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Integrated Nutrient Management: Concept and Application in Citrus

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ABSTRACT

Multiple nutrient deficiencies are common in citrus orchards the world over. Integrated nutrient management (INM), a concept that involves the combined use of chemical fertilizers, microbial inoculation and organic manures, has shown much better promise than any of the other strategies of fertilization in citrus. INM-based fertilization has a definite edge over conventional fertilization since the former advocates treatment once or twice to inflict changes in the physico-chemical and microbial environment, while the latter is effective only when practiced 3-4 times synchronizing with phenological growth stages and often 15-20 times using fertigation or even much better technicalities involved with sensor-based variable rate application using site-specific fertilization. Dual function microbes e.g. *Trichoderma harzianum*/*viride*, *Pseudomonas fluorescens*, *Bacillus polymyxa*, arbuscular mycorrhizae, etc. both having growth-promoting ability as well as strong antagonistic effect against soil-borne pathogens loaded to manure as substrate coupled with 75% of RDF (recommended doses of fertilizers) are equally effective to combat multiple nutrient deficiencies on both alkaline calcareous and acidic non-calcareous soils, irrespective of cultivar type and climate.

Keywords: deficiency, inorganic fertilization, manure, microbe, multiple nutrient

Abbreviations: AM, arbuscular mycorrhizae; **AWC**, available water content; **BMP**, best management practice; **CBP**, circular band placement; **CRF**, controlled release fertilizers; **FRT**, fertigation; **FUE**, fertilizer-use-efficiency; **FYM**, farmyard manure; **GIS**, geographic information systems; **GPS**, global positioning system; **INM**, integrated nutrient management; **ISM**, integrated soil management; **PLFA**, phospholipid fatty acid; **SOM**, soil organic matter; **WSG**, water soluble granular fertilizers; **WUE**, water use efficiency

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INTRODUCTION

Citrus is globally considered as one of the premier fruit crops, both in terms of area and production. Sub-optimum production due to the prevalence of nutrient constraints is well established in citrus, as in any other crop (Srivastava *et al*. 2008). Malnutrition of citrus orchards in Asian countries like India, Pakistan, Sri Lanka, Thailand, China, Philippines, Nepal, Iran, etc. is more or less a commonality (Ghosh and Singh 1993) with some exceptions. However, the situation

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Invited Review

Table 1 Global distribution of nutrient deficiencies in citrus orchards.

Citrus regions	Nutrient deficiencies	References
Argentina (Tucuman)	N, Cu, Fe, Mg, Zn	Aso and Dantur 1970
Australia (New South Wales, Riverland, Sunrayasia)	N, P, Cu, Mn, Zn, B	Halase 1963; Duncan 1969
Brazil (Sao Paulo, Parana)	Ca, Mg, P, K, Zn, B	Caetano *et al.* 1984; Fidalski and Auler 1997
Chile (Azapa, Elqui, Limari, Cachapoal)	N, Zn, Mn, P, S	Veregara *et al.* 1973
China (Fujian, Sichuan)	Ca, P, Fe, Mn, Zn, Mo	Li *et al.* 1998; Yin *et al.* 1998
Costa Rica (Atlantic zone)	N, P, K, Ca, Mg, Mn, Zn	Bornemisza *et al.* 1985; Alvardo *et al.* 1994; Araya *et al.* 1994
Egypt (Aswan, Beheira, Tahrir)	N, P, Fe, Mn, Zn,	El-Fouly *et al.* 1984; Salem *et al.* 1995
India (northwest, northeast, south, central region)	N, P, Ca, Mg, Fe, Mn, Zn	Awasthi *et al.* 1984; Dhatt 1989; Srivastava and Singh 2004b, 2004c, 2006b, 2008d
Iran (Jiroff valley)	Zn, Mn, Cu	Rao 1993
Israel (Negev, Sinai, Jordan valley)	Ca, Mg, Fe, Zn	Shaked and Ashkenazy 1984; Horesh *et al.* 1986
Italy (Sicily, Calabria, Barasilicata)	N, K, Mg, Cu	Pennisi 1975
Japan (Shizuoka, Ehime, Kanagawa)	N, P, K, Mg, Zn	Takatsuji and Ishihara 1980; Kozaki 1981; Wada *et al.* 1981
Kenya (Rift valley)	N, P, B, Fe, Zn, Cu, Mn, Mo	Kimani 1984
Korea (Jeju Island)	N, P, K, Ca, Mg, S, Cu, Zn	Kim *et al.* 1969; Moon *et al.* 1980
Morocco (Sou valley)	Fe, Mn, Zn	Penkov *et al.* 1979
Nepal (Dhankuta, Lamjung, Gorkha)	B, Mg, Cu, Ca, Zn	Gupta *et al.* 1989; Tripathi and Harding 2001
Pakistan (Punjab)	K, Zn, B	Haq *et al.* 1995
Sierra Lone (Sierra)	N, P, K, Ca, Mg, Zn	Haque and Godfrey 1976
Spain (Valencia, Seville, Murcia, Catania)	N, P, K, Ca, Mg, Fe, Mn, Zn	Majorana 1960; Hellin *et al.* 1988
Thailand (Korat Plateau)	Ca, Mg, P Zn	McCall 1965
Trinidad (Caribbean area)	Mg, Zn, Mn	Weir 1969, 1971
Turkey (Izmir, Aegean region)	Ca, Mg, Fe, Zn	Ercivan 1974; Saatci and Mur 2000
USA (Florida, California, Texas)	N, P, K, Fe, Mg, Zn, Mn, Cu, B, Mo	Koo 1982; Zhou and Alva 1993; Tucker *et al.* 1995; Zhang *et al.* 1997
Venezuela (Carabobo)	N, P, Ca, Mg, Zn	Pinto and Leal 1974

by contrast is extremely different in frontline citrus-growing countries like USA, Brazil, Israel, Spain, etc. in terms of rootstock options as per soil conditions, micro-irrigation/ fertigation technology, better refined diagnostic techniques, and a larger proportion of orchards being regularly fertilized based on nutrient demand and supply analysis. Single or multiple nutrient deficiency-linked decline in citrus orchard productivity is reported the world over (**Table 1**). Considering the economics of citrus production, fertilizers alone on average constitute about 20-30% of the total cost of citrus production which is a significant recurring expenditure, and a grower needs to invest every year (Srivastava and Singh 2003b, 2005a). The mechanistic steps involved in an efficient nutrition program are: absorption, translocation, and utilization of applied nutrients. All three steps are altogether different, but equally dependent on each other.

Like any other fruit tree, citrus requires 16 essential elements for normal growth, production, and quality irrespective of the source (Zekri 1995). Renewed and intensified efforts have been in progress over the past 10-15 years to grow citrus organically ever since depleting soil fertility caused serious concern with the practice of high density orcharding coupled with heavy use of chemical fertilizers that were immediately available to plants for nutrient uptake (Kohli *et al.* 1998; Srivastava and Singh 2004a, 2009a) bringing unprecedented reduction in soil organic matter (SOM; Intrigliolo and Stagno 2001). Organic manuring is often considered as a sustainable agricultural practice, and, if used appropriately, promises to offer rich dividends on a long-term basis (Ferguson 1990).

Fertilizers act in exactly the same way as nutrient from organic resources in the soil, since they are chemically the same. The advent of synthetic chemical fertilizers decreased organic fertilizer use such that it makes up only about 0.1% of all fertilizers applied to citrus today (Srivastava *et al.* 2002). However, interest in applying organic amendments to citrus is rising because of increased supplies and reduced cost of non-hazardous organic wastes. Citrus growers apply these materials for perceived or real improvements in soil physical, chemical, and biological properties, but the main benefits appear to be the increased nutrient availability. The use of organic materials as an N source is being considered as a best management practice (BMP) for N management because organic sources release N to the plant more gradually than water-soluble, inorganic fertilizer sources. Current organic amendments applied to citrus groves (biosolids, poultry waste, and composts) differ substantially from those applied in the past. The Florida Department of Agriculture and Consumer Services (FDACS) interim BMP rule for citrus stated that the contribution of plant-available N from natural organic N sources for the 1st year after application shall be 50% of the total N application. Application rates are determined by a process design that takes into account the crop N requirement and the N mineralization rate. Mineralization rate studies are being, therefore, conducted to refine this figure for accurate nutrient management planning under Florida conditions (Obreza and Ozores-Hampton 2000).

Concerns about improving nitrogen use efficiency, reducing nitrate pollution, contamination due to byproducts of various chemical pesticides in use, and continued gradual loss of SOM have always been the major core issues, and more so, citrus raised through organic manuring (Ferguson 1994). But organic manuring has yet not received the priority it deserves; as a result, soil physical, chemical, and microbiological health have not really favoured consistently high yield (Dahama 1994; Paroda 1999; Ghosh 2000). In addition to changes in land use pattern, unfavourable climatic conditions have further enhanced the rate of decomposition of SOM and its further depletion (Velayutham *et al.* 1999). These problems warrant revision of ongoing agricultural practices, and adaptation of some alternative strategies whose origin is presumed to be age-old, popularly known as organic farming or natural farming. Traditional organic manuring with special reference to rotation, use of green manures and rural agricultural waste as compost, tank silt application would all help to build a SOM base, and a reliable index of fertility. This is a long-term endeavour but once attained all parameters (physical, chemical, and biological) work at optimum. Use of microbial biofertilizers on one hand, and the utilisation of AM fungi as bioprotectors, bioregulators and biofertilizers in citrus (Manjunath *et al.* 1983; Ishii and Kadoya 1996) on the other is likely to bring a desirable change in quality production, besides beneficial impacts on soil health.

Alteration of heavy with light crop is a common feature in citrus (Reuther 1973; Moss *et al.* 1981; Monselise and Goldschmidt 1982; Haggag *et al.* 1995; Kihara *et al.* 1995). Alternate bearing is more pronounced on a tree-to-tree basis in 'Kinnow' mandarin, without any significant difference in feeder root density compared with on-and-off year trees (Jones *et al.* 1975). The present citrus production trends are characterized by either frequent crop failure or recurrence of alternate on-and-off years, setting unaccountable monetary loss to the industry (Jones *et al.* 1975; Smith 1976; Dass *et al.* 1998; Rojas 1998). In recent years, nutrient additions have been exclusively in favour of mineral fertilizers due to demographic pressure, of demands related to life styles and trade involvement. While the quick and substantial response to fruit yield due to mineral fertilizers eclipsed the use of organic manures, the inadequate supply of the latter sources exacerbated this change (Ghosh 2000). Integrated nutrient management (INM) with emphasis on the use of bio-organics is a comparatively recent concept which needs to be vigorously pursued to achieve sustainability in citrus production trend spaced over years. Additionally crop nutrition, therefore, must respect the prescriptions of INM. The merits of INM-based practices also take into account the mobilization of unavailable nutrients could also be effected by speeding up the rate of mineralization of various organic substrates.

INM as a dynamic concept of nutrient management that considers the economic yield in terms of fruit yield coupled with quality on one hand, and soil physico-chemical and microbiological health on other hand as a marker of resistance against the nutrient mining that arises because of failure to strike a balance between annual nutrient demand versus the quantity of nutrients applied. Soils under citrus differ from other cultivated soils, which remain fallow for 3-6 months every year forcing depletion of SOM (Bhargava 2002). In contrast, biological oxidation of existing C continues in soil covered under citrus (Srivastava *et al.* 2002). Multiple nutrient deficiencies are considered to have a triggering effect on potential source of atmospheric CO_2. Soil carbon stock is, hence, considered as an important criterion to determine the impact of INM in the longer version of impact assessment (He *et al.* 1997; Joa *et al.* 2006). The amount of accumulated C within the rhizosphere soil does not continue to increase with time with increasing C outputs. An upper limit of C saturation level occurs, which governs the ultimate limit of soil C sink and rate of C sequestration in mineral soils, independent of C input rate. An understanding of the mechanism involved in C stabilization in soils is needed for controlling and enhancing soil C sequestration (Goh 2004).

Recognition of the importance of soil microorganisms has led to increased interest in measuring the quantum of nutrients held in their biomass. An increase in the microbial biomass often goes along with increased nutrient immobilisation. Over the years, the concepts of INM and integrated soil management (ISM) have been gaining acceptance, moving away from a more sectoral- and inputs-driven approach. INM advocates the careful management of nutrient stocks and flows in a way that leads to profitable and sustained production. ISM emphasises the management of nutrient flows, but also highlights other important aspects of soil complex such as maintaining organic matter content, soil structure, moisture, and microbial biodiversity. Still more attention is needed towards integrated soil biological management as a crucial aspect of soil fertility management since providing protection to citrus rhizosphere against the nutrient depletion is of utmost importance for sustained orchard production in which the objectivity of INM could have far reaching consequences. Exploring microbial diversity perspectives in a citrus crop is, therefore, important and equally useful to arrive at measures that can act as indicators of soil quality and sustainable orchard productivity using biological soil management to be ultimately integrated with INM. Diagnosis of nutrient constraints and their efficient management has, therefore, now shifted in favour of INM through collective use of organic manures, inorganic fertilizers and beneficial microorganisms becomes all the more difficult.

MICROBIAL BIOFERTILIZATION

Concerns about improving nitrogen use efficiency, reducing nitrate pollution, contamination due to byproducts of various chemical pesticides in use, and continued gradual loss of SOM have always been the major core issues, and more so, in organic citrus using biofertilizers (Ferguson 1994). But, the promise of biofertilizers in citrus has yet not received the priority, it deserves, with the result, soil physical, chemical, and microbiological health have deteriorated irrecoverably in many commercial citrus belts (Dahama 1994; Paroda 1999; Ghosh 2000; Srivastava *et al.* 2002). Use of microbial biofertilizers on one hand, and the utilisation of Arbuscular mycorrhiza (AM) fungi as bioprotector, bioregulator, and biofertilizer in citrus (Ishii and Kadoya 1996; Sankaram 1996; Kohli *et al.* 1998), on the other hand, is likely to bring a desirable change in the quality production, besides beneficial impact on soil health.

Abundance of microbial diversity in citrus rhizosphere

Microbial biomass studies in citrus orchards of Zhejiang province of China showed a large variation in microbial biomass-C (1.62-3.16 mg kg^{-1}), microbial biomass-N (19.0-35.2 mg kg^{-1}), microbial biomass-P (20.2-42.3 mg kg^{-1}) which constituted 1.61-2.60, 1.2-2.5, and 2.4-8.4% of total organic-C, respectively (He *et al.* 2002). Badiyala *et al.* (1990) observed an improvement in microbiological composition of Hapludalf under 6-year-old kinnow mandarin following grass mulch application. A classical review by Bhattacharya *et al.* (1999) showed the occurrence of *Bacillus polymyxa*, *Bacillus subtilis*, *Aspergillus terreus*, and *Trichoderma viridi* as phosphate solubilizers in citrus growing soils of India, having phosphate solubilising capacity of 13.30 to 81.68% P_2O_5 through insoluble tri-calcium phosphate. Population density of phosphate solubilising microorganisms has been observed to vary from 7×10^4 to 16×10^5 g^{-1} soil (Paliwal *et al.* 1999).

Studies by Kohli *et al.* (1997) showed a higher correlation of fruit yield with the population density of *Azotobacter* (r = 0.692, p = 0.01), ammonifiers (r = 0.512, p = 0.01), and phosphate solubilising bacteria (r = 0.618, p = 0.01) than with available N (r = 0.489, p = 0.01), P (r = 0.316, p = 0.05), and K (r = 0.321, p = 0.05) in soil, suggesting the possibility of using microbial biomass and its turnover as a potential diagnostic tool for soil fertility evaluation. Significantly higher population density of *Azotobacter*, ammonifiers, and phosphate solubilising bacteria was observed in rhizosphere ($0.4\text{-}16.5 \times 10^4$, $0.5\text{-}95.0 \times 10^5$ and $0.9\text{-}78.0 \times 10^4$) than non-rhizosphere zone ($0.3\text{-}10.5 \times 10^4$, $0.5\text{-}35.0 \times 10^5$ and $0.9\text{-}38.2 \times 10^4$, respectively) of Nagpur mandarin. These observations provide an evidence about the presence of favourable soil microbial buildup (**Table 2**), which could be effectively exploited in improving the availability of nutrients from soil native pool of immobilised nutrients in soil, despite sub-optimum application of farmyard manure at an average rate of 40-50 kg $tree^{-1}$ $year^{-1}$, supplying only 200-300 g N $tree^{-1}$ compared to recommended dose of 600-800 g $tree^{-1}$. Chen *et al.* (2004) suggested that soil microorganisms that grow in soil environment with more neutral soil pH (5.5-7.5) have a greater tolerance to soil pH changes than those growing in more acidic or alkaline soil pH conditions.

AM were found in half of the 149 soil and citrus root samples collected in Apulia, Basilicata, Calabria, Messina, and Catania areas of Italy. *Gigaspora* and sour orange nurseries and 2 unidentified *Glomus*-like species were found in the other samples (Inserra *et al.* 1980). The studies for presence of AM on coffee, soyabean, lemon, and molasses grass (*Melinus minutiflora*) growing at 3 localities showed the occurrence of many species viz., *Acaulospora trappet*, *A. scrobiculata*, *Glomus macrocarpus*, *G. occultum*, and *Giga-*

Table 2 Microbial composition of rhizosphere versus non-rhizosphere zones of mandarin orchards of central India.

Locations	**Rhizosphere soil (c.f.u. g^{-1} soil)**			**Non-rhizosphere soil (c.f.u. g^{-1} soil)**		
	Azotobacter **($\times 10^4$)**	**Ammonifier ($\times 10^5$)**	**P-solubilisers ($\times 10^5$)**	***Azotobacter*** **($\times 10^4$)**	**Ammonifiers ($\times 10^5$)**	**P-solubilisers ($\times 10^5$)**
Kalmeshwer	8.0-16.5	0.5-70.0	0.9-56.0	4.0-10.5	0.5-32.0	0.9-32.0
Katol	1.5-16.0	5.0-55.0	11.0-53.0	1.0-10.2	2.0-31.1	4.0-38.2
Narkhed	1.0-15.0	3.0-95.0	8.0-78.0	1.0-8.2	1.0-31.0	3.0-31.0
Ramtek	0.4-8.0	4.0-52.0	7.0-38.0	0.5-7.0	8.0-32.0	6.0-20.0
Saoner	0.9-10.0	7.0-41.0	7.0-29.0	2.0-8.0	14.0-35.0	7.0-14.0
Hingna	3.0-10.0	10.0-30.0	7.0-20.0	0.3-2.6	9.0-24.0	1.1-34.0

Sources: Kohli *et al.* (1997); Srivastava and Singh (2006b)

spora margarita (Caldeira *et al.* 1983). Mycorrhiza species, *Glomus mosseae*, *Glomus clarum*, and *Glomus caledonium* were commonly observed in citrus orchards of Italy (Palazzo *et al.* 1992). Camprubi and Calvet (1996a) suggested *G. mosseae* and *Glomus intraradices* to be most common AM fungi in citrus soils of eastern Spain which can be introduced into soils by adopting crop rotation with mycorrhizal aromatic plants viz., *Lavandula vera*, *L. angustifolia*, *Thymus vulgaris*, and *Rosmarinus officinalis* (Camprubi and Calvet 1996b). Other genera of *Gigaspora*, *Scutellospora*, and *Glomus* have also been commonly observed in citrus orchard soils of Japan (Ishii and Kadoya 1996). Talukdar (1999) observed the population of *Glomus fasciulatum*, *Gigaspora margarita*, and *Acaulospora* sp. as 488-620 100 g^{-1} and 134-480 100 g^{-1} in citrus soil. Another study by Bhattacharya (1999) reported the distribution of AM population as 37 to 76 spores 100 g^{-1} soil with *Glomus* as most predominant genus in Nagpur mandarin growing soils of central India. The AM population was higher during early stage (pre-bearing 1-5 year old orchards) and declined during the next phase (5-10 year old orchards).

Sanikidze (1970) observed an increase in population of microorganisms, namely, *Bacillus* spp., *Penicillium*, *Mucor*, *Trichorderma*, *Aspergillus* sp., *Actinomycetes*, *Clostridium pasteurianum*, *Azotobacter* sp., *Nitrobacter* sp., and cellulose decomposing bacteria in the top soil of mandarin plantation following the application of lime and pure peat. The highest population of bacteria was observed in sweet orange followed by lemon tree rhizosphere on calcareous soils and mandarin trees growing on red soils of Georgia (Gochelashvili 1973). Another study by Saakashvili *et al.* (1971) reported most numerous saprophytic bacteria (65-70 million g^{-1} dry roots) on the roots and the least number in the outer rhizosphere (2 million g^{-1} soil). The saprophytic bacterial count was correlated directly with fruit yield.

The role of blue green algae in citrus orchards has not been studied much. In sub-tropical Russian type orchards, Gochelashvili (1978) observed fixation of N up to 48-51 kg ha^{-1}. In Spain, Pomares *et al.* (1981) recorded improvement in the yield and quality of Salustiana orange using blue green algae as an inoculant over chemical fertilizers in sandy loam soil having pH 8.4-8.5 and $CaCO_3$ 6.7-7.2%.

Inoculation of bacterium *Azospirillum brasilense* (3 g $plant^{-1}$ as a root dip at transplanting) to sweet orange cv. 'Mosambi' plants substituted for at least one forth (25%) of total N requirement (Singh and Sharma 1993). A review on the role of biofertilizers in citrus by Bhattacharya *et al.* (1999) revealed the positive relation between fruit yield of Nagpur mandarin and population density of *Azotobacter*, *Azospirillum*, and phosphate solubilisers (*Pseudomonas striata*). The review of the extensive data collected revealed 60-70% success with significant increase in yield in 10-30% of the trials.

The treatment combination of ¾P + AM + N was observed the best treatment with reference to better growth and yield of high quality fruits of 'Mosambi' sweet orange suggesting the compatibitliy of biofertilizers (AZO) and AM inoculation in combination with chemical fertilizers for better growth, yield and fruit quality. Such observations in the long term are expected to cut down the cost of chemical fertilizers, particularly N and P and building up fertility by maintaining better soil physical conditions (Chonkhe *et al.* 2000). High efficiency of *Azospirillum* for fixing nitrogen and better mobilisation of fixed phosphorus by AM even at high temperatures can make these highly suited for Mosambi sweet orange (Manjunath *et al.* 1983).

The strategy of introduction of microorganisms in citrus soil is a recent adoption and requires indepth comprehensive studies to improve the process of application for harnessing higher benefits. In a separate study, Kalita *et al.* (1996) observed the occurrence of *Bacillus subtilis*, *Bacillus polymyxa*, *Aspergillus terreous*, and *Trichoderma viridi* in citrus orchard soils of central India. These microbes could play a significant role in controlling *Xanthomonas campestris* pv. *citri*, the incitant of citrus canker.

Citrus-mycorrhiza association

Reduction in the amount of chemical fertilizers applied, priority on compost, use of soil conditioners such as charcoal and zeolite, use of grasses as mulch e.g. Bahia grass, stabilising the soil pH around 6.5-7.5, and improving the aeration are some of the soil management systems to maintain good population density of AM fungi in citrus orchards (Ishii *et al.* 1989, 1992; Huang and Tang 1994; Ishii 1994; Ishii and Kadoya 1996). The relationship between soil mycorrhizal potential left by a pre-crop and mycorrhizal benefit drawn by the succeeding AM responsive plant can be taken advantage of in the exploitation of native AM potential of soil for growth and nutrition management in citrus in low nutrient, low input-output systems of production (Panja and Chaudhuri 2004).

Combined top growth of 6 seedlings of citrus rootstocks was increased by 21-, 8- and 6-fold as a result of inoculation with *Glomus etunicatus*, *G. mosseae*, and *G. fasciculatus*, respectively, at the 4-5-leaf stage when a 12:0:6 NPK liquid fertilizer was used, but growth was only increased < 1.8-fold when a 12:6:6 liquid fertilizer was used. The rootstocks decreased in dependency on the mycorrhizae in the order: sour orange, Cleopatra mandarin, sweet orange, rough lemon, Rangpur lime, and Carrizo citrange (Nemec 1978). Rough lemon showed the highest response on soil inoculated with *G. fasciculatus* followed by *G. caledonius* inoculated soil and amended soil; *G. margarita* slightly depressed vigour. After 390 days, shoot mass and seedling height were greatest in soil inoculated with *G. fasciculatus*; root mass and stem diameter, however, differed little between this treatment and inoculation with *G. margarita* (Lee *et al.* 1978). The growth of rough lemon (*Citrus jambhiri* Lush) seedlings increased with each P increment in both in soil treated with AM than untreated soil. The relative response to P was 20-fold in treated soil and 6-fold in untreated soil. Growth in the untreated soil was positively correlated with the percentage of arbuscular mycorrhizal infection (mean 76%) while infection was absent in roots from treated soil (Weir *et al.* 1978). The influence of an AM (*Glomus etunicatus*) and burrowing nematode (*Radopholus similis*) alone and in combination on the growth of rough lemon seedlings were studied in the green house, which showed better growth of mycorrhizal seedlings than that of nonmycorrhizal seedlings or seedlings inoculated with *R. similis* (O'Bannon and Nemec 1979).

Davis (1980) observed that of sweet orange cv. 'Pineapple' seedlings infected with the arbuscular mycorrhizal fungus, *G. fasciculatus* were more vigorous than nonmycorrhizal seedlings. After 5 months of growth, sour orange rootstocks were 3.1 and 3.5 times taller, respectively, in low-P sand inoculated with *Glomus etunicatus* and in sand treated with superphosphate at 2240 kg ha^{-1} superphosphate than untreated controls Total and free amino acid contents in leaf were significantly higher in control rootstocks and were not significantly different between P and mycorrhizal treatments (Nemec and Meredith 1981). Fresh weights of the aerial parts of *Citrus limonia*, *C. aurantium*, and *Poncirus trifoliata* were 94, 48, and 31% higher for treatment having phosphate application plus mycorrhizal inoculation than application of rock phosphate alone (Tang and Cheng 1986).

Gigaspora margarita showed slight effectiveness on *Citrus volkameriana* only, and in the second experiment, *Glomus leptotichum* and *Gigaspora gilmorei* were highly effective on Rangpur lime. In the third experiment the most effective fungi for growth promotion and absorption of nutrients were again *G. leptotichum* and *G. gilmorei* on Rangpur lime, and on sweet orange, *G. leptotichum* was benefited only in the absence of added phosphate, whereas *G. gilmorei* was effective at all phosphate levels (0, 30 and 100 ppm). In the presence of these two AM fungi, the rootstocks could be cultivated with low phosphate levels and were ready for grafting within 8 months after sowing (Cardoso *et al.* 1986). Ishii and Kadoya (1994) in a study on effect of charcoal as a soil conditioner on growth of citrus trees infected with AM, observed highest percent of AM infection (52.0%) in a rice husk charcoal amended plot followed by Bahia grass (*Paspulum notatum*) as cover crop treated plot and an abandoned uncultivated plot. While, Nemec (1998) observed highest infection (64.0%) by *Glomus fasiculatum* on *Citrus limon* cv. 'Valencia' under deep tilled limestone amended soil, and proved superior to other amendments such as phosphogypsum, peat, and no till control.

Mycorrhiza dependency

Citrus is infected by several kinds of AM fungi and considered highly dependent on them (Menge *et al.* 1978a; Nemec 1979; Edriss *et al.* 1984; Dixon *et al.* 1988a; Ishii *et al.* 1992; Palazzo *et al.* 1992; Ishii *et al.* 1993) known as mycorrhizal dependence. A great diversity about the mycorrhizal dependency, expressed as dry weight ratio between mycorrhized and non-mycorrhized plants has been observed amongst citrus rootstocks (Ferreira and Polero 1984; Camprubi and Calvet 1996a; David and Janos 2007).

Root/shoot ratios indicated that rootstock dependency decreased as capacity for root production increased (Nemec 1978). Seedlings of 6 rootstocks seedling cvs, 'rough lemon', 'Brazilian' sour orange, alemow (*Citrus macrophylla*), 'Bessie' sweet orange, *Poncirus trifoliata*, and Troyer citrange were grown in pots fertilized each week with a nutrient solution (complete except for P), with ½ rate nutrient solution and without nutrients. Half the seedlings were inoculated with the mycorrhizal fungus *Glomus fasciculatum*. The cultivars exhibited the greatest mycorrhizal dependency with the least fertilization. The average concentration of P in non-mycorrhizal leaf tissues was inversely correlated with mycorrhizal dependency at the medium fertilizer regime (½ rate nutrient solution). An inverse correlation was observed between the dry weights of non-mycorrhizal roots and the mycorrhizal dependency (Menge *et al.* 1978a).

Among closely related citrus genotypes in high-P orchard soils, there is a tendency for less mycorrhizal dependent species to have lower rate of root colonization than more mycorhizal dependent species. To test this hypothesis, five citrus genotypes, namely *Citrus volkameriana*, *Citrus aurantium*, *Poncirus trifoliata*, Swingle citrumelo, and Carrizo citrange were inoculated with *Glomus intraradices* in high P soil type. More dependent genotypes allocated more carbon to starch pools in relation to non-mycorrhized plants than less dependent genotypes. Sucrose concentration was also lower in colonized roots than non-mycorrhized roots. Concentration of reducing sugars in root tissues varied in relation to mycorrhizal dependence of citrus genotypes in the same way as that of starch and sucrose, but was less responsive to mycorrhizal colonization (Graham *et al.* 1997). A value of mycorrhized dependency over 1 was observed with *Glomus fasciculatum* as the most efficient mycorrhizal species (Menge *et al.* 1978a; Chang 1984). *Poncirus trifoliata* was found to be most dependent rootstock followed by rough lemon, Troyer citrange, Rangpur lime and Carrizo citrange (Onkarayya and Sukhada 1993) based on the mycorrhizal dependency was calculated as the percentage improvement in the dry weight AM infected various rootstocks.

Sour orange and Cleopatra mandarin are more dependent than Troyer citrange and Swingle citrumelo (Camprubi and Calvet 1996a). Mycorrhizal dependency such as these, in fact, account for the success of symbiosis between host plant and mycorrhiza. Graham and Syvertsen (1985) classified the mycorrhizal dependency of citrus rootstocks inoculated with *Glomus intraradices* as Sour orange/Cleopatra mandarin > Swingle citrumelo > Carrizo citrange > Trifoliate orange. Less dependent rootstocks such as trifoliate orange and its hybrids, Carrizo citrange had greater leaf P, finer roots, slower growth rate, higher root hydraulic conductivity, transpiration and CO_2 assimilation. *Glomus fasciculatum* treated plants observed the highest mean mycorrhizal dependence, 2.12 times higher increase in growth compared over non-mycorrhized plants (Ferreira and Polero 1984).

Physiological changes

Inoculation with different mycorrhiza has been reported to bring many physiological changes in mycorrhized plants. Nagy *et al.* (1980) observed that roots of sweet orange, sour orange, rough lemon, carrizo citrange, cleopatra mandarin, and Rangpur lime had significantly higher phospholipids and triglycerides in mycorrhiza infected that did their non-infected control. Likewise, higher fatty acid was observed in seed-raised rootstocks of *Citrus reticulata*, *C. sinensis*, *C. aurantium*, *C. limon*, *C. paradisi* and *Poncirus trifoliata* x *C. sinensis* in fibrous roots infected with the arbuscular mycorrhizal fungi *Glomus fasciculatus*, *G. mosseae or G. etunicatus*, but not in non-infected roots (Nordby and Nemec 1981). Another study showed that *Glomus etunicatum* was less aggressive colonizer and produced lower rates of fungal fatty acid accumulation in sour orange seedling roots than the other *Glomus* species (Graham *et al.* 1996).

Effects of growth regulators as mediators of mycorrhizal sink strength must be considered since the carbohydrate balance is believed to change in the symbiotic association (Lewis 1975). Dixon (1990) observed higher total cytokinin activity in leaf than root tissue of *Citrus jambhiri* seedling due to differential rate of dry matter accumulation.

Dipping of sour orange and Carrizo citrange seedlings treated with *Glomus intradices* in indole-butyric acid solution (2 g litre^{-1}) for 10 seconds produced higher root and shoot growth compared to non-mycorrhized seedlings (Dutra *et al.* 1996). A similar response was observed low concentration of ethylene (0.05 ppm) in stimulating the infection and nymphal growth of AM fungi (Ishii *et al.* 1996).

Infection with AM has also been observed to alter the carbohydrate balance within leaves and roots, providing evidence about the presence of strong relationship between carbon allocation behaviour of host and AM colonization (Graham *et al.* 1997). Similar observations were made earlier by Dixon *et al.* (1988b), who observed an improvement in total sugar, sucrose, reducing sugars, and starch in *Citrus jambhiri* seedlings mycorrhized with *Glomus fasciculatum*. A number of reasons have been described for increased sink strength of AM roots. A larger root mass typically accompanies mycorrhizal infections (Menge *et al.* 1977, 1978a).

This is expected to produce a greater total demand for photosynthates. Besides, affecting respiration rate and root biomass, AM also contributes to sink demand through storage of fungal end-products and uptake of assimilates exudated from roots. Differences in root exudation between infected and non-infected roots were reported to be related to sink strength only (Ratnayake *et al.* 1978).

Ecto-mycorrhizal fungi store carbohydrates as trehalose or mannitol, thus, producing a gradient of sucrose from host to fungus (Bevege *et al.* 1975). Although, AM fungi appear to store glycogen and lipids (Bevege *et al.* 1975; Cox *et al.* 1975), they may still compartmentalise sucrose or hexose away from the host prior to use in photosynthetic reactions. According to Johnson and Hummel (1985), AM treatment improved the establishment of citrus through enhanced P uptake and reduced vulnerability to stress via hormonal regulations. Shrestha *et al.* (1995) attributed better growth of AM-infected Satsuma mandarin trees to improved photosynthesis and transpiration rates in P deficient acidic red soil under high temperature stress, suggesting, thereby, the existence of an efficient sink-source relationship in inoculated trees. Concentration of reducing sugars in root tissues varied in relation to mycorrhizal dependence of citrus genotypes in the same way as that of starch and sucrose, but was less responsive to mycorrhizal colonization (Nemec and Guy 1981; Graham *et al.* 1997). Improvement in specific activities of acid phosphatase and alphamannosidase also contributed to better performance of AM inoculated *Citrus limon* cv. 'Assam lemon' (Choudhury *et al.* 2002). Koch and Johnson (1984) observed that distribution of assimilates in sour orange and Carrizo citrange seedlings inoculated with *Glomus intraradices* was independent of phosphorus effects on photosynthates partitioning in leaves, and no showed reflection on fresh or dry weight of roots or degree of mycorrhizal dependancy of the species. AM is reported indirectly affect the partitioning of photosynthesis by altering phosphorus level of leaves. Phosphate in leaf mesophyll is known to have striking effects on the partitioning of photosynthates between translocable assimilates and stored starch (Herold 1980).

Comparative analysis of growth response of Volkamer lemon (*Citrus volkameriana*) colonized with *Glomus intraradices* mycorrhiza versus non-mycorrhized plants showed that both the types of plants grown in high P soil were similar in P concentration, daily shoot carbon assimilation, and daily shoot dark respiration. But after 15 days of transplanting, besides identical growth rates, mycorrhized plants observed 10% higher daily root growth rate. Mycorrhized plants at high soil P content had 10% higher capacity for building lipid rich roots and 51% greater root biomass allocation capacity compared to non-mycorrhized plants (Peng *et al.* 1993). Inoculation of citrus with *Glomus intraradices* increased tolerance to water stress (Johnson and Hummel 1985; Graham *et al.* 1987; Shrestha *et al.* 1996). Treatment with mycorhiza prepared the citrus seedlings to resist against the adverse effect of salinity. Hartmound *et al.* (1987) observed a proportionately higher reduction in hydraulic conductivity of roots, leaf water potential, stomatal conductance, and net assimilation of CO_2 in non-mycorrhizal plants compared to mycorrhized ones in response to salinity effect. Likewise, roots of Pineapple sweet orange accumulated higher chloride in their roots treated with mycorrhizal fungi. However, other rootstocks like Carrizo citrange and sour orange accumulated more chloride in their leaves when treated with AM.

Mineral nutrition

Rhizosphere modification through roots exudation is an important attribute that regulates not only the availability of nutrients in the soil but also their acquistion by plants. A number of studies (Tang and Wan 1980a, 1980b; Ferguson 1982; Graham and Timmer 1984, 1985; Roger 1991) have suggested that mycorrhizal fungi have helped to alleviate nutritional deficiencies, as citrus tree is mycotrophic and its root system depends on mycophytes to withdraw nutrients by plants (Tang and Wan 1980b; Bierman and Lindermann 1983). Beneficial effect of mycorrhizae is of special importance for plants possessing a coarse and poorly branched root system. External hyphae of mycorrhiza can extend as much as 8 cm away from the roots (Mosse 1981), absorbing nutrients from a much larger soil volume than the absorption zone surrounding a non-mycorrhized root (Howeler *et al.* 1987). In citrus, mycorrhizal efficiency varied with soil factors, fertilisation, cultivar, and mycorrhizal species (Sutton and Sherppard 1976; Mehraveran 1977).

Dixon *et al.* (1989) suggested that foliar application of boron stimulated the efficacy of citrus-mycorrhiza symbiosis. Selection of suitable fungal species and optimal phosphate application are, hence, important for tapping the efficiency of AM fungi. These fungi improve mineral nutrition of the host by increasing P uptake from P deficient soils (Krikun and Levy 1980; Tang *et al.* 1984; Graham and Timmer 1985; Ferguson and Menge 1986; Tang and Rai 1990; Antunes and Cardoso 1991; Fonseca *et al.* 1994; da Rocha *et al.* 1994, 1995). Based on the analysis of 26 citrus orchard soils in California, Menge *et al.* (1982) suggested that soils with < 34 mg kg^{-1} Olson - P, 1.2 mg kg^{-1} Zn, 27 mg kg^{-1} Mn or 30 mg kg^{-1} organic matter required mycorrhizal inoculation to derive maximum growth response of citrus. The majority of publications concern P nutrition and only few deal with the effect on K uptake. In studies on the mechanism of P uptake by Trifoliate orange seedlings treated with mycorrhiza, Tang and He (1991) observed 52% higher mycorrhizal infection with rock P compared to superphosphate treatment. Establishment of mycorrhizal colony stimulated the roots to release acid phosphatase enzyme into the soil, the activity of which increased by 29.8% with rock P treatment, indicating the mycorrhizal fungi linked enhancement in P-uptake from insoluble P. Edmonds *et al.* (1976) reported improved K uptake through beneficial role of ectomycorrhiza. Power (1975) showed higher K uptake in arbuscular mycorrhiza treated plants compared to non-mycorrhizal plants.

Timmer and Leyden (1978) observed that mycorrhizae were consistently absent from stunted seedlings and present in vigorous seedlings in seedbeds, nurseries, and orchards. Inoculation with *Glomus fasciculatus* increased seedlings height more than 300% and with foliar P concentrations in seedlings grown in sand culture with complete nutrient solution. Preplant application of P at 200 mg l^{-1} showed no response on growth or foliar P concentration under the similar conditions. Application of high rates of P induced Cu deficiency symptoms, which were more severe on non-mycorrhizal than mycorrhizal plants. Application of 190 to 200 kg P ha^{-1} stimulated early growth of seedlings but, inhibited mycorrhizal spore formation and induced Cu-deficiency symptoms (Timmer and Leyden 1978, 1980). A sandy loam soil deficient in available P (4.6 ppm P) was supplemented with necessary nutrients and P (as superphosphate) at 0, 6, 28, 56, 278 or 556 ppm. After 5 month of inoculation with mycorrhizal *Glomus fasciculatus* on sour orange seedlings given no P were similar to non-mycorrhial seedlings given 56 ppm P. Leaf P in mycorrhized plants was enhanced by mycorrhizal association at every level of P supply. Variation in K, Mg, and Na uptake was affected by P concentration in the seedlings, while variation in Zn, Cu, and Mn was influenced both by P concentration and mycorrrhizal presence (Menge *et al.* 1978b).

A concentration of over 50 ppm available P in soil has been reported to severely inhibit the AM colonization (Shrestha *et al.* 1993). However, insoluble phosphates, such as rock phosphate (Graham and Timmer 1985), calcium phosphate, and bone powder (Ishii 1994) are not harmful to AM fungi. A soil pH of 5.1 to 7.1 suggested by Muramatsu *et al.* (1995) proved suitable for hyphal growth of *Gigasphora ramisporophora*. Studying the influence of mycorrhiza and P application on the growth and nutrient status of citrus, Antunes and Cardoso (1991) observed a substantial increase in dry matter yield in addition to P and K contents

Table 3 Growth response of *Citrus* treated with various mycorrhizal species.

AM/*Citrus* sp.	**Response parameters**	**Location**	**Reference**
Endogon mosseae – Rough lemon	Improved height and dry mottles		Marx *et al.* 1971
Glomus mosseae – sour orange seedlings	15% higher growth depending on rootstock type	USA	Hattingh and Gerdemann 1975
G. fasciculatum	70-300% higher growth depending on *Citrus* species	USA	Kleinschmidt and Gerdemann 1972
Glomus – lemon	Increase in total biomass		Lee *et al.* 1978; Matare 1978
Glomus fasciculatum – Poncirus trifolita	Increased root system ratio, plant height, and dry weight of shoot	Argentina	Halbinger *et al.* 1984
Glomus – Citrus sp.	Increase in stem height and trunk diameter	India	Chandrababu and Shanmugam 1983
Glomus intraradices	Increase in total CHO pool as per mycorrhizal dependence of citrus genotypes	USA	Nemec 1992; Graham *et al.* 1987
Mixed inoculum of *Glomus* and *Gigaspora*	Increase in plant height, root length, leaf number, leaf area, and total dry mass of sour orange seedlings	Egypt	El-Maksoud *et al.* 1988
Glomus citricola – Poncirus trifolita	Height (300-500%), trunk diameter (40-93% increase) and fresh weight < 300-600%	China	Sheng 1990
Glomus etunicatum	Increase in dry matter and yield	Brazil	Mohoney and Nemec 1979; Antunes and Cardoso 1991
Glomus mosseae plus *50% cocoa husk*	Increase in plant height, stem diameter and number of leaves	Brazil	Jaen and Roman 1994
Glomus macrocarpum and *G. mosseae*	Increased biomass plant height, plant girth, leaf number, leaf area, leaf P and Zn concentration	India	Reddy *et al.* 1996
Glomus citricolum alongwith P fertilization on *Citrus limonia*, *C. aurantium* and *Poncirus trifoliata*	Increase in plant height, leaf number, root density and P uptake	China	Tang and Cheng 1986
Glomus epigaeum	Higher plant growth parameters, root growth, and percent infection	China	Chang and Chien 1990
Glomus aggregatum Citrus sunki	Increase in height and stem diameter	China	Cheng *et al.* 1997
Acaulospora longulata Etrophospora colombiana and *Glomus manihotis - Citrus jambhiri*	Increase in plant height, leaf number, and P uptake	Colombia	Villafane *et al.* 1989
Acaulospora sp. on *Ca*rrizo citrange	Improved stem diameter and plant height	South Africa	Zyl 1996
Glomus fasciculatum - Assam lemon	Improved growth, P uptake and enzymatic activities l acid phosphatase and manosidase	India	Choudhury *et al.* 2002
Glomus intraradices – Citrus reshini	Improved accumulation of Cu, Fe, Mn and Zn	Brazil	de Sena *et al.* 2002
Glumus clarum – Citrus aurantium	Increased P uptake of Zn, and Cu	Turkey	Ortas *et al.* 2002

at 50 ppm soluble P level through rock phosphate increased absorption of Ca and Mg has also been reported by mycorrhizal than non-mycorrhizal citrus trees (Mosse 1973; Newcomb 1975). Tang *et al.* (1989) observed 24.5% higher Ca concentration in trifoliate seedlings inoculated with *Glomus citricola* in sterilized soil.

Mycorrhizae have also been helpful in improving the uptake of diffusion limited nutrients such as P, Zn, Cu, Mn, and Fe by the host plants (Menge *et al.* 1978b; Tinker 1982; Johnson 1984; Tang *et al.* 1984; Graham 1986) on account of their ability to dissolve and promote absorption of these elements (Englander 1981). This is accomplished primarily by extension of root geometry through symbiotic association in which fungus utilizes carbohydrates produced by the host plants, and plants in turn benefit by increased nutrients uptake, especially noticeable in soils of low fertility (Nemec 1979). Graham and Fardelmann (1986) observed higher uptake of Cu by Carrizo citrange inoculated with *Glomus intraradices* while El-Maksoud *et al.* (1988) observed greater uptake of N, P, Fe, Mn, and Zn by roots and aerial parts of Sour orange seedlings inoculated with *Glomus* and *Gigaspora* sp. of mycorrhizal fungi in both calcareous and sandy soils of Egypt.

Treeby (1992) showed that under the acid soil conditions, mychorrizae are essential for satisfactory Fe nutrition, and on alkaline calcareous soil, no such treatment was observed. Strategy I mechanism (Marschner *et al.* 1986) operate under the alkaline calareous soil condition, but they may be less important on acid soil. Comparison of mineral nutrition of *Glomus intrardices* mycorrhizal versus non-mycorrhizal Carrizo citrange seedlings in acidic sand soil showed that Cu-induced reduction in P uptake of mycorrhizal plants was more closely related to inhibition of hyphal development outside the root than development of vescicles and arbuscules in the root (Graham *et al.* 1986).

Treeby (1992) observed increase in shoot Fe concentration in mycorrhized over non-mycorrhized citrus trees, more efficiently in an acidic environment. The exact mechanism of such cause and effect is still not clear, whether the endophyte is directly involved in Fe uptake, and supply to the host, or it is an indirect effect of the change in root growth habit. Onkarayya and Sukhada (1993) observed higher concentrations of P, N and Zn in AM inoculated rootstock seedlings of rough lemon (*Citrus jambhiri*), Rangpur lime (*Citrus limonia*), *Poncirus trifoliata*, Troyer citrange, Carrizo citrange, Citrumelo excluding Cleopatra mandarin.

Biometric response

Studies on effect of mycorrhizal inoculation on different plant growth attributing parameters of citrus have shown varying responses. Chang (1984) observed a large variation between rootstock type and AM fungi compatibility. Prominent effective combinations on the basis of mycorrhizal dependency comprised of: Liu Cheng sweet orange x *G. mosseae*, hybrid pummelo x *G. etunicatum*; Swingle citrumelo x *G. fasiculatum;* Rangpur lime x *G. etunicatum* or *G. fasiculatum*. Other mycorrhiza species such as *Glomus velum*, *Glomus caledoneum*, *Glomus merredum*, *Glomus macrocarpum*, and *Glomus acaulospora* equally most effective in improving growth and nutrition (P, Zn, and Cu uptake) of trifoliate orange (Vinayak and Bagyaraj 1990a, 1990b). Comparative study of translocation of ^{14}C-photosynthates to mycorrhizal (++), half mycorrhizal (0+) and nonmycorrhizal (00) split-root systems with P accumulation in leaves of the Carrizo citange seedlings inoculated with *Glomus intraradices* showed that there is an optimal level of mycorrhizal colonization above which the plant receives no enhanced P uptake, yet plant continues to partition photosynthates to metabolism of the mycorrhiza (Douds *et al.* 1988). Most studies have shown a good response of beneficial mycorrhizae on growth of various citrus cultivars across the citrus growing countries (**Table 3**).

Fruit quality

Work highlighting the response of mycorrhiza on the fruit quality is extremely scanty. Interestingly, inoculation with AM fungi improved the fruit quality of 'Satsuma' mandarin trees, with reference to Hunter's a/b value of peel colour and juice sugar content (Ishii *et al.* 1992; Shrestha *et al.* 1996). In high quality fruit producing citrus orchards, the percentage of AM infection in the roots was very high (Shrestha *et al.* 1993). Shreshta *et al.* (1996) in subsequent studies observed better fruit quality, and tolerance to water stress in 'Satsuma' mandarin trees inoculated with *Gigaspora ramisporophora*.

INORGANIC FERTILIZER USE

Based on the objective, two types of fertilization viz., corrective and preventive are usually adopted. According to Gallasch (1992), an optimum fertilizer program is one in which the cost of each unit of fertilizer applied is at least covered by an extra return of fruit yield obtained in both, the short and long term life of a citrus orchard. In a young tree care program, emphasis is placed on developing the tree canopy which will later produce large crop. Switching from a young tree program to a bearing tree, the nutrient regime within the tree, may significantly that influence the amount of fertilizers to be applied to maintain optimum productivity. There are three approaches to fertilizer recommendations that are widely used: the deficiency correction philosophy (crop response to the point of maximum economic yield), maintenance concept (aims to maintain soil fertility level slightly above the point of maximum economic yield), and nutrient removal or balanced philosophy (aims to return to the soil what is removed by the crop to maintain productivity, but often over-recommends nutrient need, since it does not take into account for the soil's ability to supply available nutrients to plants over time). An optimum supply of nutrients is, hence, aimed to meet two prime conditions: i. all nutrients should be available in quantities which exclude the possibility of absolute deficiency or excess, and ii. the proportion of all the nutrients should be such as to exclude any deficiency as no nutrient works independent to each other (Srivastava and Singh 2008b, 200b). There are two basic philosophies of fertilizer management, one is based on fertilizing the soil, and the other on fertilizing the crop (Jones Jr. 1985).

Soil fertilization

This is still the most accepted and widely used method of fertilization in commercially productive citrus orchards. The main organ for absorbing water and nutrients by a plant is its roots. Average concentration of micronutrients (mg kg^{-1}) in the fibrous roots of 'Valencia' orange grown in sand culture reported by Smith *et al.* (1953) were: B 25, Cu 157, Fe 1783, Mn 257, and Zn 462 mg kg^{-1}, whereas the average concentration (Kg tonne^{-1} fruit) of different nutrients in fruits was observed as: N 1.20, P 0.18, K 1.54, Ca 0.57, Mg 0.12, B 1.63 × 10^{-3}, Cu 0.39 × 10^{-3}, Fe 2.1 × 10^{-3}, Mn 0.38 × 10^{-3}, and Zn 0.40 × 10^{-3} (Mattos Junior *et al.* 2003). Climate- and soil-related factors such as low temperature, excessive moisture (water infiltration rate), drought, etc., however, disturb nutrient and water uptake during plant growth, the effects of which may vary from a temporary restriction of growth to reduced fruit yield and quality at harvest (Papadakis *et al.* 2004). The uptake and translocation of iron and zinc of 'Valencia' orange on trifoliate orange (susceptible to iron and zinc deficiencies) and rough lemon rootstock (resistant to iron and zinc deficiencies) were studied by Khadr and Wallace (1964). Under low iron and zinc, rough lemon absorbed and translocated both nutrients more to the top, while under high supply, the difference between rootstocks disappeared for iron. These observations suggested that iron and zinc translocation from roots to leaves may be more important problem than absorption *per se* (Srivastava and Singh 2009b).

Roots impose differential nutrient demand depending upon the sink strength, in form of fruits and newly emerging vegetative growth, which eventually dictate the nutrient requirement. Changes in the nutrient content of oranges from young and mature 'Bellamy' navel orange trees throughout fruit development showed that during early growth (Fruit dry weight <10 g), the contents of K and B (phloem mobile), and of Ca and Cu (phloem immobile) increased linearly in relation to fruit dry weight. In contrast to K and B, the Ca and Cu content plateaued at a fruit dry weight of 15 g. There was a comparatively greater influx of Ca into the albedo than the pulp during stage I of fruit development. During stage I of fruit development, normalized Ca fluxes into whole fruit and albedo tissue were higher in fruits from young trees than in fruits from mature trees (Storey and Treeby 2002).

The fertilizers are usually given to citrus orchards following three different application techniques. Some of the common techniques are: circle banding (cutting furrow 20 cm wide and 30 cm deep around the tree in circle beneath the outer canopy), strip band application (cutting parallel furrows 20 cm wide and 30 cm deep, between the tree rows), and hole placement (digging 4-5 holes, each of 15-20 cm diameter and 30 cm deep, beneath the outer canopy of each tree).

Macronutrient requirements

Response of N fertilization in improving the growth, yield, and quality of different citrus cultivars is well recognized under different agroclimatic regions of the countries like Brazil, Australia, South Africa, India, etc. (Ghosh *et al.* 1989; Tachibana and Yahata 1996). Recovery of applied N ranged from 33 to 61% and from 1 to 33% through soil and mature leaves, respectively, with maximum N-absorption at the rate of 27 mg plant^{-1} day^{-1} during the summer. On annual basis, 25% of the total N in the sweet orange tree came from the reserve-N of transplanted plant, 16% from soil, and remaining 59% from the urea applied to the soil (Boaretto *et al.* 1999). The effect of N-fertilizers at 168 kg ha^{-1} produced the best response on yield of citrus cultivars viz., 'Valencia', 'Parson' 'Brown', 'Hamlin', and 'Sunburst' sweet orange grown in Hardee county of Florida, USA (Alva *et al.* 2001).

The mathematical relation between N-fertilizer rate and yield using variance analysis showed that application of 1.18 kg N plant^{-1} on the medium fertility soil produced a yield of 40.5 kg plant^{-1} and 35.9 kg plant^{-1} with 1.03 kg N plant^{-1} on poor fertility soil (Liu *et al.* 1994). Contrary to foliar fertilization, soil application of macronutrients proved more efficacious. The optimum requirement of macronutrients for different commercial citrus cultivars (**Table 4**) suggested a large variation in recommendations due to cultivar specificity to nutrient acquisition (by roots, movement across roots to xylem, distribution and remobilization), and final utilization in growth and metabolism in addition to difference in soil and climate.

The reports about the shortage of S in citrus orchards are extremely limited. The response of Ca and Mg application is common as an amendment in citrus orchards established on soils of varying acidities. Lime (up to 12 tonnes ha^{-1}) and phosphogypsum (up to 4 tonnes ha^{-1}) incorporation to the surface soil have proved effective in alleviating subsoil acidity, increase Ca and Mg content, and base saturation near 60% down to 60 cm depth in the soil profile. These changes improved the yield of 'Valencia' orange (Quaggio *et al.* 1992, 1998). Other amendments like gypsum (Anderson 1968), sulphur (Rasmussen and Smith 1959), magnesium sulphate (Mdinaradze and Datuadze 1987), magnesium carbonate (Koo 1966), basic slag (Koo 1964), and phosphogypsum (O'Brien and Sumner 1988) have also shown promising results citrus orchard. Koo (1971) in two long term trials testing sources and rates of Mg on 'Marsh' grapefruit and 'Valencia' orange, reported

Table 4 Optimum macronutrients for different commercial citrus cultivars through soil application.

Country	Dose	Crop/*Citrus* spp.	Reference
Algeria	600 g N – 150 g P_2O_5 – 600 g K_2O tree^{-1}	Clementine	Dris 1997
Algeria	240 g N – 40 g P_2O_5 – 400 g K_2O tree^{-1}	Dancy mandarin	Pedrera *et al.* 1988
Algeria	450 kg N – 0-180 kg P – 0-30 kg K ha^{-1}	Valencia orange	Sarooshi *et al.* 1991
Algeria	120 kg N – 150 kg P – 75 kg S – 6 kg Cu – 0.8kg Mo – 5.0 kg Zn ha^{-1}	Neck orange	Lim *et al.* 1993
Australia	450 kg N – 30 kg P – 180 kg K ha^{-1}	Valencia orange	Bevington 1984
Australia	22.5-25 kg N – 5-12.5 kg P_2O_5 – 10-12.5 kg mu	Satsuma mandarin	Wang 1985
Brazil	200 kg N – 140 kg P – 210 kg K ha^{-1}	Pera sweet orange	Canteralla *et al.* 1992
Brazil	180 kg N – 90 kg P – 180 kg K ha^{-1}	Pera sweet orange	Rodriguez 1980
Egypt	600 g N – 135 g P – 285 g K tree^{-1}	Navel orange and Balady mandarin	El-Hagah *et al.* 1983
Egypt	750 g N – 200 g P_2O_5 – 500 g K_2O tree^{-1}	Egyptian Balady lime	Ahmed *et al.* 1988
Egypt	1500 g N – 400 g P_2O_5 – 750 g K_2O tree^{-1}	Egyptian Balady lime	Maatouk *et al.* 1988
Egypt	500 kg N – 100 kg P – 100 kg K ha^{-1}	Satsuma mandarin	Kacharava 1985
Egypt	100 kg N – 200 kg P_2O_5 – 300 kg K_2O ha^{-1}	Valencia orange	Goepfert *et al.* 1987
Egypt	475 g N – 320 g P_2O_5 – 355 K_2O tree^{-1}	Satsuma mandarin	Koseoglu 1995b
France	180 g N – 90 g P_2O_5 – 45 g K_2O – 800 g CaO tree^{-1}	Clementine	Aubert and Vullin 1998
Greece	0.5 kg N – 0.5 kg P_2O_5 – 1.0 kg K_2O ha^{-1}	Grapefruit	Androulakis *et al.* 1992
Greece	1.02 kg N – 0.58 kg P_2O_5 – 0.55 kg K_2O tree^{-1}	Satsuma mandarin	Liu *et al.* 1994
Greece	420 g N – 323 g P_2O_5 – 355 g K_2O tree^{-1}	Satsuma mandarin	Koseoglu *et al.* 1995a, 1995b
India	500 g N – 100 g P_2O_5 – 400 g K_2O tree^{-1}	Mosambi sweet orange	Ghosh 1990
India	125 g N – 175 g P – 100 g K tree^{-1}	Satsuma mandarin	Hong and Chung 1979
India	160 g N – 320 g P – 480 g K tree^{-1}	Valencia late orange	Hernandez 1981
India	2.72 kg N – 1.81 kg P – 0.60 kg K tree^{-1}	Sathgudi sweet orange	Reddy and Swamy 1986
India	800 g N – 170 g P_2O_5 – 391 g K_2O tree^{-1}	Mosambi Sweet orange	Desai *et al.* 1986
India	250 g N – 250 g P_2O_5 – 500 g K_2O tree^{-1}	Coorg mandarins	Kannan *et al.* 1989
USA	625 kg N – 525 kg K_2O ha^{-1}	Valencia orange	Tucker *et al.* 1990

that application of 1.5 tonnes MgO ha^{-1} increased the yield by 12.6% and total soluble solids by 14.7% over low rate of 0.60 tonne MgO ha^{-1}. Dolomite application at the much lower rates, 400 kg ha^{-1} year^{-1} produced an additional fruit yield 75 tonnes ha^{-1} in 'Satsuma' mandarin in 6 years of experiment compared to application at 200 kg ha^{-1}year^{-1} (Shimorgori *et al.* 1980). Anderson (1987) later comparing the results of 17-year-old study on response of 'Valencia' orange to lime application reported that increase in soil pH from initial value of 5.2 to 7.0 increased the yield by 50% in first 7-years period which further improved the yield by 200% in next 10-years with no significant yield difference between limestone and dolomite. Specialized with slow release nutrients extensively tested all over the citrus growing countries especially as a method of reducing nitrate leaching (Khalaf and Koo 1983; Ferguson *et al.* 1988; Wang and Alva 1996; Paramasivam and Alva 1997; Obereza *et al.* 1999; Schumann *et al.* 2003) have also attracted citrus researchers. Most of these studies conducted on young trees were short term experiments focussed mainly the effect of several controlled release fertilizers on tree growth with very few on fruit yield (Koo 1986; Zekri and Koo 1992). Controlled release fertilizers compared to soluble fertilizers have proved to be very effective in increasing growth due to continuous rather than fluctuating nutrient supply (Khalaf and Koo 1983; Koo 1988), besides reducing the rates and number of applications during the growing season (Zekri and Koo 1991).

A large number of commercially exploited coating materials viz., sulphur, osmocote, isobutylidene diurea, crotonylidene, triazimes, gypsum, phosphogypsum, ureaform, magnesium ammonium phosphates, etc. (Maynard and Lorenz 1979) have been tested in citrus. The research studies with various controlled release fertilizers (CRF) products showed that nitrate leaching potential could be reduced compared to similar rates of conventional soluble fertilizers. Obreza *et al.* (1999) reviewed the performance of five CRFs on young 'Valencia' oranges and the economics of using these fertilizers instead of conventional soluble granular products. They found that the CRFs produced similar or better yields, but that the cost of fertilizing trees with CRFs alone at the full N rate was four times the conventional fertilization cost, and the return was only 15% greater. They concluded that the high cost of CRFs currently makes them uneconomical for exclusive use in citrus production. For this reason, the current ridge citrus, N-BMPs do not account for the use of any CRFs. Most recently, tests on mature 'Hamlin' oranges with CRFs in Florida flatwoods soils have been more encouraging (Obreza and Rouse 2006). These CRFs performed better when applied once a year at 220 kg N ha^{-1} than water-soluble fertilizer applied three times a year at 180 kg N ha^{-1}. These observations suggest the favourable economic CRFs would undoubtedly be a valuable addition to the current citrus best management practices for not only N-use-efficiency, but could be an effective supplement to other important nutrients like P, K, Ca, Mg, and S as well (Maynard and Lorenz 1979).

Micronutrient requirements

The chelates like Fe-EDTA on acid soils and Fe-EDDHA an alkaline soils are most widely used in citrus (Leonard and Stewart 1952). The optimum dose of chelates depends on the tree size, degree of chlorosis, soil type, and management practices. The studies carried out worldover have, therefore, shown some diversity in optimum doses of micronutrients (**Table 5**) due to difference in nutrient supplying capacity of soil conditioned by soil properties, (e.g. texture, pH, salinity, calcareousness, cation-anion ratio, etc.) nutrient requirement by specific rootstock –scion combination, planting density, irrigation source, region specific cultural practices, the agro-climate etc. The combination of soil application and foliar spray has also produced equally good results, e.g. $ZnSO_4$ - K_2SO_4 (0.5% foliar spray) - K_2O as K_2SO_4 (210 g tree^{-1} soil application) for 'Kinnow' mandarin (Singh *et al.* 1989) and $ZnSO_4$ - $FeSO_4$ - $MnSO_4$ (50 g tree^{-1} each soil application) - (0.50% foliar application) for 'Sathgudi' sweet orange (Devi *et al.* 1996).

Site-specific nutrient management

Large variation in tree canopy and subsequently, the tree-to-tree yield difference are common in many of the large size citrus orchards. Knowing the required nutrients for all stages of growth, and understanding the soil's ability to supply those needed nutrients are critical to profitable crop production. The recommendations on fertilizer application may not, however, produce the same magnitude of yield response when practised in an orchard of large area, because of

Table 5 Optimum micronutrients for different commercial citrus cultivars through soil application.

Country	Dose	Crop/*Citrus* spp.	Reference
Cuba	$MnSO_4$ (483 kg tree^{-1}) - $ZnSO_4$ (303.8 g tree^{-1})	Valencia orange	Garcia-Alvarez *et al.* 1983
Georgia, USSR	Zn-aldehyde (4-12 kg ha^{-1})	Satsuma mandarin	Mdwaradze 1981
India	$ZnSO_4$ (500 g tree^{-1})	Sweet orange cv. Blood Red	Khera *et al.* 1985
India	$ZnSO_4$ - K_2SO_4 (0.5% foliar spray) - K_2O as K_2SO_4 (210 g tree^{-1} soil application)	Kagzi lime	Singh *et al.* 1989
India	$ZnSO_4$ (100 g tree^{-1} soil application) - (0.5% foliar spray)	Sathgudi orange	Devi *et al.* 1996
India	300 g $ZnSO_4$ tree^{-1} year^{-1}	Nagpur mandarin	Srivastava and Singh 2009b
USA	Fe - Mn - Zn-EDTA (292 g - 292 g - 315 g ha^{-1})	Valencia orange	Alva and Tucker 1992
USA	$ZnSO_4$ (810 g tree^{-1} soil application) - $MnSO_4$ (630 g 100 gallon^{-1} foliar spray)	Lemon	Embleton *et al.* 1966
USA	Zn-EDTA 30 g tree^{-1}	Grapefruit cv. Rio Blood	Swietlik 1996
USA	Zn-EDTA 2.1 g m^{-2}	Valencia orange	Anderson 1984
USA	Zn (3 g) - B (3 g) - Mo (1.5 g tree^{-1})	Valencia orange	Egorashvili *et al.* 1991

its inability to accommodate variation in soil fertility status. Slight changes in the nature of soil, local climate, and agronomic practices etc. may seriously affect the nutrient utilisation capacity of the plant.

Conventional long-term fertilizer trials (Tiwari 2002) revealed that: i) omission of limiting macro- or micronutrient led to its progressive deficiency due to heavy removals; ii) sites initially well supplied with P, K or S become deficient when continuously cropped using N alone; and iii) fertilizer rates considered optimum still resulted in nutrient depletion at higher productivity levels, if continued, become sub-optimum rates. There is a strong necessity to keep overall nutrient balance in relation to total crop load. Application of a single rate of nutrients may result in over-application of nutrients at some sites and under-application at other sites, often lead to reduced FUE. Under such circumstances, site specific nutrient management is adopted in bigger orchards requiring variable precision application as per soil variability so as to improve the orchard efficiency (average yield of specified trees in relation to average orchard yield) in ultimate terms (Srivastava and Singh 2008a).

With new advances in technology, grid sampling for precision citriculture is increasing. The first step in the process is to divide large fields into small zones using a grid. Next, a representative location within the grid is identified for precision soil sampling. Grid sampling is integrated into global positioning system (GPS) based soil sampling and nutrient-mapping that in turn uses a geographic information systems (GIS) to employ variable rate technology for fertilizer application (Schumann *et al.* 2003; Zaman *et al.* 2005).

Variable rate fertilization

Variable rate fertilization is one of the most effective techniques for rationale use of fertilizers executed by matching the fertilizer rate with tree requirement on the basis of individual tree size. Site specific management of 17-year old 'Valencia' grove (2980 trees) in Florida using automated sensor system equipped with differential GIS and variable rate delivery of fertilizers (135-170 kg N ha^{-1} year^{-1}) on tree size basis (0-240 m^3 tree^{-1}), achieved 38-40% saving in granular fertilizers cost. While, conventional uniform application rate of 270 kg N ha^{-1} year^{-1} showed that trees with excess N (>3%) had canopies less than 100 m^3 with lower fruit yield and inferior quality (Zaman *et al.* 2005). In another long term experiment, the large fruit yield difference of 30.2 and 48.9 kg tree^{-1} initially observed on shallow soil (Typic Ustorthent) and deep soil (Typic Haplustert) in an orchard size of 11 ha, reduced to respective fruit yield of 62.7 and 68.5 kg tree^{-1} with corresponding fertilizer does (g tree^{-1}) of 1200 N – 600 P – 600 K – 75 Fe – 75 Mn – 75 Zn – 30 B, and 600 N – 400 P – 300 K – 75 Fe – 75 Mn – 75 Zn – 30 B, suggesting the necessity of fertilizer application on variable rate application for srationality in fertilizer use (Srivastava *et al.* 2006, 2008).

Analysis of tree size of 3040 trees space of 40-acre grove showed a skewed distribution with 51.1% trees having 25-100 m^3 tree^{-1} size classes and a median size of 82 m^3 tree^{-1}. At a uniform fertilization rate of 240 kg N ha^{-1} year^{-1}, the leaf N concentration of 12 trees with different canopy sizes that were randomly sampled in the grove showed optimal levels (2.4-2.6%) in the large trees and excess levels (> 3%) in the medium to small trees (Tucker *et al.* 1995). From the regression line, trees with excess N had canopies < 100 m^3 tree^{-1} and constituted 62% of the grove. Under such conditions, variable rate fertilization can, therefore, saves production cost, reduce N leaching, and increase yields per variable acre (Schumann *et al.* 2003). A 30% saving in granular fertilizer cost was estimated for this 'Valencia' grove if variable N rates were implemented on a per tree basis ranging from 129 to 240 kg N ha^{-1}year^{-1}. For comparison purposes, the eastern half of the grove received the full uniform rate of 240 kg N ha^{-1} year^{-1}. No fertilizer was allocated by spreader to skip or reset of one-to-three year age. Due to a very restricted root system, new resets should be fertilized individually, usually by hand (Tucker *et al.* 1995), ensuring that the granules are accurately placed adjacent to the tree. Application of variable fertilizer rate technology in this grove saved in nitrogen equivalent to the 32 to 43% reduction of N rates achieved through use of fertigation and foliar sprays of urea (Lamb *et al.* 1999).

Fertigation

Low water use efficiecy - (WUE) and fertilizer-use-efficiency (FUE) are amongst the major production related constraints (Germanà 1992; Srivastava and Singh 2003a). Basin irrigation is widely used in citrus orchards, but it has several drawbacks in terms of conveyance, percolation, evaporation, and distribution losses, yet without much adverse impact on growth, yield, and fruit quality (Shirgure *et al.* 2000, 2003). In light of growing scarcity of water and poor WUE under basin irrigation, micro-irrigation has gained wide spread application in citrus orchards. However, the efficacy of drip irrigation is often questioned, especially where soil moisture deficit stress is used to regulate the stress for induction of flowering in the areas lacking in low temperature deficit stress e.g. central India (Dass *et al.* 1998). The lack of uniformity in moisture distribution within the trees' and rhizosphere due to variation in sub-soil properties can adversely affect the development of desired fruit size (Srivastava and Singh 2003a). Any method of irrigation capable of replenishing the plant's evapotranspiration demand, and simultaneously keeping the soil moisture within the desired limit during different ontogenic stages, would ensure a production sustainability of citrus orchards in addition to prolonged orchard's productive life (Pyle 1985). Besides the mobility of nutrients, fertigation has several advantages over broadcast application of granular fertilizers (Willis *et al.* 1991) with respect to development of uniform root distribution in wetted zone, an important pre-requisite for better FUE (Zhang *et al.* 1996), improvement in fruit quality (Bowman 1996), and effective placement of nutrients and flexibility in application frequency (Ferguson and Davies 1989). However, increasing fetigation frequency from 12 times a year to 80 times a year showed no reduction in leaching losses of N in Hamlin orange grown on Candler sand (Syvertsen and Jifon 2001).

Bester *et al.* (1977) observed an increase in leaf nitrogen levels of young trees fertigated frequently with NPK solution when compared to a broadcast fertilizer application using sprinkler irrigation system, but no significant difference was observed with respect to P and K levels. Similar observations were later made by Intrigliolo *et al.* (1992) while comparing a single annual application of NPK to continuous fertigation. Other studies showed far superior results with fertilizers applied through drip irrigation (fertigation) in Spain (Legaz *et al.* 1981), central India (Shirgure *et al.* 2001a, 2001b), and in Arizona (USA) using microsprinklers over basal fertilizer application under flood irrigation (Weinert *et al.* 2002). Studies from Zhang *et al.* (1996) evaluating the effect of fertigation versus broadcast application of water soluble granular fertilizer on the root distribution of 26-year-old 'White Marsh' grapefruit trees on sour orange rootstock, showed 94% of the root density in the top 0-30 cm depth with soluble granular fertilizers. These observations supported the earlier observations that shallow depth of wetting and delivery of nutrients, in fertigated production systems, results in concentration of most of the roots in the surface soil (Alva and Syvertsen 1991; Zhang *et al.* 1998). Fruit yield of Nagpur mandarin with different micro-irrigation systems on Vertic Ustochrept was significantly higher (48.2-58.9 kg tree^{-1}) over basin irrigation (32.3 kg tree^{-1}) with corresponding WUE of 0.19-0.24 versus 0.109 t^{-1} ha^{-1} cm^{-1} and leaf N content of 2.38-2.42% versus 2.01-2.12% (Shirgure *et al.* 2001c, 2003). Fertigation (application of nutrients through the irrigation) has produced better results in improving the tree growth, fruit yield, quality, the reserve pool of soil nutrients, and consequently, the plant nutritional status (Zhang *et al.* 1996; Shirgure *et al.* 2001a). Other studies (Shirgure *et al.* 2001a, 2001b) in central India showed far superior results with fertilizers applied through drip irrigation (fertigation) over basal fertilizer application using basin/ flood irrigation.

Koo (1984a, 1984b) while describing the importance of ground coverage of orchard floor by fertigation reported that the treatment having 37% coverage of ground and 82% of canopy area produced fruit yield higher than the broadcast fertilizer treatment covering 100% of soil surface and 53% canopy area. These observations suggested the importance of canopy coverage for high nutrient uptake efficiency and higher yield. Similarly He *et al.* (2004) stressed upon under-canopy fertigation than in spaces between the trees for improved P-uptake efficiency in grapefruit. Response of six year-old 'Hamlin' orange to fertigation frequency using 324 to 464 g N/tree, showed NUE ranged from 24 to 41% of N applied, but no effect of fertigation frequency on the amount of N taken up by the trees, was observed when fertigation frequency increased from 12 to 80 times year^{-1} (Syvertsen and Jifon 2001). While, Alva *et al.* (2003) earlier found that 18 split fertigation applications through microsprinklers under the trees increased the fruit yield with fertigation than equivalent rates of granular fertilizer treatments due to greater nutrient uptake efficiency.

Alva *et al.* (2003) later studied the comparative response of 32 months-old non-bearing 'Hamlin' orange trees on a Candler fine sand (Typic Quartzipsamments) using three methods of fertilization namely, fertigation (FRT), controlled release fertilizers (CRF), and water soluble granular fertilizers (WSG) at two rates, high and low fertilizers rates. Total N content in tress which received the higher fertilizer rates were 82.3, 70.2, and 41.4 g tree^{-1} for the FRT, CRF, and WSG sources, respectively. The corresponding values for the low- fertilizer rate treatments were 38.6, 50.4, and 28.4 g tree^{-1}. However, the proportion of total N partitioned to leaves was greater for WSG than for the CRF and FRT sources at both the fertilizer rates. Similar observations were made through the response of 25 yr-old 'Hamlin' orange in Highland county with varying N rates (112-180 kg ha^{-1}) and fertilizer management practices (WSG, CRF and FRT). Spring flush leaf N content increased with increasing N rates decreased in the order of FRT > WSG > CRF (Paramasivam *et al.* 2000). Other studies by He *et al.* (2003) involving CRF (1 application year^{-1}), FRT (15 applications year^{-1}), and WSG (3 applications year^{-1}) showed no response of fertilizer sources either on fruit yield of grapefruit or leaf nutrient composition on Arenic Glossaqualf soil.

Irrigation at 20% depletion of available water content (AWC) combined with fertilizer treatment of 500 g N + 140 g P + 70 g K tree^{-1}year^{-1} produced a significantly higher magnitude of fruit yield per cubic metre of canopy in addition to higher nutrient status and fruit quality compared to other treatments involving irrigation either 10% depletion or 30% delpetion of AWC with 600 g N + 200 g P + 100 g K tree^{-1} year^{-1} in 14-yr-old Nagpur mandarin (*Citrus reticulata* 'Blanco') on an alkaline calcareous Lithic Ustochrept soil type (Srivastava *et al.* 2003). Field experiments on response of pre-bearing acid lime plants to differential N-fertigation versus circular band placement (CBP) method of fertilizer application showed superiority of former over latter treatments. The higher leaf N, P and K with 80% fertigation over 100% N through CBP further demonstrated that saving of N up to 20% can attainable (Shirgure *et al.* 2001c). Experiments carried out by Garcia-Petillo (2000) demonstrated 50% higher leaf N content with 64% higher yield on cumulative basis in fertigation treated trees compared to conventional method of fertilization.

Very little work has been done on fertigation of micronutrients. The major constraint for limited studies on micronutrients is the restricted movement of micronutrients in soil. As soon as the micronutrients are added in soil a major proportion is fixed (immobilized) rendering their reduce uptake efficiency. Studies on effects of the frequency of iron chelate supply by fertigation on iron chlorosis in citrus (Banuls *et al.* 2003) showed comparatively higher fruit yield and quality, besides higher Fe content in leaves. Effect of magnetized water on the fruit yield and transporting distance (mobility) of different nutrients within rhizosphere having sandy loam texture was studied at Wadi E Molake, Ismalia, Egypt. Induced magnetic increase of nutrient extraction from soil was highest for Fe (extractable Fe reached 9 times as much that extracted from normal plots), Zn increased 5 times, P 3 times, and that increase in Mn was only 80%. Fruit yield reached maximum at a water traveling distance of 600 m beyond the magnetron (Hilal *et al.* 2002).

Foliar fertilization

The absorption of nutrients by citrus leaves may be similar to that by roots, the main difference being the transport through plasmalemma. As transport through plasmalemma is an active process, the uptake rate of most of the nutrients is influenced by the physiological status of the leaf (Mengel and Kirby 1987). In leaf tissues, in contrast to the root, this active uptake process is usually not the limiting step in ion uptake. The rate of uptake is controlled by the diffussion of plant nutrients from the water film on the leaf surface (which is usually higher than in the soil solution) through the cuticle and cell material to the plasmalemma. Foliar uptake is believed to consist of two phases viz., nometabolic cuticular penetration and further translocation into protoplast. Cuticular penetration is a diffusive process influenced by temperature and concentration gradient, which is generally considered to be the major route of entry and metabolic mechanisms that account for element accumulation against a concentration gradient. The second process is responsible for transporting ions across the plasma membrane and into the cell protoplast. Trace elements taken up by leaves can be translocated to other plant tissues, including roots where the excess of some metals seem to be stored. The rate of trace element movement among tissues varies greatly, depending on the plant organ, its age, and the type of element involved (Srivastava and Singh 2005b).

Foliar sprays of urea (28-31 kg N ha^{-1}) in 'Valencia' orange (Albrigo 1999), multiple application at 1% urea in

'Codoux' clementine mandarin (El-Otmani *et al.* 2002), 10% KCl in 'Eureka' lemon (Qin *et al.* 1996), 5% KNO_3 with 18-20 ppm 2,4-D in 'Shamouti' orange (Erner *et al.* 1993), only 5% KNO_3 in 'Valencia' orange (Koo *et al.* 1984), 1% urea – 5% KNO_3 – 10 ppm GA_3 in Clementine mandarin (El-Otmani *et al.* 2004), 2% Ca $(NO_3)_2$ – 2.38% KNO_3 in Fortune mandarin (Albrigo and Galan Sauco 2004), 0.15% potassium nucleotide in Ponggan mandarin (Jiang *et al.* 2001), and 0.5% K_2SO_4 – 0.2% active dry yeast in Balady mandarin (Ebrahiem *et al.* 2000) demonstrated that only two nutrients, N through urea or low biuret urea and K as KNO_3 or K_2SO_4 are widely used through effective through foliar application.

Likewise, the foliar sprays proved to be more efficient when nutrients were combined with growth regulators (Kannan and Mathew 1970; Kannan 1980). As much as 70 to 80% of a 5% urea (23.3 g N liter^{-1}) solution was absorbed within 24 h (Impey and Jones 1960) and up to 57% of the applied ^{15}N urea (1.77% N) within 48 h (Lea-Cox and Syvertsen 1995) through abaxial surface of young old 'Washington' navel leaves and 'Valencia' leaves, respectively. Urea uptake by young citrus leaves can be up to 6-fold greater than uptake by older leaves, respectively. Such differences could be attributed to increase in epicuticular wax concentrations as leaves aged since nitrogen (Bondala *et al.* 2001). Embleton and Jones (1974) presented evidence from eight field trials over 56 experiment years that citrus production could be maintained by applying 3-6 foliar applications of urea per year, thus implying that 16-33% of the annual requirement of citrus could be supplied with a single foliar application. Foliar N applications could, thus, serve as an alternative to conventional soil fertilization to reduce nitrate losses to groundwater systems and to reduce soil salinity (Embleton *et al.* 1978)

Weinbaum (1978) estimated that a single application of foliar-applied NO_3 would provide only 0.7% of the total seasonal N demand of 2-year old non-bearing pruned trees, but the potential for increasing the concentration of KNO_3 in the spray solution is limited by the tolerance of the foliage to resist salt burn (Leece and Kenworthy 1971). Twenty-four percent of applied ^{15}N –urea was taken up after 1 hour and 54% after 48 h. On an average, only 3 and 8% of K $^{15}NO_3$ was taken up after 1 and 48 h, respectively, in potted 18-month old *Citrus paradisi* (L.) 'Redblush' grapefruit. Urea increased leaf N concentration by 2.2 mg N/g or 7.5% of total leaf N after 48 h compared to a 0.5 mg N/g increase or 1.8% of total leaf N for KNO_3. Since cuticle is nonpolar, movement of ionic compounds like KNO_3 through cuticle might be expected to be less than that of a polar, but nonionic compound like urea (Lea-Cox and Syvertsen 1995). Uptake of ^{15}N from soil and the subsequent partitioning in 6-month-old citrus seedlings was strongly influenced by total N supply and the N demand for new growth, with a larger proportion of applied ^{15}N taken up when N supply was relatively low (Wallace 1954; Lea-Cox 1993). Citrus roots have a greater N uptake-efficiency at low soil N concentrations, it follows that the same would be true for the foliar uptake mechanism; i.e. the greatest concentration gradient exists from the surface into the leaf when leaf or shoot N is low. It is, therefore, hypothesized that foliar N uptake is likely to be more efficient when the demand of N is high, regardless of whether this demand is a function of low N or rapid growth (Lea-Cox and Syvertsen 1995).

Foliar sprays of urea have been reported to enhance the number of flower buds, flowers per inflorescence, and yields under California winter conditions (Lovatt *et al.* 1988; Ali and Lovatt 1992). The timing of such foliar sprays is very important, since trees may not be able to translocate sufficient major nutrients (NPK) to large number of flowers following the initiation of flower bud differentiation due to depletion of nutrients of older leaves during the flowering and fruit set periods along with a large increase in nutrients in new leaves and setting fruits (Sanz *et al.* 1987; Ruiz and Guardiola 1994). Sprays of urea (28-31 kg N ha^{-1}) and Nutriphite (6.1 l ha^{-1} of 0-28-26 product) applied continuously during winter or late, just before full bloom, significantly increased the 'Valencia' orange yield from 978 to 1074-1150 boxes ha^{-1} (Albrigo 1999). A large variation exists with regard to foliar recommendation of micronutrients containing inorganic salts as well as synthetic chelates (**Table 6**).

ORGANIC MANURING

The practice of organic manuring in citrus is quite age old. Gordzhomeladze (1990) evaluated the response of 7-year-old 'Meyer' lemon and 'Kowano-Wase' satsuma mandarin on non-eroded, moderately or heavily eroded soils with different inter-row soil treatments. The studies suggested that

Table 6 Foliar spray recommendations of various micronutrients.

Macronutrient	Crop/*Citrus* spp.	Source
Fe-EDDHA (7 mg Fe l^{-1})	Valencia orange	Zude *et al.* 1999
Fe-polyflavonoid (1%)	*Citrus limon*	Fernandez-Lopez *et al.* 1993
Fe (50 ppm) - Mn (5 ppm) Zn (75 ppm)	Washington Navel	Hassan 1995
$FeSO_4$ - $ZnSO_4$ (0.5% each)	Kinnow mandarin	Dixit *et al.* 1979
Fe - Mn - Zn (1.2% each)	Washington Navel	Maksoud and Khalil 1995
Mn - Zn (0.40-0.80%)	Valencia orange	Alva and Tucker 1992
$MnSO_4$ - $ZnSO_4$ (0.15%)	Thompson Navel	Razeto *et al.* 1988
$MnSO_4$ - $ZnSO_4$ (0.5% each) - $CuSO_4$ (0.25%)	Coorg mandarin	Nanaya *et al.* 1985
$MnSO_4$ (0.45 kg 378.5 l^{-1}) - $ZnSO_4$ (0.23 kg 378.5 l^{-1})	Lemon	Alcarez *et al.* 1986
$FeSO_4$ (0.25%) - $MnSO_4$ (0.05%) - $CuSO_4$ (0.25%) - $ZnSO_4$ (0.05%) - $MgSO_4$ (0.05%)	Mosambi sweet orange	Desai *et al.* 1991
$ZnSO_4$ (0.5%) - Borax (0.2%)	Kinnow mandarin	Singh and Misra 1986
Zn-EDTA (0.5%)	Mosambi sweet orange	Dube and Saxena 1971
$ZnSO_4$ (0.6%) - 20 ppm 2,4-D	Kagzi lime	Singh and Misra 1986
$ZnSO_4$ (0.5%) - K_2SO_4 (4%)	Kagzi lime	Singh *et al.*1989
$ZnSO_4$ (0.5%) – $FeSO_4$ (0.5%)	Kagzi lime	Ingle *et al.* 2002
Zn-EDTA - Mn-EDTA (0.10%)	Lemon	Rawash *et al.* 1983
Zn-EDTA (0.10%)	Washington Navel	El-Gazzar *et al.* 1979
$ZnSO_4$ (0.5%) - $CuSO_4$ (0.25%)	Kinnow mandarin	Arora and Yamdagni 1986
$ZnSO_4$ (0.61 g l^{-1}) - $MnSO_4$ (1.2 g l^{-1})	Valencia orange	Garcia-Alvarez *et al.* 1986
$ZnSO_4$ (0.5%) - $CuSO_4$ (0.3%) - Borax (0.3%)	Kinnow mandarin	Singh *et al.* 1990
Zn-EDTA (0.4%) - Cu-EDTA (0.2%)	Kinnow mandarin	Sharma *et al.* 1999
$ZnSO_4$ (0.5%) - urea (1.5%)	Kagzi lime	Rathore and Chandra 2001
Ammonium molybdate (500 mg l^{-1})	Satsuma mandarin	Huang and Wang 1991
B (0.2-0.4%)	Kinnow mandarin	Rai and Tewari 1988
Borax (0.2%) - $MgSO_4$ (0.2%) - $ZnSO_4$ (0.1%) - Yemianbao	Jiaogan mandarin	Wang 1999
$ZnSO_4$ (0.5%) - Borax (0.2%) - $FeSO_4$ (0.4%)	Mosambi sweet orange	Ghosh and Besra 2000

the highest yield was obtained by sowing vetch, oat, and soybean in the autumn and ploughing in the spring on non-eroded soil. While, Huang (1998) in other studies demonstrated the response of different green manure crops viz., 'Indian' cowpea (*Vigna unguiculata*), groundnut, soybean, vetch and Chinese milk vetch (*Astragalus sinicus*) in hill-side citrus orchards after twenty years of experimentation. Santinoni and Silva (1996) on the other hand, made different observations on the response of 'Willow' leaf mandarin (*Citrus deliciosa*) and Cleopatra mandarin (*Citrus reshini*) trees to different soil management regimes. The highest (366 kg tree^{-1}) and lowest (208 kg tree^{-1}) cumulative yield of six years were observed with disking between rows and with herbicide treatment in the rows and *Chloris gayana* grown between the rows by hand weeding in the rows, respectively. Non-linear regression models have shown wide application in many of the fruit crops (Doving and Mage 2001; Correia *et al.* 2002) for yield predictions in relation to plant nutrition.

Wide plant–to–plant and row–to–row spacings are commonly used for citrus plantation and the growers are, therefore, tempted to utilise the ample space left between plants by growing intercrops, the success of which is often compromised with the health of citrus as a main crop, in addition to orchard productivity, especially under irrigated conditions (Cary 1981; Stofella *et al.* 1986). Most of the citrus-based intercropping studies have addressed the problems associated with the cropping system in pre-bearing orchards (Singh *et al.* 1999). Limited studies are available with respect to evaluation of intercrops in bearing citrus orchards. Consequently, the reports about the beneficial effect of intercrops on the health of main crop or fruit yield are conflicting (Gordzhomeladze 1990; Santinoni and Silva 1996; Huang 1998). The major points of difference among these studies include: growing intercrops under rainfed or irrigated conditions, environmental conditions, crop duration, and nutrient requirement of intercrops (Reddy *et al.* 2003).

The optimum levels of nutrients for intercropped orchards were collectively determined using non-linear multiple regression analysis ($R^2 = 0.713$, $p = 0.01$) as: 2.18% N, 0.08% P, 1.24% K, 61.2 ppm Fe, 52.3 ppm Mn, 15.8 ppm Cu, and 18.6 ppm Zn in relation to fruit yield of 50.6 kg tree^{-1}. In order to obtain fruit yield in intercropped orchards on par to monocultured orchards, different nutrient levels viz., 2.50% N, 0.13% P, 2.78% K, 60.4 ppm Fe, 48.1 ppm Mn, 18.3 ppm Cu, and 29.0 ppm Zn were predicted to be maintained which is a rather difficult task to accomplish (Srivastava *et al.* 2007). The poor fruit yield of 23.2-46.2 kg tree^{-1} was predicted for orchards with intercrops like maize, wheat, and okra. While the optimum level of leaf nutrient concentration vis-à-vis fruit yield predicted for legume based intercropped orchards (67.8-71.3 kg tree^{-1}) were significantly higher than monocropped (66.7 kg tree^{-1}) and the other intercropped based orchards. The specific intercrop-based yield prediction models could further monitor the desired nutrient level to be maintained in main crop for sustainable citriculture (**Table 7**).

Influence of cover crops on main crop

Earlier studies have shown an improvement in fruit yield under cover crops compared to clean cultivation (Jones *et al.* 1961; Gordzhomeladze 1990; Fageria 2007). As early as Batchelor and Webber (1948) observed reduction in citrus yield using lucerne as intercrop. On the other hand Gill (1988) reported that highest yield of stylo (*Stylosanthus hamata*) under lemon and kinnow in comparison to guava and mango. In the studies carried out at National Research Centre for Agroforestry, Jhansi, India showed the highest yield of urd (4.3 q ha^{-1}) was observed in association with kinnow mandarin compared to urd yield (2.5 q ha^{-1}) in association with ber (pers. comm.). Studies by Gonge and Kale (1997) showed non-significant influence of intercrop with vegetables on growth parameters of citrus plants studied at various stages. While, 8-10 cm thick paddy straw mulch in Assam lemon (*Citrus limon* Burm.) on sandy soil of India showed significant improvement in growth and yield (Nath and Sarma 1992). Another study by Chowdhury and Deka (1997) showed highest coconut yield (8365 nuts ha^{-1}) where Assam lemon was involved as one of the crops under mixed cropping sequence (Coconut – colocasia – betelvine – banana – Assam lemon). Cultivation of soil (43-49% sand and 23-30% clay) with *Acanthus mollis* and *Amaranthus retroflexa* in spring liberated good amount of tied N which benifitted the Satsuma mandarin trees in improving the fruit yield from 66.0 to 77.7 tonnes ha^{-1} and from 67.7 to 80.7 tonnes ha^{-1} in 1987-89 and 1988-89, respectively (Pisa and Fenech 1990). The performance of Coorg mandarin (*Citrus reticulata* Blanco) was poor when grown along with coffee plantation in Kodagu district of Karnataka, India (Kerikanthimath *et al.* 1997).

Rodriguez *et al.* (1964) in Brazil observed a better yield of citrus trees where a leguminous cover crops or a deal mulch is used. Additionally cover crops proved to be effective in providing protection to the citrus trees from freeze (Jordan 1982; Parsons *et al.* 1985; Jackson and Ayers 1986; Santinoni and Silva 1996). Economides (1976) examined the effects of 3 different soil management treatment on growth, yield and fruit quality of Valencia orange trees planted at 5.4 × 5.4 m spacings (343 trees ha^{-1}). The soil management treatments receiving winter grown cover crop of *Vicia sativa* treatment were 26.5% larger, and produced 15.0% more fruits, than trees on plots receiving summer clean cultivation or zero tillage herbicide weed control soil management treatment, respectively. The average annual fruit yield for the 10 years period (1964-1973) was observed to be: 43.4, 36.4 and 31.4 metric t ha^{-1}, respectively, in *Vicia sativa* treatment, summer clean cultivation, and zero tillage. Pehrson (1971) in California suggested prostate spurge as a suitable cover crop, since it grows mainly during the summer months, which provides good protection against soil erosion without increasing the winter frost hazard. The studies by Srivastava *et al.* (2007) suggested soyabean as most suitable intercrop for Nagpur mandarin grown on black clay soils of Central India. It is recommended the gram, peas, and guar for use of intercrops which provided

Table 7 Leaf nutrient composition and fruit yield of main crop ('Nagpur mandarin') under different intercrops in relation to monocropped orchards.

Intercrops	**Yield**		**Nutrients concentration in main crop**						
	Main crop (kg tree^{-1})	**Intercrop (tonnes ha^{-1})**	**N**	**P**	**K**	**Fe**	**Mn**	**Cu**	**Zn**
			----------------(g kg^{-1})--------------			-------------------(mg kg^{-1})----------------------			
Wheat (*Triticum aestivum L.*)	33.2	0.80	1.62	0.07	0.89	70.4	54.9	15.3	16.1
Maize (*Zea mays* L.)	28.4	1.20	1.50	0.06	0.82	67.8	50.8	15.7	15.0
Cotton (*Gossypium hirsutum* L.)	50.3	0.10	1.78	0.07	1.30	79.3	58.7	16.8	17.9
Marigold (*Targets exacta* L.)	52.2	2.80	1.96	0.06	1.53	81.4	60.8	18.7	18.6
Chickpea (*Cicer arientinum* L.)	71.7	0.40	2.30	0.11	1.95	87.4	70.4	21.9	22.1
Soybean (*Glycine max*. L.	72.8	0.48	2.40	0.14	2.20	85.6	71.8	22.5	21.9
Okra (*Abelmoschus esculentus* L.)	53.1	0.60	1.88	0.11	1.51	78.8	54.9	19.1	18.2
Intercropped	51.4	-	1.90	0.08	1.44	78.7	59.1	17.1	15.5
Monocropped	68.5	-	2.29	0.13	2.47	79.2	63.8	21.7	23.2
CD ($P = 0.05$)	2.4	-	0.10	0.01	0.20	1.8	3.1	0.92	1.6

Sources: Srivastava *et al.* (2005, 2007)
CD = Critical difference

beneficial effects on health of the citrus trees. Huang (1998) based on 20 years of experimentation in hillside citrus orchards on red soil at 275-900 m altitude showed that Indian cowpea (*Vigna unguiculata*), groundnut, soyabean, vetch, and Chinese milk vetch (*Astragalus sinicus*) as suitable green manure crops. But, leguminous green manure crops needed phosphorus fertilization at the rate of 375-600 kg ha^{-1} before sowing.

Yesilsoy *et al.* (1987) observed an improvement in yield and quality of clementines and sweet oranges by ploughing the vetch (*Vicia*) oats green manure crop. Potential of citrus (grapefruit cv. 'Ruby Red' Swingle citrumelo) – cowpea (*Vigna unguiculata*) intercropping in south Florida on raised beds (15.2 cm apart and 107 cm high) planted with 2 rows of trees spaced 7.3 m apart with 5.2 m in row spacing (246 trees ha^{-1}) produced a yield of 1.84 t ha^{-1} compared to 2.78 t ha^{-1} as monoculture (Stofella *et al.* 1986). Mandarins are grown in south India in coffee estates as shade trees along with *Eucalyptus tereticornis*, *Casuarina equisetifolia* and *Grevillea robusta*. Mandarin trees growing with *Grevillea robusta* yielded as much as mandarin trees growing alone, followed by trees growing with *Causuarina equisetifolia*. But, *Eucalyptus tereticornis* had an adverse effect on mandarin yield (Hanamashetti *et al.* 1987). Allelopathic interactions could also leave the same effect as the extreme end of minimum tillage. A better fruit yield of mandarin was obtained on red earth soil (humus 1.2-3.0%, pH 4.7-4.8) cultivated with lupins (*Lupinus albus* Linn.), peas (*Pisum sativum* Linn.) and *Lespedeza bicolor* (Tavartkildaze 1969; Hurcidze 1969). Sweet orange (*Citrus sinensis* Osbeck) intercropped with Cassava (*Manihot esculenta* cv. 'TMS 30572') plus maize (*Zea mays* cv. 'TZSR-W'), egusi melon (*Citrullus lanatus* cv. 'Bara') followed by soybeam (*Glycine max* cv. 'TGX-1805-17F'), chillip pepper (*Capsium frutescens* cv. 'NHVIB') plus amaranthus (*Amaranthus caudetus* cv. 'Large green') showed that fruit yield of sweet orange intercropped with chilli pepper plus amarathus did not differ significantly from yields of monocropped sweet orange trees. However, intercropping with chilli pepper plus amarathus gave the highest yield efficiency of sweet orange trees (Aiyelagbe 2001).

Cover crops and changes in soil properties

Luo *et al.* (1992), based on 8 years of experiments, showed yellow clover (*Melilotus officinalis*) as a promising green manure crop for citrus which can add 7.5-12.0 tonnes ha^{-1} green biomass adding 36.7-58.8 kg N, 3.7-6.0 kg P, and 23.2-37.2 kg K ha^{-1} into the soil. Bin (1983) suggested the role of green manure in raising the soil fertility through the expansion of soil nitrogen source, concentrating and activating the soil phosphorus pool, maintaining and renewing the SOM improvement in soil structure and soil-nutrient-nutrient supplying capacity. Application of 20 cm thick grass mulch in a nonirrigated orchard of 13-15 year old 'Satsuma' and 'Dahong' sweet orange trees on *Poncirus trifoliata* for three years increased the SOM, available N, P, and K by 68, 67, 86, and 107%, respectively, at Rongjiang county, Guizhou, China (Jiang *et al.* 1997). Mowing of sod-like *Stylosanthes gracilis* in citrus orchard reduced the root competition on low P soil that finally improved the P uptake by plant (Yao *et al.* 2004).

Litter fall and decomposition were studied in agroforestry system involving large cardomon (*Amomum subulatum*) and Nagpur mandarin (*Citrus reticulata* 'Blanco') in the Sikkim Himalaya, India. There were stands with N_2-fixing trees (*Alnus nepalensis* over large cardamom and *Albizia sitpulata* (*A. chinensis*) over mandarin agroforestry or without them (but with native non-symbiotic mixed multipurpose tree species in the case of mandarin, and natural mixed species forest cover in the case of cardamom) in both the systems. The total annual litter (litter + crop residue) production was higher in *Alnus*-cardamom than in the forest cardamom stand and in the mixed tree species-mandarin than in the *Albizia* mandarin stand. The ratio of litter production to floor litter was higher in the N_2-fixing species than in mixed tree species and crops. The P turnover in N_2-fixing *Alnus* and *Albizia* twigs was faster than in the twigs of mixed tree species. The N_2-fixing tree species increased the N and P cycling through production of more aboveground litter and influenced greater release of these nutrients (Sharma *et al.* 1997a). In another study by Sharma *et al.* (1997b) on seasonal soil nutrient dynamics under same experimental set up. C/N ratio was observed higher in cardamom agroforestry indicating lower N availability than in mandarin agroforestry. Cardamom stands with *Alnus* showed a relatively narrower C/N ratio. N_2-fixing species helped in maintenance of SOM levels with higher N-mineralization rates and land use changes from natural-forest system to agroforestry system with sparse tree populations. Ratios of inorganic P/total-P were lower in cardamom agroforestry than mandarin agroforestry.

Organic mulching

Organic mulches have proved very effective in maintaining slow release of nutrients for the long term health and fertility of soil, besides suppressing weeds. Geotextile mulches (peper or woven plastic fabrics) are also often used by some growers, but are costly. Mulches other than live mulches (cover crops) have also proved effective in citrus orchards. Bredell *et al.* (1976) examining the effects of various types of mulches on soil behaviour and growth of Valencia orange trees, showed that mulched trees out-yielded the trees receiving grass sod culture by a factor of two. They further found that under plastic mulch, soil at 10 cm depth was 1°C warmer at night and 1°C cooler during the day than grass sod or bare soil.

Khurtsidze (1972) and Chkheidze and Akhaladze (1975) suggested an improvement in mandarin yield by 40% by mulching soil with peat at the rate of 300 t ha^{-1} in Georgia. Sod culture in the form of *Stylosanthes gracilis* showed a much better response with reference to beneficial effect on soil microbial activity and stability of soil structure over *Pueraria javanica* or *Digitaria abscendens* (Godefray and Bourdeaut 1972). Other studies (Mikaberidze and Rosnadze 1972; Bredell and Barnard 1974) showed higher tree volume of young Valencia budded on rough lemon mulched with black perforated polythylene, which not only reduced soil moisture evaporation, but maintained the daily soil temperature fluctuation at minimum upto 30 cm depth. Pacheco *et al.* (1975) observed least sheet erosion with mulching or perennial soyabean cut in flow or perennial soyabean with seeds harvest using green manuring with cowpea (*Vigna sinensis*) or soil cultivation under sweet orange on Rangpur lime. Other study by Saha *et al.* (1974) observed best response of lemon (*Citrus limon* Burm.) on growth, flowering, and fruit set using clean cultivated soil covered with straw mulch. Amami and Haffani (1973) observed that on a lighter sandy soil, black plastic conserved the most moisture, while on clay soil, straw mulch (15 tonnes ha^{-1}) gave the highest yield of Maltaise orange, besides improvement in fruit quality and soil texture.

According to Beraya and Akhaladze (1971), mulching with peat and black polythylene improved mandarin yield by 90 and 36%, respectively on a south-west 10-14° slope without irrigation. Similar results were reported through other studies by Rosnadze (1969, 1971) with young mandarin trees and by Strauss (1966) using saw dust. Sheet mulches create barrier for weeds besides checking the soil moisture loss to a considerable extent. A black polythylene mulch, placed around trickle irrigated orange trees at planting, increased yields by 36% after 4 years (Bacon 1974). The mulch also increased tree size, but circumference was increased by 12% and the canopy surface area by 25%. The soil temperature at 10 cm depth was up to 2.5°C higher under the mulch, but the differences were much less under trees with more complete shading. These observations suggested that mulching may be important in extending the root growing early in the life of the trees, but becomes less effective after canopy development.

The effects of three different cover crops on the chemical, biological, and structural characteristics of an orchard soil in the Ivory Coast were examined by Godefray and Bourdeaut (1972). They compared a 10-year-old natural grass cover (composed of *Pospalum* and *Digitaria abscendens*), with a 3-year-old *Stylosanthes gracilis* cover (preceded by a 10-year-old natural grass cover), and a 10-year-old *Pueraria javanica* cover. *S. gracilis* was equally as good as natural grass in increasing soil microbiological activity, and as good as *P. javanica* in improving soil structural stability. In the latter respect, however, natural grass was inferior to both *S gracilis* and *P. javanica*. The results further advocated that *S. gracilis* could be preferred as a soil cover, not only for its beneficial effect on soil microbiological activity and soil structural stability, but also for its ease of maintenance.

Eaks and Dawson (1979) evaluated the effects of vegetative ground cover and bare soil on Valencia orange fruit rind colour. The ground cover composed of naturally occurring herbs and grasses, were mown regularly at a height of 5 cm. They found the higher carotenoid and lower chlorophyll content in the fruit peel from ground cover plots than in fruits from bare ground plots. Regreening of fruit was also significantly less on ground cover plots. The improvements in quality parameters such as better colour and reduction in regreening on ground cover plots to lower average (2.5°C) temperature maintained at 10 cm depth compared to bare soil. At the same soil depth, daily maximum temperature was up to 5°C (and daily minimum temperatures up to 5.6°C) less under ground cover than bare soil. Suitability of different mulches on citrus showed that out of the mulches tested, only yard waste and rice hulls were not harmful to any of the growth parameters of citrus, which could be a suitable substrate for the growth of three bioagents viz., *Trichoderma harzianum*, *Gliocladium virens*, and *Pseudomonas fluorescens*, indicating thereby the mulch characteristics which favour healthy roots of citrus, also favour growth of certain useful bioagents (Casale *et al*. 1995).

Response of green manuring

The practice of green manuring, growing a crop like *Sesbania*, and ploughing in the soil holds promise in citrus orchards. Non-availability of some organic manures in adequate quantity is common problem. Efforts to take advantage of biological-N fixation and recycling of biological waste are, thus, necessary. Tavartkiladze (1969) observed higher yield in mandarin with the use of lupins, peas and *Lespedeza bicolor* as green manure crops coupled with NPK (g tree^{-1}) at a rate of 80 g N, 300 g P_2O_5, and 100 g K_2O tree^{-1}. Hurcidze (1969) observed a good response of legumes as green manure in silt soils of Kolkhida in improving the productivity of mandarins. Release of NH_4-N and NO_3-N during decomposition of green manure residue at varying soil moisture levels indicated an increase in accumulation of NH_4-N with an increase in soil moisture tension from 0.01 to 0.9 Mpa while NO_3-N release was 14 times less at 0.9 Mpa than 0.01 Mpa soil moisture tension (Brar and Sidhu 1995). On the other hand, comparison of oilcake, fresh green manure, and rice straw showed that oilcake was not as effective as the other two sources in reclamation of purple soil of the newly established orchard (Zhou *et al*. 2001).

Increase in available N was observed invariably in soil treated with poultry manure compared to swine manure or FYM (Rayar 1984). More and Ghonsikar (1988) reported that the availability of P increased when superphosphate was mixed with poultry manure and applied to soil than application of superphosphate alone. Sharma and Saxena (1990) confirmed that poultry manure followed by castor cake and FYM increased the P availability in soil. Adding single superphosphate and poultry manure together to soil resulted in higher P availability. Application of poultry manure decreased the adsorption capacity and increased the soluble-P and phosphorus desorption (Reddy *et al*. 1980). A marked increase in the exchangeable K due to application of poultry manure was observed in a study by Madhumita *et al*. (1991). A long-term comparison of the effect of poultry manure and compost with reference to soil quality changes in organically managed citrus orchard at Sicily, Italy showed that these manures weakly affected soil properties, through they increased the soil potentially available nutrients (Canali *et al*. 2004).

INTEGRATION OF MANURES AND FERTILIZERS

Improvement in fruit eating quality of Satsuma mandarin treated with rapeseed cakes and Qixing organic compound poultry manure (Huang *et al*. 1995; Shi *et al*. 2000), promising role of chicken manure in citrus fertilization program in Florida USA (Fischer 1992), and Urea-N + farmyard manure for better pre-bearing performance of kinnow mandarin (Dudi *et al*. 2003) supported integrated basis of nutrient management. As early as 1969, Ozordzadze observed that the average yield of ‘Satsuma’ mandarin doubled with peat + fertilizer treatment and farmyard manure + P, K nutrients compared to unfertilized trees. A number of studies indicated improved efficacy of fertilizer nutrients with combined use of manures and fertilizers (Prasad and Singhania 1989; Rokba *et al*. 1995) or combined use of inorganic fertilizers (Singh *et al*. 1993; Medhi *et al*. 2006) in addition to enzymatic activities (acid phosphatase, dehydrogenase, and urease) of soil (Tiwari 1996).

The response of different rootstock types viz., sour orange, Swingle citrumelo, Troyer citrange, and cleopatra mandarin seedlings grown on a mixture of peat, vermiculite, and sand showed an increase in root: shoot dry weight ratio by 15 and 21%, with application of 0.5 and 1% root solution, respectively, as bio-stimulant containing humic acids, marine algae extracts, plant metabolite, and vitamin B (Swietlik 1991). According to Hsiung and Iwahori (1984), organic salts of calcium were more effective than inorganic salts in retarding abscission of the explants when added to ethephon solution. In particular, calcium propionate and calcium salicylate were highly effective, followed by calcium acetate. Reddy *et al*. (1980) showed that animal manure increased soluble phosphorus in soil. Many organic materials like manures, muck, cake fertilizers, and peat mixed with $FeSO_4$ alleviated the Fe-deficiency induced chlorosis on

Table 8 Change in organic carbon stock (%) over initial values due to different organic manuring treatments (Pooled data 2003-2007) to ‘Nagpur’ Mandarin in central India.

Treatments	Initial	2004-05	2005-06	2006-07	Net increase over initial
T_1 - Farmyard manure	0.50	0.59	0.57	0.56	0.06
T_2 - Vermicompost	0.51	0.58	0.61	0.64	0.13
T_3 - Poultry manure	0.54	0.58	0.63	0.65	0.11
T_4 - Neem cake	0.52	0.54	0..57	0.60	0.08
T_5 - Green manure (Sunhemp)	0.58	0.62	0.68	0.74	0.16
T_6 - Inorganic fertilizers (NPK)	0.54	0.56	0.55	0.57	0.03
CD (*P=0.05*)	NS	0.02	0.02	0.04	0.02

T_1 – T_4 were computed on N-equivalent basis T_1(60 kg tree^{-1}), T_2(40 kg tree^{-1}), T_3(30 kg tree^{-1}), T_4(20 kg tree^{-1}), T_5 (seeds of *Crotolaria junces* sown beneath tree canopy), and T_6(600 g N – 200 g P_2O_5 – 100 g K_2O tree^{-1})
Source: Gupta and Srivastava (2007)

Table 9 Change in available nutrients (mg kg^{-1}) in soil as influenced by different organic manuring treatments (Pooled data 2003-2007) to 'Nagpur' mandarin in central India.

Treatments		**Macronutrients**			**Micronutrients**			
		N	**P**	**K**	**Fe**	**Mn**	**Cu**	**Zn**
T_1	Farmyard manure	118.6	12.9	143.7	10.6	12.1	1.1	0.94
		(2.20)	(0.084)	(0.87)	(92.5)	(42.5)	(7.9)	(17.7)
T_2	Vermicompost	179.5	14.7	244.3	14.0	19.9	3.0	1.40
		(2.34)	(0.104)	(1.32)	(117.6)	(58.1)	(11.0)	(22.5)
T_3	Poultry manure	183.7	15.9	200.1	12.9	16.4	2.9	1.20
		(2.32)	(0.081)	(1.08)	(107.0)	(51.2)	(10.1)	(21.0)
T_4	Neem cake	142.7	10.6	158.5	10.8	12.3	2.0	1.10
		(2.24)	(0.084)	(0.99)	(104.2)	(43.4)	(9.0)	(20.5)
T_5	Green manure (Sunhemp)	188.2	17.6	258.5	18.2	22.4	4.6	1.30
		(2.48)	(0.127)	(1.85)	(125.7)	(66.4)	(12.7)	(24.9)
T_6	Inorganic fertilizers (NPK)	109.1	11.2	168.2	12.1	10.3	1.5	1.00
		(2.11)	(0.084)	(0.88)	(87.3)	(39.3)	(6.0)	(18.9)
	CD (*P* = 0.05)	3.6	1.1	9.1	1.1	2.1	0.69	0.10
		(0.11)	(0.016)	(0.12)	(2.6)	(3.3)	(0.9)	(0.42)

T_1 – T_4 were computed on N-equivalent basis T_1 (60 kg $tree^{-1}$), T_2 (40 kg $tree^{-1}$), T_3 (30 kg $tree^{-1}$), T_4 (20 kg $tree^{-1}$), T_5 (seeds of *Crotolaria junces* sown beneath tree canopy), and T_6 (600 g N – 200 g P_2O_5 – 100 g K_2O $tree^{-1}$)
Figures in parenthesis indicate leaf nutrient composition
Source: Gupta and Srivastava (2007)

Table 10 Response of different INM-based treatments on fruit yield of Kinnow mandarin (Location 1: Soil order Entisol) and Khasi mandarin (Location 2: Soil order Alfisol).

Treatments	**Location 1: Ludhiana, Punjab**		**Location 2: Tinksukia, Assam**	
	2005-06	**2006-07**	**2005-06**	**2006-07**
T_1	72.8	46.4	82.8	84.4
T_2	78.2	49.5	72.9	74.8
T_3	82.2	53.6	79.8	78.0
T_4	72.2	44.4	107.1	110.8
T_5	69.6	40.3	87.3	88.7
CD (*P* = 0.05)	4.6	2.9	10.7	14.9

T_1 - RDF (recommended doses of fertilizers, 600 g N – 300 g P_2O_5 – 600 g K_2O – 7.5 kg neem, cake $tree^{-1}$), T_2 – 100% R DF + AM (arbuscular mycorrhiza)500 g $plant^{-1}$) - PSB (phosphate solubilising bacteria 100 g $plant^{-1}$) – Az (*Azospirillum* 50 g $plant^{-1}$) , T_3 – 100% RDF – AM – PSB – Az – Th (*Trichoderma harzianum*) 100 g $plant^{-1}$, T_4 - 75% RDF – AM – PSB – Az – Th, and T_5 – 50% RDF – AM – PSB – Az – Th
Sources: Medhi *et al.* (2006), Murti *et al.* (2008)

calcareous soils (Loeppert and Clarke 1984; Loeppert 1986; Chen *et al.* 1990).

In long-term evaluation of different organic manuring treatments maximum net increase in organic carbon content was produced by treatment effect of green manuring (sunhemp) (0.16%)-followed by vermicompost (0.13%), poultry manure (0.11%), neem cake (0.08%), farmyard manure (0.06%), and inorganic fertilizers (0.03%) over three years. A marginal increase in organic carbon content in response to inorganic fertilizers refutes the conventional notion that long sustained use of inorganic fertilization has incurred depletion in soil organic carbon, responsible for deterioration in soil quality and inducing nutrient mining (**Table 8**; Gupta and Srivastava 2007). On the other hand, changes in soil fertility status in response to different organic manuring treatments showed (**Table 9**; Gupta and Srivastava 2007) a consistent increase in almost all the nutrients (available nutrients in soil or leaf nutrients concentration)) with all the treatments. Green manuring treatment produced the maximum increase in available nutrients followed by poultry manure, vermicompost, neem cake, farmyard manure, and inorganic fertilizers. These responses were well supported by the changes in leaf nutrient concentration. The efficiency of different treatments in relation to leaf nutrients concentration was rated as: green manure > vermicompost > poultry manure > neem cake > farmyard manure > inorganic fertilizers. Considering these observations, green manuring and vermicompost treatments, have so for produced the best response, although such studies deserve to be interpreted on long term basis. Inclusion of AM (arbuscular mycorrhiza 500 g $plant^{-1}$) + PSB (phosphate solubilising bacteria 100 g $plant^{-1}$) + Az (*Azospirillum* 100 g $plant^{-1}$) + Th (*Trichoderma harzianum* 100 g $plant^{-1}$) to 75% RDF improved the fruit yield of 'Kinnow' mandarin on rough lemon at Ludhiana, Punjab (Location 1) and in 'Khasi' mandarin at Tinsukia, Assam (Location 2) through different INM-based treatments (**Table 10**).

Application of farmyard manure (FYM) in combination with nutrients like N, P, and K improved the leaf area (Pennisi 1971; Motskobilli 1984; Plamenac 1985; Beridze 1990), winter hardiness (Motskobilli 1986) in 'Satsuma' mandarin, canopy volume by substituting up to 50% N with FYM in 'Coorg' mandarin (Mustaffa *et al.* 1997), and fruit quality (juice, total soluble solids, rag content, etc.) in 'Nagpur' mandarin (Huchche *et al.* 1998), 'Blood Red Malta' variety of sweet orange treated with combination of $(NH_4)_2SO_4$ + farmyard manure (Dhillon *et al.* 1961), 'Matau Peiya' cultivar of pummelo treated with dolomite + organic fertilizer (Chen *et al.* 1997), and 'Satsuma' mandarin treated with NPK plus farmyard manure + CaO (Pirchalajsvili 1970) in comparison to inorganic chemical fertilizers carrying NPK alone.

Highest fruit yield with improved quality was obtained with 25 kg FYM with 400 g N - 150 g P - 300 g K $plant^{-1}$ in 'Khasi' mandarin on acid red soils (Ghosh and Besra 1997), 150 kg FYM – 1500 g N – 440 g P_2O_5 – 600 g K_2O $tree^{-1}$ in Navel orange (El- Koumey *et al.* 2000), 52 kg FYM – 1.82 kg $(NH_4)_2SO_4$-N $tree^{-1}$ in 'Balady' mandarin (Gamal and Ragab 2003), and 15 kg neem cake - 800 g N - 300 g P_2O_5 - 600 g K_2O $tree^{-1}year^{-1}$ in sweet orange (Tiwari *et al.* 1997). Arsenidze and Chanukuvadze (1988) observed maximum yield of 'Satsuma' mandarin for the trees receiving PK Ca + FYM with N was applied as ammonium nitrate at 100 g $tree^{-1}$ to 4 to 5 year old tree in Western Georgia. The best fruit yield and quality of 'Balady' mandarin was obtained with the use of FM (a by-product of sugar industry) at a rate of 120 kg + and inorganic 6.0 kg N $tree^{-1}$ (Ebrahiem and Mohamed 2000). The amount of nitrogen fertilizer in a high density planting of 'Satsuma' mandarin can be reduced to 100 kg ha^{-1} $year^{-1}$, if 20 tonnes rice straw ha^{-1} $year^{-1}$, or 200 kg ha^{-1} $year^{-1}$ when no organic matter is applied, without any yield reduction (Tachibana and Yahata 1996). Apart from higher fruit yield (163.3 kg $tree^{-1}$), reduced fruit drop (19.7%) was also observed with integrated use of pig manure (110 kg tree^{-1}) + urea-N (750 g tree^{-1}) + muriate of potash (650 g tree^{-1}) compared to fruit yield (107 kg tree^{-1}) and fruit drop (24.6%) with pig manure (110 kg tree^{-1}) alone in Khasi mandarin (Dubey and Yadav 2003).

Microbiological analysis of citrus soil treated with PK (phosphorus and potassium) or PK + different N types (Gochelashvili 1984) indicated that the soil microflora in young orchards was more responsive to mineral N rates than in mature orchards. In trials with young lemon trees, cv. 'Meyer', NOMF (an organo-mineral fertilizer prepared from peat enriched with neutral solution of Ca industrial waste, Mg, Al, and some other elements) + NPK applied in spring with N as a top dressing in summer, produced 29-38% higher fruit yield. While other study by Lomtadze and Muradova (1986) reported 15-17% higher yields in the first 3 cropping years than NPK alone with peat + NPK applied in spring and N in summer. Influence of different combinations of organic fertilizers like groundnut cake, neem cake, and farmyard manure along with urea-N as inorganic fertilizer showed higher increase in canopy volume and girth of 'Coorg' mandarin by substituting 25% of urea – N with groundnut cake (Mustaffa *et al.* 1997). Highest fruit yield and improved quality (Ghosh and Besra 1997) and concentration of different nutrient in index leaves (Singh *et al.* 1993) were observed with 25 kg organic matter in combination with 400 g N – 150 g P - 300 g K in Khasi mandarin and sweet orange grown, respectively, on acid red soil under humid tropical climate of north-east India and alkaline sandy loam soil of northwest India.

Beridze (1990) observed highest yield of 6.6 tonnes ha^{-1} from the trees receiving basal dressing of 150 kg N – 120 kg P_2O_5 – 80 kg K_2O – 25 kg peat ha^{-1} as a mulch plus 55 tonnes ha^{-1} farmyard manure in 5-year-old 'Meyer' lemon tree. In Georgia, on a podzolized brown earth soil with a low humus N (2.6-3.16%), P (6.8-7.5%), and K (17.4-22.1%), the growth and yield of lemon trees were greater with NPK than FYM application alone (Marsanija 1970). Application of manures and/or fertilizers increased organic carbon, NH^{4+}-N, NO_3-N, and Olsen-P in the soil. Soil pH increased and organic carbon decreased with the increase in the time of incubation. Phosphorus enriched manures maintained a higher level of phosphorus in soil solution for a longer period than the fertilizer alone (Prasad and Singhania 1989). Addition of manure delayed the hydrolysis of urea, and thus, reduced the loss of nitrogen. Nitrogen and phosphorus enriched manures maintained a higher level of available nitrogen and phosphorus in the soil for a longer period than the fertilizer alone. Hsiung and Iwahori (1984) on the other hand, observed that organic salts of calcium was more effective than inorganic salts in retarding abscission of the explants when added to ethephon solution. In particular, calcium propionate and calcium salisylate were highly effective, followed by calcium acetate.

The effect of N viz., 0, 200, 400, 600, and 800 g plant^{-1} year^{-1} through urea and farmyard manure application on yield, quality and shelf-life were studied by Huchche *et al.* (1998). Differential N levels were supplemented with doses of P, K, and farmyard manure. The farmyard manure at 25 kg plant^{-1} year^{-1} alone was kept at the control. Application of N significantly increased the yield of Nagpur mandarin with increasing N rates as compared to farmyard manure alone (**Table 11**). There was no adverse effect of chemical N on physico-chemical properties of fruits. Storage of fruits for 12 days at 20-28°C, 50-70% relative humidity and for 80 days at 5-6°C, 85-90% relative humidity revealed no adverse effect of chemical inorganic N (up to 600 g plant^{-1} year^{-1}) supplemented with P, K, and farmyard manure on weight loss and decay (%) in Nagpur mandarin. The shelf life of fruits was not significantly better when fruits were grown in farmyard manure alone. According to Gill *et al.* (1998), the lowest urease activity was recorded in the plot without organic amendment, while the highest activity was observed in wheat straw amended combined harvested plot followed by N plus farmyard manure plots.

Quality response on various citrus cultivars to combined application of organic manure alongwith inorganic N, P, and K fertilizers is reported widely (Rokba *et al.* 1995; Borah *et al.* 2001). The beneficial effect of supplying 'Balady' mandarin trees grown in sandy soil (during both off or on year bearing state) with filter mud (FM, a by-product of the sugar industry) or farmyard manure (FYM) on growth, nutrition, yield, and fruit quality was studied during 3 successive seasons of 1997-1999. Supplying trees with organic fertilizers in combination with the mineral N source improved shoot length, N, P, and K content in leaves, fruit set, yield, number of fruits per tree, fruit weight, juice percentage, percentage of total soluble solids, and ascorbic acid content. Application of FM provided overall better results compared to that of FYM. The best yield and fruit quality were obtained with the use of FM at 120 kg + 6.0 kg inorganic N tree^{-1} and the rest to be added via any mineral N-source (Ebrahiem and Mohamed 2000). Similarly, response of 20-year-old Washington Navel to combination of chemical fertilizers (200 g N as ammonium sulphate – 100 g P_2O_5 as calcium superphosphate – 120 g K_2O tree^{-1} as potassium sulphate) and FYM (0.06 Mg^3 tree^{-1}) during 2002-04 on sandy soil of El-Tahreer Egypt, showed significantly higher fruit yield, leaf N, P, K, Ca, and juice total solids compared to FYM alone (Maksoud and Haggag 2004).

Another study on effect of various components of INM as application of individual higher doses of farmyard manure (50 kg tree^{-1}) and conjoint use of iron pyrites (200 g) – farmyard manure (25 kg – pressmud 2 kg ha^{-1}) on acid lime (*Citrus aurantifolia* Swingle) on changes in soil fertility status (Aariff and Begum 2007) showed much higher status of available N (196.7 to 219.2 kg ha^{-1}), P(27.6 to 35.1 kg ha^{-1}), K (342.4 to 361.3 kg ha^{-1}), and S (8.4 to 17.4 kg ha^{-1}). Application of 5 kg vermicompost and 20 kg FYM in the months of November and May under sub-humid tropical climate of central India significantly ($p<0.05$) improved the fruit yield and quality over either of individual effect of two, manures individually or when applied in combination with inorganic chemical fertilizers (**Table 12**).

Joe *et al.* (2006) investigated the effect of different me-

Table 11 Response of farmyard manure alone and in combination with inorganic fertilizers on yield, quality and postharvest weight loss and decay at ambient and refrigerated conditions in 'Nagpur' mandarin (pooled data of three growing seasons).

Treatment	Yield	Quality			Weight loss and decay at			
N:P:K + farmyard manure (tree^{-1})	(Fruits tree^{-1})	Firmness (kg force)	Juice (%)	TSS/acid	Ambient condition -----------------(%)-----------------		Refrigerated condition ------------------(%)----------------	
					Weight loss	Decay	Weight loss	Decay
O:200:100 g + 25 kg	524	2.73	41.15	14.24	11.97	1.15	11.28	11.90
200:200:100 g + 25 kg	556	2.73	44.79	12.12	10.84	1.51	10.43	7.15
400:200:100 g + 25 kg	575	2.82	42.88	13.89	11.74	2.22	10.41	8.83
600:200:100 g + 25 kg	658	2.79	44.97	13.89	11.13	0.30	10.91	9.85
800:200:100 g + 25 kg	706	2.76	43.16	14.32	11.63	2.38	11.35	14.67
FYM (25 kg)	495	2.81	44.69	13.14	12.94	1.99	12.88	10.75
LSD (P = 0.05)	112	NS	NS	NS	NS	NS	NS	NS

NS = non-significant
FYM : Farm yard manure
Source: Huchche *et al.* (1998)

Table 12 Response of manure versus integrated treatment of manure plus inorganic fertilizers on yield and quality of Nagpur mandarin.

Treatment	Fruit yield (tonnes ha^{-1})	Fruit quality (%)	
		Total soluble solids	Juice
T_1	28.0	9.62	38.7
T_2	30.7	10.52	41.2
T_3	52.5	10.83	43.3
CD (P = 0.05)	2.2	0.33	1.03

T_1 20 kg FYM (farmyard manure), T_2 recommended doses of fertilizers as 50 kg FYM – 600 N – 200 P_2O_5 – 100 K_2O g tree^{-1}, T_3 5 kg vermicompost + 20 kg FYM tree^{-1}

Source: Ramamurthy (2006)

thods of fertilizers applied for 10 years such as NF (no fertilization), N-P-K (28-40-48 kg 10 acre^{-1}), 3N-3P-3K (84-120-84 kg 10 acre^{-1}), compost (2 tonnes 10 acre^{-1}), and compost plus N-P-K on the density and biomass C of microorganisms, enzyme activities, and amount of phospholipid fatty acid (PLFA) in Satsuma mandarin orchard. No significant difference in the density of microorganisms and biomass C was observed between treatments. However, the density of acid resistant bacteria (613 × 10^3 c.f.u. g^{-1} dry soil) in NF was about twice higher than that in 3N-3P-3K (324.8 × 10^3 c.f.u g^{-1} dry soil) and the number of *Bacillus* spp. in compost treatment was highest. There was a seasonal fluctuation in the number of microorganisms; fluorescent *Pseudomonas spp*. was dominant in spring and gram negative bacteria were in fall. The activity of soil acidic phosphatase was observed as 311.5 (NF), 478.4 (N-P-K), 586.3 (3N-3P-3K), 548.7 (compost), and 503.3 (compost-N-P-K). The activity of CMCase (Carboxyl methyl cellulase) was observed in the order of: 17.5 (NF), 68 (N-P-K), 20.5 (3N-3P-3K), 116.5 (compost), and 106 (compost-N-P-K). The amount of PLFA was significantly high in compost-N-P-K and compost. Principal components analysis with PLFA data showed that microorganisms in compost and compost-N-P-K formed different community from them in other treatments.

Rhizosphere modification through root exudation is an important attribute that regulates not only the availability of nutrients in soil but also their acquisition by plants. Effect of inoculation of AM (*Glomus deserticola*) and *Azotobacter chroococuum* in different combinations with FYM and inorganic fertilizers was studied for 6 seasons on the performance of Kinnow mandarin on alkaline loam soil. Combined use of AM and FYM reduced the soil pH from 8.5 to as low as 6.4. While AM in comparison to *Azotobacter chroococcum* modified the rhizosphere favourable to improve soil nutrient availability and consequent uptake by plants towards better growth, yield, and quality (Usha *et al.* 2004).

Integration of oilcakes and fertilizers

Various studies involving combination of oilcakes with inorganic fertilizers have shown promising results. These included : combination of 15 kg neem cake and 800 g N - 300 g P – 600 g K tree^{-1} year^{-1} in sweet orange on alkaline loam soil (Tiwari *et al.* 1997), 15 kg neem cake – 600 g N - 300 g P - 300 g K along with 15 kg neem cake plant^{-1} year^{-1} in Acid lime on alkaline black clay soils (Ingle *et al.* 2001), 7.5 kg neem cake – 600 g N – 300 g P – 600 g K plant^{-1} year^{-1} in 'Khasi' mandarin on acidic loam soil in Tinsukia belt of Assam (Borah *et al.* 2001), at 7.5 kg castor cake 400 g N – 150 g P – 300 g K plant^{-1} year^{-1} in 'Sathgudi' sweet orange on alkaline sandy loam soil in Tirupati, A.P. (Seshadri and Madhavi 2001), and 7.5 kg neem cake – 800 g N – 200 g P – 300 g K tree^{-1} year^{-1} in Acid lime on black clay soil of central India (Hiwarale *et al.* 2004).

Addition of KCl or $MgSO_4$ (0.15 kg tree^{-1}) with peanut oilcake (1.75 kg tree^{-1}, containing 6.3% N, 1.2% P, and 0.6% K) on red loam soil (pH 6.2, available N 100.6 mg kg^{-1}, P 10.6 mg kg^{-1}, and K 77.0 mg kg^{-1}) significantly increased the yield of *Citrus sinensis* L. Osbeck cultivar, Liu Cheng by 16.8 or 10.9%, respectively. Similarly, the average fresh fruit weight increased by 10.5 or 7.6%, respectively. Qualitywise with peanut oil cake, the application of KCl or $MgSO_4$ enable citrus fruits to observe 3.99 or 1.77% increase of soluble sugar and 0.39 or 0.11% decrease of citric acid over those of peanut oilcake alone treatment. The °Brix/acid ratio, hence increase from 11.8 with peanut oil cake to 31.1 with peanut oilcake plus KCl or 15.9 with peanut oilcake plus $MgSO_4$ (Huang and Yang 1990). Application of neem cake at rate or 7.5 kg + 75% of RDF (recommended doses of fertilizers) produced a better buildup in soil fertility with reference to available N, P, and K (Mukherjee *et al.* 1991).

FUTURE RESEARCH

Despite many cutting edge technologies addressing a variety of core issues of nutrient management, many more issues are yet to be attempted with respect to INM-based citrus production *vis-à-vis* rhizosphere dynamics. Studies on biochemical response in relation to varying nutrient supply systems (through INM modules) especially under agropedological conditions facing multi-nutrient deficiencies and establishing the causal relationship between the physicochemical and microbiological changes within rhizosphere and to be able to coordinate changes in shoot system (changes in canopy size and fruit yield i.e yield efficiency), are very much imperative that are seemingly most sensitive to various combinations of remediative treatment.

Nutrient dynamics is another virgin area where limited attempts have been made using citrus as test crop. Amongst different nutrients, Zn has attracted worldwide investigation from various angles. The changes in rhizosphere bring different simultaneous changes in microbial diversity *vis-à-vis* C_{mic}, N_{mic}, P_{mic} and nutrient regime especially for diffusion limited nutrients like P, Zn, Fe, Mn, etc. has to find serious considerations in any nutrient management program that involves INM-based corrective treatments. Additionally, the conditions under which citrus trees are most likely to respond to corrective Zn-treatments are still not fully understood. The role of Zn in flowering, fruit set, fruit quality (external and internal) and juice shelf life; models defining the critical periods of Zn-supply to assure sustained response and its uptake for helping the management decision under different citrus-based cropping systems; and devising means for improved Zn-uptake efficiency need to be attempted to unravel many of the complexities involved with Zn-nutrition under INM-based production management.

Out of different soil properties, the microbial biomass is the one biological property of soil that undergoes immediate change in response to fertilizer like input. Studies, therefore, need to be undertaken with a view to explore the possibility whether microbial properties could be used as a potential tool for finding out soil fertility constraint instead of available supply of nutrients in soil. Simultaneously, eye should be kept on long term changes in total carbon pool of soil to arrive at the logistic conclusion that sequestration of carbon through improved production level could rejuvenate the lost productivity potential of nutritionally depleted soil. However, it remains to be further established that any change in microbial diversity within the rhizosphere is brought about with different sources of substrate, and if there is any, how the nutrient dynamics is associated with orchard productivity.

Impacts due to environmental changes and anthropogenic activity are the potential threats to the conservation of soil quality, while expanding citriculture to marginal soils having a wide range of limitations. With the availability of more technical know-how on efficient use of bulky organic manures, prolonged shelf life of microbial bio-fertilizers, and better understanding on citrus-mycorrhiza symbiosis with regard to nutrient acquisition and regulating the water relations, a more effective integrated citrus production system could be evolved in future. The molecular approach to breeding of mineral deficiency resistance and mineral efficiency would facilitate to produce nutritionally efficient biotypes in order to maximise the quality production on sustained basis. Fertilizer applications are currently managed to protect environmentally sensitive areas by using controlled release fertilizers (use of organic manures, a befitting option), frequent low concentration fertigation, multiple applications, and variable rate application technology in order to improve fertilizer use efficiency. However, using newly emerging techniques of nutrient management and site specific management on the principles of INM could be worked out accommodating soil's nature and properties. Simultaneously, concreted efforts would be required to develop INM-based yield monitors and soil quality indicators.

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