, yield, quality, and shelf life. These include: 1.5% urea (Kannan *et al*. 2002), urea-double superphosphate – K_2SO_4 at 0.50% each (Govind and Singh 2003) in citrus; 1% KCl (foliar spray) – 50 kg K_2O ha^{-1} (soil application) in groundnut (Umar *et al*. 1999); 1% NPK (foliar spray) = 50 kg N – 30 kg P ha^{-1} (soil application) in wheat (Arif *et al*. 2006); foliar spray of 2% urea – 2% potassium nitrate – 2% muriate of potash in cotton (Brar and Brar 2004) 0.50-1.0% KCl – 100 mg L^{-1} GA_3 in grape (Niu *et al.* 2008); 0.32-0.65% B (Dutta 2004), 0.50% B (foliar spray) – 5 kg ha^{-1} borax (soil application) in litchi; (Dutta *et al*. 2000) 0.50% Fe-DTPA (Álvarez-Fernández *et al*. 2004) in pear; 0.25% B (foliar spray) – 5 kg borax ha^{-1} (soil application) in cauliflower (Singh 2003); 0.5% $ZnSO_4$ (Sarma *et al*. 2005), 0.50% $ZnSO_4$ – 0.10% NAA (Sharma *et al*. 2005) in cabbage; $FeSO_4$-$CuSO_4$-$ZnSO_4$ at 0.40% each (Samant *et al*. 2008), 0.50% $ZnSO_4$- 0.10% borax (foliar spray) – 200 N – 50 P – 400 K kg ha^{-1} (soil application) in banana (Jeyabaskaran and Pandey 2008); $FeSO_4$ – $MnSO_4$ – $CuSO_4$ – $ZnSO_4$ at 0.10% each (foliar spray) – 150 N – 90 P – 90 K kg ha^{-1} (soil application) in tomato (Guvenc and Badem 2002; Bhatt and Srivastava 2006); 0.50% urea (Charbaji *et al*. 2008) in onion; 0.80% NPK (foliar spray) – 50 kg N – 50 kg P – 25 kg ha^{-1} (soil application) in green chilly (Baloch *et al*. 2008); and 0.60% $Ca(NO_3)_2$ – 0.80% KH_2PO_4 (Peyvasi *et al*. 2009) in tomato.

Efficacy of foliar sprays

The cuticle plays an important role in absorption of foliar applied nutrients. Reducing the urea solution pH from 8.0 to 4.0 decreased the amount of urea penetrating the cuticle (Orbovic *et al*. 2001). It consists of an insoluble biopolymer matrix (cutin and/or cutan) with waxes both embedded (intra-cuticular) and deposited on the surface (epicuticular) (Matas *et al*. 2005). Cuticles have been shown to be permeable to water and ions, and also to polar compounds, e.g. cuticles are 10-20 times more permeable to urea than inorganic ions (Kersteins 2006; Schreiber 2006). A high cuticular affinity also exists between various micronutrients viz., Mn, Cu, and Zn, which decreased in the following order: Cu > Zn > Mn. Cu reduced the cuticular retention of Zn, revealing high selectivity of Cu over Zn (Chamel and Gambonnet 1982). The cuticle is a chemically heterogenous membrane of variable structure and composition, depending on many factors (Jeffree 2006).

Two distinct cuticular pathways in the cuticle have been suggested (Schlegel *et al*. 2005; Schönherr 2006), viz., i) uncharged molecules dissolving and diffusing in lipophilic domains made of cutin and cuticular waxes (lipophilic pathway) and ii) ionic species crossing lipid membranes through aqueous pores (Schönherr *et al*. 2005), micropores, and spaces between molecules (Luque *et al*. 1995). While it is clear that surfactants increase spray droplet retention and wetting by lowering the surface tension, the effect of surface-active agents on the uptake of foliar sprays is very complex, and the underlying mechanisms are not fully understood (Liu 2004b). Some surfactants have also been shown to have a plasticizing effect, promoting the fluidity or even solubilzing cuticular waxes (Tamura *et al*. 2001; Perkins *et al*. 2005), while others may hydrate the cuticle and increase the permeability of the plasma membrane (Wang and Liu 2007; Bai *et al*. 2008).

Numerous other factors such as pH, the oxidation-reduction state, competing cations, hydrolysis, polymerisation, and the formation of insoluble salts (e.g. phosphate, oxalate, etc.) govern metal mobility within plant tissues (Eichert and Goldbach 2008). These factors account for differential concentration of nutrients due to selectivity behaviour of leaves arising either because the transport properties of each cell type allow them to absorb only particular nutrients from the transpiration stream or because each nutrient moves along a different pathway in leaf and so is only available to certain cell types (Karley *et al*. 2000).

This is very important where multi-nutrient spray is employed at an early growth stage. Under such conditions, it is necessary to reach a compromise between early application and allowing the crop to attain a leaf area large enough to effectively absorb the applied nutrients. For example, maximum accumulation of K in leaf takes place by the end of the fruit set stage, thereafter the rate of nutrient accumulation by leaf is considerably slow (Srivastava and Singh 2006). Therefore, foliar application of nutrients in perennial crops unlike annual crops, must be restricted up to the period as long as wax deposition on leaf cuticle has concentrated enough to restrict any foliar absorption of nutrients (Fernández and Ebert 2005), whereas in annual crops, such conditions are not common (Guvenc and Badem 2002;

Matas *et al*. 2005; Peyvasi *et al.* 2009).

Better efficiency of foliar-applied nutrients can be obtained only when there is a maximum concentration of root absorbed nutrients. For example, Swietlik and Zhang (1994) observed foliar sprays of Zn less effective than Zn application to the roots in alleviating severe Zn-deficiency in sour orange, because foliar absorbed Zn was not translocated from the top to the roots. The study further suggested the involvement of two mechanisms operating at two tiers of structural organisation: one in the roots and the other in the shoots. An unequal amount of a given nutrient absorbed by a crop from a deficient soil is often related not only to different nutrient requirements within the vegetative tissues, but to the kind and extent of root development (Swietlik 2002). Foliar treatment with Fe-containing solutions induced significant changes in concentration of several nutrients as compared to those found in Fe-deficient peach (*Prunus persica* L. Batsch) leaves, with changes being similar in treated and untreated leaf areas. These results indicated that some leaf mineral composition changes typical of chlorotic leaves and dependent on leaf Fe-concentration rather than on leaf chlorophyll content (Fernández *et al*. 2008).

ORGANIC MANURING

Use of commercial fertilizers has only a short history compared to the length of time that man is known to have grown crops. Organic sources play a critical role in both short-term nutrient availability and long-term maintenance of SOM, especially in smaller holder farming systems (Pang and Letey 2000). Despite this importance, there is little predictive understanding for the management of organic inputs in different agrosystems (Palm *et al*. 2001). Crop yields are a fundamental factor of economic success and depend very much on N fertilization (Pang and Letey 2000). Before making use of imported fertilizers, assessing the physical and biological condition of the soil and optimizing the level of OM are the methods preferred in organic farming to solve nutrient deficiency problems (Mader *et al*. 2002). A crucial question is how to guarantee optimum nutrition along with production on a sustained basis by organic measures only (Rynk 2002).

Studies carried out by Singh *et al*. (2009) using ginger (*Zingiber officinale* Rosc.) as test crop suggested the best response of treatment involving FYM (3.3 Mg ha^{-1}) – Indian beech tree (*Ponngamia pinnata* L.) – oil cake (0.03 Mg ha^{-1}) – neem (*Azadirachta indica*) oil cake (0.l83 Mg ha^{-1}) – Sterameal (0.83 Mg ha^{-1}) – rock phosphate (0.83 Mg ha^{-1}) – wood ash on Entisol soil type while another study by Sankar *et al*. (2009) on onion (*Allium cepa* L.) suggested that the combination of cow urine (3%) – FYM (supplying 50% RDF, i.e. 750 kg N ha^{-1}) – PM (50% RDF i.e. 750 kg N ha^{-1}) – biofertilizers (AB, PSM and AM at 5 kg culture ha^{-1} each) produced the highest bulb yield over exclusive use of inorganic fertilizers on equivalent basis.

Manures applied to soil improve its quality by altering the chemical and physical properties, increase OM content, water holding capacity, overall diversity of microbes, provide macro- and micronutrients essential for plant growth and suppress diseases with indirectly contribute to plant growth enhancement (Scheurell and Mahaffe 2004; Heather *et al.* 2006). Certain microorganisms present in compost and compost extracts such as *Trichoderma*, *Rhizobacteria*, and fluorescent *Pseudomonas* are known to stimulate plant growth (Sylvia 2005). These microbes benefit plants through different mechanisms of action including the production of secondary metabolites such as antibiotics and hormone-like substances, the production of siderophores, antagonistic to soil-borne root pathogens, phosphate solubilization, and nitrogen fixation (Dubeikovsky *et al.* 1993). Such composts having microbes of twin utility hold more promise in INM package.

Substrate dynamics

Consistent efforts are being made to find alternatives to conventional fertilizers, media and practices, although chemical properties of formulated substrates may affect plant growth and nutritional response in varied ways viz., i) improvement in soil hydraulic properties, ii) maintenance of better available pool of nutrients, and iii) establishment of dynamic soil microbial environment, more suited to crop requirement (Dutt *et al.* 2002; Altland and Buamscha 2008). The origin of a substrate and its pH are considered two most important guiding principles in developing a substrate dynamic to plant's rhizosphere in addition to physical stability, ease in rewetting ability to withstand compression, and low shrinkage rate over time (Roose and Haase 2000; Altland 2006). Dutt and Sonawane (2006) observed excellent performance of chrysanthemum (*Chrysanthemum indicum* L.) on a substrate containing cocoa-peat-compost-rice husk. Recently, studies (Buamscha *et al*. 2007; Altland *et al.* 2008) documented that DFB (Douglas Fir Bark) alone provided sufficient micronutrients for annual vinca (*Catharanthus roseus* L.) grown at low pH (4.6-5.5) while Hernández-Apaolaza *et al.* (2005) suggested that the use of pink bark in coconut (*Cocos nucifera* L.) coir-based media formulations served as one alternative of recycling waste materials. Fisher *et al*. (2006) suggested peat-based substrate treated with lime to adjust pH within an optimum range.

Coir dusts with a particle size distribution similar to peat showed comparatively higher aeration and lower capacity to hold total and easily available water. An air-water balance similar to that in peat became apparent in coir dust at a comparatively lower coarseness index (29% vs. 63% by weight in peat). Stepwise multiple regression analysis showed that particles with diameters in the range of 0.125 to 1 mm had a remarkable and highly significant impact on the physical properties studies, while particles < 0.125 mm and > 1 mm had only a slight or non-significant effect (Abad *et al.* 2005).

Four types of media [coir, 1 coir: 2 peat (by volume), peat, and sandy loam soil] were evaluated by Merhaut and Newman (2005) for their effects on plant growth and nitrate (NO_3^-) leaching in the production of oriental lilies (*Lillium* L.) 'Starfighter' and 'Casa Blanca'. Results indicated that the use of coir and peat did not significantly influence plant growth (shoot dry weight) relative to the use of sandy loam soil. However, substrate type influenced the amount of NO_3^- leached through the media and N accumulation in the shoots for 'Starfighter', but not for 'Casa Blanca'.

Various recipes for potting mixes exist that do not contain synthetic components (Kuepper and Adam 2003; Salifu *et al*. 2006). Koller *et al*. (2004) used several plant- and animal-based substrates in the production of vegetable transplants. They stipulated that plant-based substrates should be mixed into the potting medium 2 weeks before sowing seed to prevent damage. Worm castings of EF have been tested as a component of media for organic production to tomato, and it was found that seedling development improved as percent of worm castings in the medium increased (Ozores-Hampton and Vavrina 2002). Regardless of their origin these materials and practices are generally referred to as being alternatives to conventional fertilizers, media, and practices. To be accepted as commonplace in the industry, alternative materials and practices must be compared to existing conventional materials and practices (Russo 2005).

For example, a typical substrate tested in azalea (*Rhododendron atlanticum*) and camellia (*Camellia japonica*) (Merhaut *et al*. 2006; Blythe *et al*. 2006) consisted of 5 sphagnum peatmoss; 4 pine bark (6.7-9.5 mm): 1 washed builders sand (by volume); amended with dolomite 65 at a rate of 0.59 kg m^{-3} and ultrafine calcium sulfate at a rate of 0.59 kg m^{-3}, mixing the substrate and amendment. The nutrient composition (mg L^{-1}) was observed as: 1306 Ca, 019 Mg, 2.62 Fe, 0.59 Mn, 0.75 Zn, 0.11 Cu and 0.01 Mo. The substrate was later mixed with different controlled release fertilizers, CRF viz., Omocote (24-4-9), Nutricote (18-6-8), Multicote (17-5-11 + minor nutrients), and Polyon (17-5-11 + micro nutrients), all having 365 days release formulations in terms of highly acidic pH and particle size distribution.

Crop residue is another option to be used as a strong support to substrate in any INM programme. For example, in India, crop residues available are estimated to be 600 million Mg. Rice and wheat are two major crops, generating around 250 million Mg of residues (Selvakumar *et al.* 2008). Decomposing paddy straw is a problem because it contains approximately 40% cellulose, 20% hemicellulose and 12% lignin, and has high C: N. Several strains of mesophilic and thermophilic microorganisms were screened for utilization of paddy-straw. Four fungi, *Phanerochaete sporium*, *T. viride*, *Aspergillus nidulus*, and *A. awamori* were identified by Selvakumar *et al.* (2008) to carry out solid state fermentation of paddy straw; all combinations were good. The process involved construction of perforated brick tanks for proper aeration for composting of paddy-straw. The straw was supplemented with poultry droppings (8: 1) or urea at 0.5% to bring down the C: N ratio of the straw. A tank of 1 m^3 can accommodated 80 kg of straw. Rock phosphate (1%) along with inoculum containing 4 fungi was applied at 0.5 kg ton^{-1} straw and mixed in the tank. Moistened paddy with sufficient water, and within 2-3 months, compost with a C: N ratio of 15: 1 can be successfully obtained. Such an attempt needs to be replicated using other crop residues as substrate. Siddiqui *et al.* (2008) observed that the application of *T. harzianum*-inoculated rice straw compost not only improved the morpho-physiological characters of okra but reduced the wet rot incidence compared to control, and offered an environmentally friendly alternative to inorganic fertilizers/fungicides, resulting in higher yield.

Coinoculation or combined inoculation of different microbe types is another area which can be gainfully exploited in formulating the microbially-rich substrate, provided that information on the synergism between different microbes is known (Marschner *et al.* 2004). In the past, a number of studies have suggested the coinoculation of different microbes, which can be summarized as: *A. brasilense* – *P. striata*/*B. polymyxa* in sorghum (Alagawadi and Gaur 1992), *A. lipoferem* – *Agrobacterium radiobacter*/*A. lipoferem-Arthrobacter mysorens* in barley (Belimov *et al.* 1995), *A. brasilense* – *Rhizobium* in lentil (Yadav *et al.* 1992) and chickpea (Fabbrie and Del Gallo 1995), *A. brasilense* – *A. chroococcum* – *Klebsiella pneumoniae* – *R. meliloti* in alfalfa (Hassouna *et al.* 1994), *A. brasilense* – *R. leguminosarum* in soybean (Neyra *et al.* 1995), and *A. brasilense*/*Streptomyces mutabilis* – *A. chroococcum* in wheat (Elshanshoury 1995). Many studies on coinoculation of microbes involving AM fungi and bacteria have also been suggested for improvement in both yield and quality. These include: *A. brasilense* – *G. fasciculatum* in wheat (Gori and Favilli 1995), strawberry (Bellone and de Bellone 1995); *A. brasilense* – *Pantoea dispersa* in sweetpepper (Amor *et al.* 2008); and *A. chroococcum* – *G. mosseae* in pomegranate (Aseri *et al.* 2008).

Various steps involved in preparation of dynamic substrate has been further depicted through a flow diagram (**Fig. 2**) in fulfilling rhizosphere's diverse requirements.

Cover crops/intercrops

Use of cover crops is an important component of INM where a series of cover crops viz., annual yellow sweet clover (*Melilotus indica*), Canada field pea (*Pisum arvense*), Colorado river hemp (*Sesbania microcarpa*), common

Substrate Dynamics

↓

Isolation and characterization of rhizosphere soil collection from farm growing wide range of crops

↓

Partitioning of microbial population from farms of differential productivity with reference to specific crop

↓

Identification of microbe type contributing high productivity

↓

Isolation of dual purpose microbe (e.g. *Pseudomonas fluorescens, Trichoderma viride / harzianum*, *Glomus* sp., etc.) to meet two ends, one having the ability for mobilising the soil unavailable pool of nutrients, and another with antagonistic effect against soil borne diseases (e.g. *Phytophthora* causing root rot diseases including gummosis)

↓

Loading such dual purpose microbes in suitable substrate of organic origin (e.g. farmyard manure or any crop residue)

↓

Preparation of substrate of varying chemical and microbial composition using preferential microbial loading

↓

Evaluation substrate with reference to transformation and availability of nutrients, yield, quality and shelf life

↓

Multi-location appraisal for rhizospheric changes and crop responses for large scale recommendation

Fig. 2 Steps involved in developing microbially enriched substrate.

vetch (*Vicia sativa*), cowpea (*Vigna unguiculata*), crotolaria (*Crotalaria striata*), Egyptian clover (*Trifolium alexandrinum*), hairy indigo (*Indigofera hirsuta*), Natal grass (*Tricholaena rosea*), purple vetch (*Vicia atropurpurea*), rape (*Brassica napus*), small seeded broad bean (*Vicia faba* var. minor), tangier pea (*Lathyrus tingitanus*), trieste mustard (*Brassica juncea*), velvet bean (*Mucuna utilis*), white mustard (*Brassica alba*), cowitch (*Macuna pvuriens*), Asian ticktrefoil (*Desmodium heterocarpon*), yellow peanut (*Arachis pintoi*), green round leaf pea (*Chamaecrista rotundifolia*), centurion (*Centrosoma pascuorum*), and babuia (*Centrosoma brasiliancum*) have been suggested through a large number of studies (Lichtenberg *et al.* 1994; Bradshaw and Lanini 1995; Hartwig and Ammon 2002; Isaac *et al.* 2007; Tanimu *et al*. 2007). These cover crops have shown multiple responses in terms of yield improvements; weed suppression; and improvements in soil water conservation, soil hydraulic properties, and soil fertility. Cover crops are further classified on the basis of their functions such as smother crops (used to suppress weeds), catch crops (used to reduce leaching losses of nutrients), green manure crops (sown annually and incorporated into soil prior to maturation), and insectary crops (used for attracting beneficial anthropods).

1. Cover crops and changes in soil properties

Mineralization of N was highest in *Sesbania rostrata* followed by rice straw, and FYM while rice straw caused N immobilization during the initial period of incubation (Samarah and Bordoloi 1994). Mahler and Auld (1989) observed that winter wheat yield averaged 6.6, 6.4, and 6.3 Mg ha^{-1} with green manure pea, seed pea, and summer fallow with N fertilizer equivalent of 94, 75, and 68 kg ha^{-1}. Many green manure crops furnish a succeeding rice crop with N equivalent of 50 to more than 100 kg fertilizer N ha^{-1}. In the long run, green manuring has more important effects on soil properties than the ability to supply N (Bouldin 1988; McVay *et al*. 1989; Decker *et al*. 1994; Sainju *et al*. 2007). In a comparatively recent study, Matos *et al.* (2007) observed that pineapple with cover crops as Bermudagrass (*Cynodon dactylon*) and pearl millet (*Penniselum americanum*) showed no depletion in soil fertility than without these cover crops. In another study, Tanimu *et al*. (2007) observed significantly ($p<0.05$) higher soil fertility induced yield of maize on plots earlier grown leguminous crops such as green round leaf pea (*Chamaecrista rotundifolia*), centurion (*Centrosoma pascuorum*) and babuia (*Centrosema brasilianum*) than plots without leguminous crops. Recently, Ganeshamurhty and Srinivasarao (2009) observed that sustained use of pulses in the field triggered the multiplication capacity of earthworms, thereby helped in improving soil quality parameters.

Cover crops known as green manures, are grown and incorporated (by tillage) into the soil before reaching full maturity, and are intended to improve soil fertility and quality. The supply of readily metabolizable C through organic manuring is likely to have been the most influential factor contributing to the biomass C increase (Ros *et al*. 2003) and influence on root biomass (Sainju *et al*. 2001). According to earlier studies (de Neve and Hofman 2000), SMB responded rapidly to addition of readily available C through cover crop residues. The positive effect on SMB (Pascual *et al.* 1998) observed in soil amended with compost is due to direct (microbial growth in these manures and indirect effect (improved plant growth).

Cover crops have the potential to increase C sequestration, organic matter, soil aggregation, water infiltration capacity, water holding capacity and root growth of crops. A crop of cotton intercropped with legume (crimson clover, *Trifolium incarnatum*) returned 9-32% higher C within 15 cm of Plinthic Kandiudult soil type than cotton with non-legume cover crop (rye as *Seaele cereale* L.). Soil active C pools varied between summer and winter due to differences in temperature, moisture, and substrate availability in dryland cotton. In irrigated cotton, lower C/N ratio of legume cover crops increased C mineralization in the spring, but greater residue C from legume and non-legume cover crop mixture and succeeding cotton increased soil C storage (Sainju *et al.* 2007). Additionally, incorporation of organic amendments to soil influences soil enzymatic activities, because added material contained intra- and extracellular enzymes, and stimulated microbial activity in the soil (Pascual *et al.* 1998). Even citrus pulp as an amendment has shown improvement in soil quality parameters in terms of SMB and stimulation in EA of alkaline phosphatase, glucosidase, and arylsulphatase (Meli *et al*. 2007).

Evaluation of different cover crops in vineyards showed that cover crops viz., crested wheatgrass (*Agropyron cristatum* L.), pubescent wheatgrass (*Elytrigia intermedia* L.), and perennial rye (*Lolium perenne* L.) depleted soil water least with minimum effect on leaf water potential (Olmstead *et al*. 2001) and improvement in SMB (Ingels *et al*. 2005). Organic mulches provide slow release nutrients for the long-term health and fertility of soil, besides enhancing soil aggregation and water holding capacity upon decomposition. Out of many legume crops tested on well- and poorly-drained soil types, *Indigofera hirsuta* produced the highest dry matter (10.4 Mg ha^{-1}) in well-drained sandy soil compared to pigeonpea, *Cajanus cajan* and rattle bush, *Crotalaria mucronata* (10 Mg ha^{-1}) in poorly-drained clay soil (Anderson 1980). A comparison of treatments involving: i) incorporation of the whole of the faba bean-rye green manure crop into the soil when 30% of its flowers were open; ii) permanent soil cultivation; and iii) burrying the organic part of the green part remaining after the harvesting of aerial parts showed that, though structural stability, organic content, and the C/N ratio of the soil in all treatments were similar, but the infiltration rate was highest in treatment consisting of burying the underground part after harvest of the aerial part (MacRae and Mehuys 1985; Sarker *et al.* 2003).

Response of vermicompost

Vermicomposting is the bio-oxidation and stabilization of organic matter involving the joint action of earthworms (Oligochaete annelids) and microorganisms (Aira *et al.* 2007), thereby, turning wastes into a valuable soil amendment called VC. The compost is rich in both macro- and micronutrients, N fixers, and humus-forming microorganisms (Bano *et al.* 1987), besides acting as a bioconcentrator of heavy metals and toxic substances (Edwards and Thompson 1973). Vermicomposting could be developed and applied as a useful tool for profitable utilization of organic wastes for: i) organic pollution retardant by rapid reduction of bulk and elimination of offensive odor, ii) production of vermi-fertilizer for application in both annual as well as perennial crops for providing efficient nutrition, and iii) production of earthworm tissue systems for large-scale proliferation. Native earthworm species which are surface feeders, easy to breed, and responsive to improved cultural techniques, are ideal for vermicomposting (Bugg 1994; Wang *et al*. 2007).

Chemical, microbial, and growth regulator analysis of earthworm casts by Grappelli *et al*. (1985) showed that these casts have nearly neutral soil pH (6.5) with 51.60% water content, 16.78% total C, 1.37% inorganic C, 1.63% total N, 0.40% NO_3-N , 0.92% total PO_4-P, 0.14% available PO_4-P, 1.61% K_2O, 8.60% total Ca, 0.14% available Ca, 2.51% total Mg, 0.45% available Mg, 910.10 mg kg^{-1} Fe, 218.40 mg kg^{-1} Mn, 7.20 mg kg^{-1} Cu, 0.35 mg kg^{-1} B, 68.30 mg kg^{-1} Zn, 1.8×10^8 cells g^{-1} bacteria, 2.8×10^6 cells g^{-1} actinomycetes, 2.0×10^5 cells g^{-1} fungi, 2.75 μm g^{-1} GA_3, 1.50 mm g^{-1} cytokininns (inole pyruvic acid), and 3.80 μm g^{-1} IAA on a dry weight basis. Studies later suggested an enrichment technique of vermicompost with *Azotobacter chroococcum*, *Azospirillum lipoferum*, and *Pseudomonas striata* for improved solutilization of rock phosphate (Kumar and Singh 2001; Kumari and Kumari 2002). Biochemical properties of

Table 4 Bioconversion efficacy of commercially exploited earthworm species.

Earthworm species	Macronutrients (%)			Micronutrients (ppm)			
	N	P	K	Fe	Mn	Cu	Zn
Initial							
EF	1.82	0.07	0.64	4321.0	310.4	36.1	34.6
EE	1.80	0.06	0.70	4442.1	290.6	39.2	29.2
LM	1.76	0.06	0.68	4396.4	298.0	38.1	30.1
PE	1.72	0.07	0.70	4398.2	302.1	40.2	30.6
40 days							
EF	2.36	0.08	1.09	4822.0	359.6	46.1	92.7
EE	2.20	0.07	0.90	4843.1	361.6	42.6	44.8
LM	1.92	0.07	0.72	4499.3	309.8	39.1	41.2
PE	2.02	0.08	0.96	4539.6	358.9	45.0	46.8
80 days							
EF	2.61	0.10	1.32	5816.0	398.2	49.8	103.6
EE	2.41	0.08	1.12	5019.3	400.6	48.1	58.2
LM	2.01	0.08	0.80	4520.6	319.8	40.8	43.9
PE	2.16	0.09	1.01	4628.1	371.8	47.9	52.9
120 days							
EF	2.72	0.13	1.56	6982.0	422.8	56.8	132.8
EE	2.58	0.12	1.38	5218.1	406.1	49.6	69.2
LM	2.12	0.10	0.92	4618.1	323.8	41.0	48.7
PE	2.38	0.10	1.12	4823.0	381.1	46.4	58.1

Source: Gupta and Srivastava 2005

EF: *Eisenia foetida*, EE: *Erudrilus eugineae*, LM: *Lampito mauritil*, PM, *Perionyx excavatus*

vermicompost showed that activity of cellulolytic enzymes was higher in casts than in soil, while activities of urease, protease, and phosphatase were lower in worm casts than undigested soil (Zhang *et al*. 2000). These observations suggested that earthworms use microorganisms as a secondary food resource (Zachariah and Chhonkar 2004; Zhang *et al*. 2004).

Earthworm activity and changes in soil properties

Native species of earthworms viz., *Lampito mauritil* (LM), *Perionyx excavatus* (PE), *Drwida wilsii* (DW), *Eisenia foetida* (EF), and *Eudrilus eugineae* (EE) were found to be efficient for vermicomposting (Sarkar 1994). Use of native worms with high bio-efficiency and productivity proves to be more field-worthy and effective in a limited bio-kinetic zone. Various studies (Edwards and Lofty 1982; Haines and Uren 1990) reported smaller earthworm population in cultivated than non-cultivated soils.

Four commercially exploited earthworm species viz., EF, EE, LM, and PE were evaluated for bioconversion ability of animal dung to mature vermicompost with reference to changes in nutrient concentration (**Table 4**). EF induced maximum magnitude of improvement in nutrient concentration when compared the values at zero day (initial value) to values those obtained after 120 days of incubation. Different nutrients were increased in magnitude of, e.g. N by 1.49-fold, P by 1.85-fold, K by 2.43-fold, Fe by 1.61-fold, Mn by 1.36-fold, Cu by 1.57-fold, and Zn by 3.84-fold by EF. Contrary to these observations LM, the least efficient earthworm species improved the concentration of different nutrients viz., N by 1.20-fold, P by 1.66-fold, K by 1.35-fold, Fe by 1.05-fold, Mn by 1.09-fold, Cu by 1.08- fold and Zn by 1.62-fold. The multiplication capacity was also observed to be much higher in the case of EF compared to the remaining three earthworm species. At the end of 120 days of incubation the highest number of adults was observed in EF (1035) followed by PE (873), LM (644), and EE (551), thereby, suggesting the highest efficacy of EF both in terms of bioconversion efficiency and multiplication capacity (Gupta and Srivastava 2005).

Bugg (1994) reported about the involvement of earthworms in the process of nitrification. Influence of two species of earthworm viz., EF and EE was studied by Talashilkar *et al*. (1999) on the changes in chemical parameters governing the compost maturity of local grass, mango leaves, and farm wastes. A decrease in the C: N ratio and an increase in humic acid (HA), cation exchange capacity, and water soluble carbohydrate were observed up to 150 days of composting. In another study, Rao *et al*. (1997) observed considerable increase in available K extracted from the wormcasts over non-ingested soil, due to partial conversion of non-exchangeable K with exchangeable form, as a result of shift in soil K equilibrium.

The benefits of earthworms on soil physical conditions are well documented (Atiyeh *et al*. 2001; Mota *et al*. 2007; Munnoi and Bhosle 2008). These benefits include: mixing of OM from the surface into lower soil horizons, improvement of aggregate stability through castings, and hydraulic properties of the soil through the creation of permanent burrows (Chan and Heenan 1992; Lee and Pankhurst 1992; Friend and Chan 1995; Trojan and Linden 1998). Munnoli and Bhosle (2008) observed that microbes in 1 g of pressmud derived vermicompost with 100×10^9 cfu g^{-1} held 200 g of soil in position. The actual beneficial effect varies with different species of earthworms (Lee 1985). The exact reason is not clear, but this could be due to the higher organic C levels and better drainage found in the burrowed clays (Chan *et al*. 1988). The higher organic C levels provide a larger food reserve, making it possible to support a larger number of earthworms and better drainage of water within the soil profile. Cast production can be as high as 50 Mg ha^{-1} $year^{-1}$ (Lal and De Vleeschauwer 1982). In both temperate and tropical regions, the wormcasts have more favourable soil conditions for plant growth (Lal and Akinremli 1983) while, there have been evidences of favourable effect of earthworm activity on the availability of N and P in the soil, relatively less is known about its effect on the behaviour of K. Zaller (2006) suggested vermicompost extract very effective as foliar spray in field grown tomato.

In Vertisols, large and deep macropores exist in two forms viz., temporary macropores in the form of cracks that close up when the soil is wet and swells, and more permanent macropores created by earthworms and plant roots which remain open when wet (Bridge and Ross 1984). According to Line (1994), significant improvement in water holding capacity and aeration of soil were obtained in soil treated with earthworms composted with a mixture of wool wastes of *Eucalyptus* with seaster (*Aster alfinus*, a common European aster that grows in salt marshes) wastes in 3: 1 (bark: seaster) or 4: 1 (sawdust: seaster) ratio, due to greater earthworm population forming extensive vertical burrow systems in the surface 20 cm soil depth (Carter *et al*. 1994).

Dhawan and Kide (1994) studied changes in CEC during 120 days of composting of sugarcane trash and cowdung slurry and which showed an increase in CEC of the composted product from 37.1 to 122.6 cmol (p^+) Kg^{-1} after 120 days of composting. Similar observations were made by Manna *et al*. (1994) who observed an increase in CEC of the crop residues inoculated with vermicompost for a period of 180 days. The faster mineralisation of organic matter due to earthworms activity resulted in an increase in water soluble carbohydrates content of the composted residues.

Earlier, many studies (Tiwari *et al*. 1989; Hullegalle and Ezumah 1991) under field conditions and under controlled conditions (Mulongoy and Bedoret 1989; Basker *et al*. 1993) have shown greater effect of earthworm activity on the available K in cast soil as compared with the surrounding soil. Another way by which earthworms influence K nutrition is through their seasonal vertical migration, which brings K from the K-rich horizon of sub-soil to the surface soil in the rooting zone. A considerable increase in the K extracted by different extractants from the wormcasts was observed over non-ingested soil. Higher K release constants (a) were recorded for the casts than non-ingested soil (Rao *et al*. 1997). An agronomic response of vermicompost has been observed in crops like ginger (Vastrad *et al*. 2002); tomato (Atiyeh *et al*. 2001; Azarmi *et al*. 2008); spinach, potato, turnip (Upadhyay *et al*. 2003; Alam *et al*. 2007; Ansari *et al*. 2008); okra (Gupta *et al*. 2008); sorghum (Reddy and Ukhura 2004); and carrot (Alam 2005), suggesting vermicompost as a composite nutrient source.

PM treatment

PM is one of the promising bulky OMs, and if handled properly, is the most valuable of all manures produced by livestock (Henuk and Dingle 2003). It has historically been used as a source of plant nutrient and soil amendment as well. The nutrient value of PM varies considerably (1.60-3.03% N, 1.00-2.63% P_2O_5, 1.20-2.30% K_2O, 2.10-6.15% Ca, 0.15-0.30% Zn, and 20-25 ppm B) depending upon the conditions under which it is processed (Zublena *et al*. 1993; Nicholson *et al*. 1996). A review of nutrient composition of different types of PMs viz., deep litter, broiler house, and cage manure showed a varying nutrient composition (1.70-2.20% N; 1.41-1.81% P, 0.93-1.30% K, 0.90-1.10% Ca, 0.45-0.68% Mg, and 90-308 ppm Zn) due to varying ratio of litter to manure and the moisture content (Amanullah *et al*. 2007).

1. Litter amendment

Aluminum potassium sulphate (Alum) as an amendment of poultry litters has been suggested as the best management practice to economically reduce the potential environmental effects (ammonia volatilization and soluble phosphorus in run-off water) of poultry production (De Laune *et al*. 2006). Past research has shown that alum treatment reduced NH_3 emissions from litters, decreased the loss in runoff of P and trace metals from litter-amended soils, improved poultry health, and reduce the cost of poultry production. Alum treatment decreased litter pH and the water solubility of P, As, Cu, and Zn (Warren *et al*. 2008). Alum-treated houses also had higher litter total N, NH_4-N, and total S concentration, and thus a lesser overall losses from litters (Gilmour *et al*. 2004; Staatt *et al*. 2004). While adding alum to poultry litter inhibited organic P mineralization during storage, and promoted the formation of alkaline extractable organic P that sustained lower P solubility in the soil environment (Warren *et al*. 2008) and P losses were reduced substantially (Moore and Edwards 2007). Thus, alum appears to have promise as a best management practice for high value PM production. Future research should focus on long-term transformation of P, Al, As, Cu, and Zn in soils amended with alum-treated litters (Sims and Luka-McCafferty 2002; Moore and Edwards 2005, 2007).

2. Composting PM

Composting or the biological degradation of organic wastes has been investigated as a method of stabilizing poultry litter and manure prior to application in soil. This process of composting produces a material with several distinct advantages over other bulky manures. The high level of dehydrogenase activity in the soil treated with PM suggested the availability of high quantity of biodegradable substrates (in agreement with higher content of labile C in these soils) and hence, an improvement in their microbial activity (Tejada *et al*. 2006). Parameters like dehydrogenese activity (Tiquia 2005), dissolved OC (Mez-Branda *et al*. 2008), and an integrated use of chemical, thermal, and microbiological properties (Mondini *et al*. 2008) have been suggested as reliable indices for assessing compost stability.

The method of composting significantly influenced the nutrient value of manure. Kirchmann and Witter (1992) reported a C: N ratio of 17.9 and 11.7, respectively, in anaerobically and aerobically decomposed PM while another study by Sims *et al*. (1992) observed a C/N ratio of 18.3 in anaerobically composted PM suggesting the superiority of the latter type of manure. The effect of aerobic composting time for changes in micronutrient composition (Fe, Mn, Cu, and Zn) suggested a hint for immobilization of Mn and Zn with respect to water extraction and of Cu and Fe with respect to acid (1 N nitric acid) extraction and increased lability of Mn and Zn to acid extraction after composting (Ihnat and Fernandes 1996). Composting poultry litter under anaerobic conditions helped to greater recovery of final product and negligible loss of nutrients, particularly N (Kirchmann and Witter 1989). The agronomic efficiency of manure can further be improved by composting with rock phosphate (phosphocompost) and elemental sulphur (sulfocompost) according to Mahimairaja *et al*. (1995). The enhanced use of bioinoculum in combination with chemical amendments accelerated the compost maturity and shortened the usual period of composting (Manna *et al*. 2000; Silva *et al*. 2009). Thompson (2004) observed that total recovery of ^{15}N from winter applied PM averged 56% under barley-ryegrass sequence.

Atkinson *et al*. (1996) suggested that different N compounds and nutrients are recycled rather than fixed during composting of poultry litter. Volatilisation loss of N is the major constraint during the process of open air, anaerobic or aerobic composting (Mahimairaja *et al*. 1994). Conservation of N was found to be better under anaerobic storage conditions (Kirchmann and Witter 1989). These authors reported lower losses of N under anaerobic conditions but higher under aerobic conditions. Wolf *et al*. (1988) found that 37% of total-N in surface-applied PM was volatilized in 11 days, which significantly reduced the amount of N available for plant uptake while Bitzer and Sims (1988) reported that 69% of organic N in PM mineralized in 140 days in a sandy soil, but volatilization took place instantly up on incorporation. The C: N ratio of composted PM is reported to be as low as 7.9 (Kirchmann and Witter 1992), 9.7 (Nadar *et al*. 1992), and 6.3 (Nicholson *et al*. 1996) depending upon the duration of composting and other prevailing conditions. de Laune *et al*. (2006) observed that composted poultry litter, regardless of treatment, had higher P concentration than fresh poultry litter and reduced the N: P ratio by as much as 51%.

3. Manuring and changes in soil properties

Manure is considered very effective in remediation of degraded soils (Khaleel *et al*. 1981) and in meeting the plant nutrient requirement Fisher 1992). Consequently PM has shown superiority over many other conventionally used manures in improving different soil quality parameters (Giardini *et al*. 1992; Pimpini *et al*. 1992; Agbede *et al*. 2008). Much of the N content of PM is in stable organic form which is converted into inorganic plant available N in several years (Mondini *et al*. 1996). Field evaluation of N availability from fresh and composted PM showed a much higher available N index value from composted manure (Muñoz *et al*. 2008). Past studies (Gales and Gilmour 1986; Chescheir *et al*. 1986) suggested that immobilization was responsible for reducing inorganic N shortly (1-2 weeks) following the application of poultry waste.

Mullins (2002) observed poultry litter and bedding material to be very useful in improving the pH of acidic soil due to varying amounts of $CaCO_3$ present in poultry feed. Giardini *et al*. (1992) reported that PM treatment significantly decreased bulk density and increased total microporosity, infiltration capacity, and available water capacity. Overall efficiency of OMs with respect to native plant nutrient availability in an acid Alfisol showed the following trend: PM > pig manure > FYM. Other soil properties such as pH, humic, and fulvic C contents showed differential patterns with nutrient availability at different intervals. The contribution of HA towards nutrient availability was highest under low organic matter status soil; while in case of high organic matter status soil, fulvic acid showed the maximum positive correlations (Madhumita Das *et al*. 1991).

Studies carried out by Tejada *et al*. (2006) showed that enzyme activity from PM-amended Calciorthid soil was 5, 15, 13, 19, 22, 30 and 6% greater than cotton gin compost-amended soil for SMB, urease, protease, β-glucosidase, alkaline phosphotase, arylsulfatase, and dehydrogenase activities, respectively. Application of FYM (18 Mg ha^{-1}) or PM (10 Mg ha^{-1}) produced the highest rhizome yield (38.3-39.3 Mg ha^{-1}) of turmeric (*Curcuma longa* L.) compared to control (19.4 Mg ha^{-1}) on Alfisols (Sanwal *et al*. 2007).

Crop response

Poultry manure showed a high magnitude of response on different growth and yield attributing parameters in addition quality in a wide range of crops. These crops include: tomato (Argerich 1998), jute (Adenawoola and Adejero 2005), pumpkin (Awodun 2007), sorghum (Agbede *et al*. 2008), soybean (Chiezey and Odunze 2009) and wheat (Petric *et al*. 2009). These responses suggest PM is another equally nutrient-rich source holding strong potential in INM.

INTEGRATION OF INM COMPONENTS

Organic versus inorganic fertilization

Irrespective of the mode of any nutrient management, fertilizers act exactly in the same way as nutrient from organic sources in soil, since they are chemically the same (Srivastava *et al*. 2002). The plant itself cannot discriminate where the nutrient is coming from (Trewaves 2001). Many studies in the past have not supported any of the two philosophies (organic and inorganic fertilization) of meeting the nutrient requirement of a crop, either through exclusive use of organics or through inorganic chemical (synthetic) fertilizers (Bronick and Lal 2005; Wei *et al*. 2006). This has indeed warranted in-depth analysis to provide a sound scientific basis to support either of the two or a combination of two-philosophies. Inorganic chemical fertilizers due to their readily soluble nature, they are easy to blend and control rate, timing, uniformity, and frequency of application to meet nutrient needs in any crop type and provide a predictable response. On the other hand, OM, which although contain all nutrients, might not match the soil or crop needs, besides the uncertain timing and variable amount of nutrient release as a major constraint towards sustained response (Srivastava *et al*. 2008).

OM as amendment has been observed to increase soil respiration and level of soluble organic C, and SMB-C by a factor of 2-3 compared to the control whereas an inorganic N fertilizer had little effect on any of these, parameters. Total manure-derived CO_2-C was equivalent to 52% of applied stock piled manure-C and 67% of the applied rotten manure. Estimates of average turnover rates of microbial biomass ranged between 0.72 and 1.22 Mg $year^{-1}$, and were lowest in manured soils with large qualities of soluble C (Rochette and Gregorich 1998). Apart from microbial biomass changes, effectiveness of AM under chemical fertilizers versus biodynamic farming, was also influenced (Zaller and Köpke 2004).

Colonisation by AMF of white clover (*Trifolium repens* L.), perennial ryegrass (*Lolium perenne* L.), and paspalum (*Paspalum dilatatum* Poir.) was lower in conventionally managed pastures using chemical fertilizers than in the biodynamic pastures (Ryan *et al.* 2000). In another study, Zaller and Köpke (2004) in a experiment conducted on Fluvisol, evaluating the comparative effect of traditional and biodynamic FYM amendment in grass-clover- potatoes- winter wheat-field beans-spring wheat-winter rye crop sequence, observed that plots receiving either prepared or non-prepared FYM (30 Mg ha^{-1} $year^{-1}$) showed a significant increase in soil pH, P, and K concentration, microbial biomass, dehydrogenase activity, decomposition (cotton strips), earthworm cast production, and altered earthworm community composition than plots without FYM application. On the other hand, the biodynamic preparation of FYM with fermented residues of six crop plants (grass, clover, potato, wheat, bean, and rye) at the rate of 6 g Mg^{-1} FYM, significantly decreased soil microbial basal respiration and metabolic quotient compared to non-prepared FYM.

Manures blended with either mineral fertilizers or any organic residue have not only improved the available supply of nutrients in soil, but produced a residual effect as well, of course to a lesser magnitude than chemical fertilizers (Srikant *et al*. 2000). Application of Zn as Zn-enriched slurry and P-enriched manures maintained a higher level of Zn (Singhania *et al*. 1984) and P (Prasad and Singhania 1989) in soil solution for a longer period than fertilizer alone. Herencia *et al*. (2008) reported that the addition of vegetable compost did not cause a significant effect on the total nutrient content of the soil (Xerofluvent), but resulted in an increase in all extractable forms of micronutrients compared to soil with mineral fertilization.

An experiment conducted to determine the long-term (1994-1999) effects of dairy manure and chemical fertilizer on soil quality properties and C sequestration in an alfalfa (*Medicago sativa* L.) and orchard grass (*Dactylis glomerata* L.) forage systems showed that long-term application of dairy manure slurries significantly increased total organic, microbial biomass, potentially mineralizable, extractable and labile C pools, respectively, improved soil aggregate stability, decrease in SMRR, and subsequently produced an improved soil quality (Min *et al*. 2003; Bulter and Muir 2006). Relatively smaller amounts of total, microbial biomass, extractable and labile C pools with an increase in SMRR, and increase in soil acidity accompanied by a decrease in aggregate stability suggest that long-term and continuous use of inorganic fertilizers for crop production did not improve soil quality or enhance C sequestration (Anwar *et al*. 2006). In an another study, the effects of long-term addition of organic and inorganic fertilizer amendments at lower rates on soil chemical and biological properties showed that the organic amendments increased the C_{org} content of the soil, but had no significant effect on the dissolved organic C content. The C: N ratio was highest in the straw treatment and lowest in the mineral fertilizer treatment. Of the enzymes studied, only protease activity was affected by different organic amendments. Bacterial and eukaryotic community structures were significantly affected by C_{org} content and C: N ratio (Marschner *et al*. 2003).

While evaluating the long-term effect of cattle manure application on soil microbial population and community structures, Parham *et al*. (2003) observed that the richness and evenness of the bacterial community were enhanced by manure treatment. The treatments that included N and P were positively correlated with soil productivity. Pernes-Debuyser and Tessier (2004) suggested changes in soil water retention properties and soil stability as good indicators of long term manure treatment.

In another study, Peck *et al*. (2006) assessed the apple orchard productivity and fruit quality under organic (ORG), conventional (CON), and integrated management (INT). ORG crop yields were two-thirds of the CON and about half of the INT yields in 2002, but about one-third greater than either system in 2003. High but inconsistent ORG yields with smaller fruits were the result of several factors, including unsatisfactory crop load management, higher pest and weed pressures, lower leaf and fruit tissue nitrogen, and deficient leaf tissue Zn concentration. Despite production difficulties, ORG apples had 6-10 times higher flesh firmness and texture than CON, and 4-6 times higher than INT apples with equal or better overall acceptability, firmness, and texture. Neither laboratory measurements nor sensory evaluations detected differences in soluble solid concentration (SSC), titrable acid (TA) or the SSC: TA ratio. Consumers were unable to discern the higher concentrations of flavor volatiles found in CON apples. For a 200 g fruit, ORG apples contained 10-15% more TA than CON apples and 8-25% more TAA than INT apples. Across most parameters measured in this study, the CON and INT farm management systems were more similar to each other than either was to the ORG system. Despite limited technologies and products for organic apple production, the ORG apples showed improvements in some fruit quality (Peck *et al.* 2006). Reganold *et al.* (2001) earlier carried out qualitative assessment of different cultivation systems which revealed that the ORG system ranked first in overall sustainability, followed by INT, and last by the CON system.

Cavagnaro and Jackson (2007) compared available supply of different micronutrients under varying management practices. Soil data analysis indicated significant management effects on soil chemical properties: soil pH and soil exchangeable Na and Ca were higher on organic farms, whereas soil extractable Fe and Mn were greater on conventional farms. Even though there were no differences in soil extractable Zn, the concentration of Zn in fruits was significantly higher on a conventionally managed farm.

Besides appraisal on soil health assessment, quality of produce is another parameter that holds promise, especially when the impact or organic versus inorganic fertilization is evaluated. For example, nutritional quality differences between apple production systems have only been explored by Weibel *et al.* (2000), who found organically grown apples to have more polyphenols than those grown under an integrated fruit production system. Comparative studies (Carbonaro and Mettera 2001; Carbonaro *et al.* 2002) of antioxidants in other perennial horticultural crops showed higher concentrations of polyphenols and other antioxidants in organic pears (*Pyrus communis* L.) and peaches (*Prunus persica* L.). However, conventionally grown yellow plum (*Prunus domestica* L.) had higher concentration of polyphenols and quercetin than those grown organically, whereas other flavonoids and several vitamins were higher in organically grown fruits (Lombardi-Boccia *et al.* 2004).

Combined use of INM components

The studies carried out on INM have shown a strong influence of cropping sequence in mitigating declining soil fertility (Singh *et al.* 2008). In a long-term evaluation of INM-based treatment involving application of fertilizer nutrients (40 N - 8.73 P kg ha^{-1} for sorghum (*Sorghum bicolor* L.) and 8.73 P kg ha^{-1} for chickpea (*Cicer arietinum* L.) along with FYM, use of N-fixers (*A. brasilense* and *Rhizobium*), phosphate solubilizers (*Bacillus megaterium*), and VAM (*G. fasciculatum*) significantly increased the grain ($r = 0.618$, $p < 0.05$) and straw yields ($r = 0.602$, $p < 0.05$) and decreased the C: N and C: P ratios. The results suggested that for maximum crop yield, only 50% of the required fertilizer when supplemented with bioinoculants (Saini *et al.* 2004). A wide range of crops (**Table 5**), annual or perennial, have shown a high magnitude of response through different combinations of INM. These summarized results are more of interpretative than suggestive, affirming the practice leading to significant reduction in load on the use of inorganic chemical fertilizers under INM. Various components of INM

Table 5 INM recommendations for different horticultural crops.

Crop	INM recommendations
Banana (*Musa paradisiaca* L.)	160 N – 40 P – 320 K (g tree^{-1}) – FYM (15 Mg ha^{-1})
Banana (*M. paradisiaca* L.)	300 N – 75 P – 300 K (g tree^{-1}) – AM (50 g tree^{-1})
Bitter gourd (*Momordica charantia* L.)	70 N – 25 P – 25 K (kg ha^{-1}) – neem cake (2.5 Mg ha^{-1})
Bottle gourd (*Lagenaria siceraria* Mol.)	40 N – 20 P – 20 K (kg ha^{-1}) – VC (5 Mg ha^{-1})
Turmeric (*Curcuma longa* L.)	25 N – 60 P – 36 K (kg ha^{-1}) – FYM (5 Mg ha^{-1}) – AB (2.5 kg culture ha^{-1})
Coconut (*Cocus nucifera* L.)	600 N – 1200 P – 1500 K (g palm^{-1}) – FYM (50 kg palm^{-1})
Coriander (*Coriandrum sativum* L.)	10 N – 20 P – 30 K (kg ha^{-1}) – FYM (5 Mg ha^{-1}) – AB (10 kg culture ha^{-1})
Fenugreek (*Trigonella foenum graecum* L.)	50 N – 25 P – 40 K (kg ha^{-1}) – AB (15 kg culture ha^{-1})
Custard apple (*Annona squmosa* L.)	125 N – 65 P – 125 K (g tree^{-1}) – AB (100 g culture tree^{-1}) – AM (50 g culture tree^{-1})
Brinjal (*Solanum melongena* L.)	75 N – 37.5 P – 22.5 K (kg ha^{-1}) – FYM (12.5 Mg ha^{-1}) – AB (50 g culture kg^{-1} seed) – PSM (100 g culture kg^{-1} seed)
Brinjal (*Solanum melongena* L.)	45 N – 45 P kg ha^{-1} – PM (3 Mg ha^{-1})
Okra (*Abelmoschus esculentus* L.)	25 N – 12.5 P – 12.5 K (kg ha^{-1}) – FYM (15 Mg ha^{-1}) – AB/AC (20 g culture kg^{-1} seed)
Okra (*A. esculentus* L.)	45 N (41 kg ha^{-1}) – PM (25 kg ha^{-1})
Onion (*Allium cepa* L.)	75 N – 37.5 P – 75 K (kg ha^{-1}) – AB slurry (2 kg culture ha^{-1}) – FYM (2 Mg ha^{-1})
Tuberose (*Polianthes tuberose* Lin.)	200 N – 200 P –150 K (kg ha^{-1}) – FYM(5 Mg ha^{-1}) – BF (3 kg culture ha^{-1})
Cabbage (*Brassica oleracea* L.)	120 N – 60 P – 80 K (kg ha^{-1}) – AM – AB – PSM (2 kg culture ha^{-1})
Okra-pea-tomato (*A. esculentus* L. – *P. sativum* L. – *L. esculentum* L.)	80 N – 15 P – 30 K (kg ha^{-1}) – AM (100 g culture kg^{-1} seed)
Tomato (*L. esculentum* L.)	150 N – 112.5 P – 82.5 K (kg ha^{-1}) – FYM (25 Mg ha^{-1})
Tomato (*L. esculentum* L.)	150 N – 60 P – 60 K (kg ha^{-1}) – AC – PSM (50 g culture kg^{-1} seed)
Tomato (*L. esculentum* L.)	100 N – 45 P – 60 K (kg ha^{-1}) – PSM (10 kg culture ha^{-1})
Tomato (*L. esculentum* L.)	100 N – 80 P – 80 K (kg ha^{-1}) – AB (5 kg culture kg ha^{-1})
Mango (*Mangifera indica* L.)	145 N – 335 P – 420 K (g tree^{-1}) – AC (200 g culture tree^{-1})
Tea (*Camellia sinensis* L.)	75 N – 60 P – 45 K (kg ha^{-1}) – DCC – AM – AB – PSM (50 kg ha^{-1} each)
Rose (*Rosa indica* L.)	60 N (g m^{-2}) – FYM (5 kg m^{-2})
Broccoli (*Brassica oleracea* gemmifera)	60 N – 30 P – 30 K (kg ha^{-1}) – PM (2.5 Mg ha^{-1})

Sources: **1.** Jeyabaskaran *et al.* 2001; **2.** Singh and Singh 2004; **3.** Rekha and Gopalakrishnan 2001; **4.** Bairwa and Fageria 2008; **5.** Selvarajan and Chezhiyan 2001a; **6.** Marimuthu *et al.* 2001; **7.** Selvarajan and Chezhiyan 2001b; **8.** Selvarajan and Chezhiyan 2001c; **9.** Balakrishnan *et al.* 2001; **10.** Nanthakumar and Veeraragavathatham 2001; **11.** Shelke *et al.* 2001; **12.** Ray *et al.* 2005; **13.** Yadav *et al.* 2006; **14.** Yadav *et al.* 2005; **15.** Barman *et al.* 2003; **16.** Bahadur *et al.* 2004; **17.** Singh *et al.* 2004; **18.** Kumar and Sharma 2004; **19**. Gajbhiye *et al.* 2003; **20.** Kumar and Srivastava 2006; **21.** Bhadoria *et al.* 2007; **22.** Feza Ahmed *et al.* 2003; **23.** Easwaran *et al.* 2006; **24.** Singh 2006; **25.** Maurya *et al.* 2008

FYM: Farmyard manure, PM: Poultry manure, AB: *Azospirillum brasilense*, AM: *Arbuscular mycorrhiza*, PSM: Phosphate solubilizing microorganism, AC: *Azotobacter chroococcum*, BF: *Bacillus firmus*, DCC: Digested coirpith compost

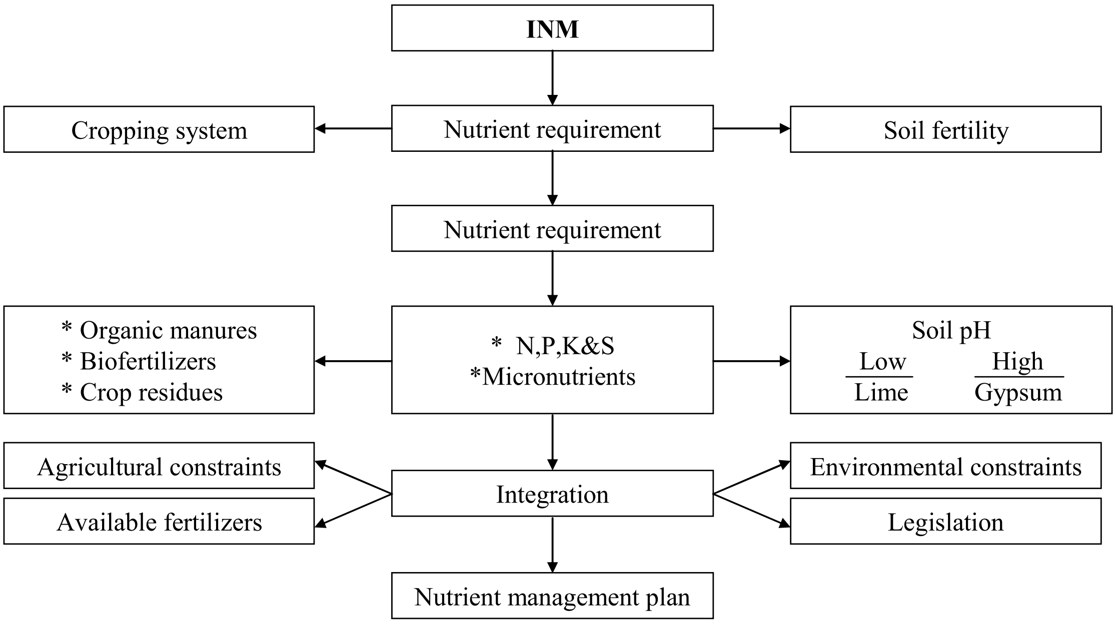


Fig. 3 Schematic plan for INM.

are further summarized (Srivastava *et al.* 2008) through a flow diagram (**Fig. 3**).

The ultimate rationale of INM is, hence, the judicious use of its all the three principal components viz., exploiting the existing synergism between dual purpose microbe (growth promoting as well as biocontrol agent against soil-borne pathogens) types with limited use of inorganic chemical fertilizers, triggering the multiplication of indigenous soil microbial diversity through a suitable substrate of organic origin, in such a way that the nutrients inflow always exceeds the nutrients flow leaving the system, besides ensuring the market favouring production economics. However, still there are many core areas where an urgent redressal is required in order to tag INM, a globally vibrant nutrient management strategy.

FUTURE PERSPECTIVES

Of many issues blocking the large-scale application of INM, the biggest constraint lies in the judicious use of organic inputs with regards to differential nutrient release pattern and timely availability in bulk quantity. In order to integrate promising organic resources into INM practice, an organic resource database with respect to nutrient contents and quality parameters of FYM and crop residues comparable to that of alterative nutrient sources such as different plant parts and types; nutrient stock within a farm unit as a source of nutrients for soil fertility management; and hypotheses for predicting N release rates (Palm *et al.* 2001), are suggested. This preemptive exercise with respect to INM strategy, the required will produce the sustainable impact on crop as well as soil health. Such an effort is, however, diluted due to little information available on crop-specific composition of the microbial community and the role of dominant microbial population in guiding the yield or quality.

The interactions of microbial inoculants with native soil microorganisms are likely to be complex, and a better mechanistic understanding is necessary to predict short-and-long term effects of those interactive or synergistic groups of microorganisms on chemical and biological pool of nutrients in soil. In this regard, much better results are anticipated through the coinoculation of different microbes with *Azospirillum* as a helper microbe in combination with other bacteria, fungi, and AM as one of the frontiers of developing rhizo-specific substrate. However, the mechanism by which *Azospirillum* sp. and other promotive rhizobacteria influence plant growth is yet to be understood including the nutrient release behaviour of different nutrient carriers as substrates other than peat, perlite, zeolite, and coconut coir, which are studied in-depth.

Crop residues as an effective substrate need strong intervention in INM for long-term assessment of soil fertility transformation with microbial loading, although the relationship between the microbial biomass and chemical properties of soil is well understood. But, the segregation of different nutrients in relation to phonological growth stages of annual versus perennial crops is still an issue requiring concerted efforts in order to derive improved nutrient use efficiency by proper scheduling of organic fertilization. The information on phytochrome synthesis mechanism involved in promoting the growth of microbially inoculated plants will further help in proposing some useful hypotheses with regard to cause-and-effect relationship.

The thresholds of microbial partitioning are even now less understood, which quite often undermines the microbial characterization of the rhizoplane and rhizosphere of many commercial crops. Very limited studies have been carried out to separate the differences in yield potential arising out of genotype versus improved INM practices or genotype versus a plant's internal metabolic efficiency of nutrient use. The multi-pronged effect of OMs on soil quality changes is often associated with a negative impact, e.g., during transition from inorganic to organic management, and a decline in productivity warrants strict regulation of organic fertilizer quality and applied quantity to avoid any possible contamination of productive farm land.

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