Diagnosis and Remediation of Nutrient Constraints in Citrus

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LITERATURE CITED

I. INTRODUCTION

Citrus is claimed to have originated in south China and the Cathaysian ancient continent including Sichuan, Kangdian, south of Yangtze river, and Indo-China peninsula, then dispersed into India, Africa, and Australia according to theories of continental drift, the ecological, and geological vicissitude (Zhou 1990). Globally, citrus is the leading fruit crop, with a total production of 104.5 million tonnes (mt), the maximum of 32.6 mt in Asia followed by 25.8 mt in South America, 23.6 mt in North & Central America, 10.7 mt in Europe, 10.1 mt in Africa, and 0.61 mt in Oceania (FAO 2004). The commercial cultivation of citrus, is confined upto an altitude as high as 2400 m above mean sea level (msl), but some of the ornamental species of citrus are grown upto 2800 m above msl in the areas close to the equator. Agrometeorologically, citrus is grown under tropical and sub-tropical arid climate representing $24\text{-}38^{o}$ at either side of equator with hot days/cool nights and little exposure to prolonged freezing temperature or relatively free from frost. The highest quantum of production harvested globally comes from citrus growing in soil represented by the orders, Alfisol, Oxisol, Ultisol, Entisol, and Inceptisol (Srivastava and Singh 2003).

A. Nutritional Significance

Citrus fruits are a rich source of minerals and vitamins. The manifestations of scurvy disease are prevented by its regular intake. In addition, citrus fruits have a high K level and relatively low Na concentration (Gallasch et al. 1984). The exceedingly favorable ratio of K to Na imparts therapeutic utility to citrus juice (McHard et al. 1980). Sweet orange juice is a much better supplier of the requirement for Cu than for Zn. From the levels of vitamin-C, -B, and folic acid, it is obvious that the inclusion of citrus fruits and products in the diet is greatly beneficial in meeting the recommended daily allowance and preventing even the sub-clinical signs of their deficiencies(Breeling 1971).

B. Historical Viewpoint

There are three basic requirements for successful cultivation of citrus, namely climate relatively free from frost, good quality of irrigation water, and a reasonably deep and uniform fertile soil with high internal drainage (Chapman 1961). Citrus nutrition has been a subject of comprehensive research over the last 70 years or so, and will continue to stake claim in the years ahead, not because of growing concerns in the light of chronic soil fertility- related problems, but increasing emphasis laid towards quality citrus production has warranted a worldwide investigation on the subject from various angles. However, a substantial success has already been achieved from the identification of various nutrient constraints in the field using much improved diagnostic techniques, monitoring methodologies coupled with much better efficiency of applied fertilizers to remediation of various nutritional constraints. For example, in the last 30 years in Indian River area (known across the world for production of high quality grapefruit) the yields of grapefruit, have increased considerably from 25-40 tonnes/ha to 50-80 tonnes/ha (He et al. 2000) due to increase in planting density from 120-150 to 250-300 trees/ha (Davies 1997), adoption of efficient irrigation systems (Zekri and Parsons 1989b), use of fertigation (Alva and Paramasivam 1998) or slow release fertilizers (Zekri and Koo 1992; Boman 1993).

Dynamics of nutrient availability under a perennial crop like citrus is quite different to that of an annual crop. The available nutrient is defined as: (i). the ions in the soil that possess the mobility to reach the plant; (ii.) the metabolically active chemical form or forms of an essential plant nutrient in the soil, the absorption of which is verified by the response on plant growth and yield; and (iii.) availability means susceptibility to absorption by plants in an effective quantity. Nutrients are often absorbed, but not accompanied by any response, thereby (ii) and (iii) become redundant. Phenomenon governing the bases for flow of nutrients from soil to root include the ability of ions to move against a concentration gradient, and the ability of plant roots to selectively absorb or exclude specific ion(s).

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 by contrast is extremely different in countries like USA, Brazil, Israel, Spain etc. The efficient fertilizer use is identified as one of major causes of low orchard productivity and absence of information on scientific know-how about the techniques of nutrient monitoring, and accordingly the precise fertilizers use to make nutrient management exercise all the more difficult. Considering the economics of citrus production, fertilizers alone on an average constitute about 20-30% of total cost of citrus production (Srivastava and Singh 2003). This is a significant recurring expenditure, a grower needs to invest every year. The mechanistic steps involved are absorption, translocation, and utilization of applied nutrients. All three steps being altogether different, but dependent on each other. A holistic benchmark analysis of various components leading to remunerative soil and plant nutrition management is, therefore, imperative to sustain the pressure of increased nutrient demand accruing from two diverse cultivation methods, intensive cultivation (featuring high density planting with low volume fertigation) and extensive cultivation (often adapted under high altitude citriculture). Diagnosis of nutrient constraints and their efficient remediation are the two pillars of citrus nutrition. The necessity of balanced nutrition has to be, hence, viewed from the angle of striking a balance of nutrient demand between above ground canopy and root volume in relation to total nutrient requirement.

II. DIAGNOSTIC METHODS

The nutrient diagnostic tools viz., leaf analysis (Chapman 1949; Malavolta et al. 1962; Jones and Embleton 1969; Embleton et al. 1975; Du Plessis 1977; Hernandez 1988; Srivastava et al. 1999), soil analysis (Chapman 1961; Du Plessis 1977; Jorgenson and Price 1978; Srivastava and Singh 2001; 2002), deficiency symptomatology (Parker 1934; Chapman 1939; Chapman and Brown 1941; Chapman et al. 1943; Smith and Reuther 1949; Wallihan and Garber 1966; Zekri, 1995a, 1995b, 1995c, 1995d; Srivastava and Singh 2003), juice analysis (Moss and Higgins 1978; Gallasch et al. 1984), and metallo-enzyme analysis (Bar-Akiva 1965) to a lesser extent, are commonly, used for identifying the nutritional problems of citrus orchards. Of late, other studies propagated peduncle analysis (Ismail and Habeeb 1972), root analysis (Alva et al.1995), and flower analysis at 60-120 days after anthesis (Pestana et al. 2001) as a prognosis of nutrient deficiency. But a representative and reproducible sampling in the later methods of analysis was not practicable. Ichiki (1985) suggested color standards for identifying nutritional problems in the field. Practical color charts of 9-shades designed for field nutritional diagnosis, was composed of 172 types from GY2 to GY8 using the Munsell color system based on leaf color measurements, but found no wide field utility considering the chlorophyll as a poor indicator of nutrient status.

A. Leaf Analysis

Leaf analysis integrates all the factors that might influence nutrient availability in soil and plant uptake, and pinpoints the nutritional balance of the plant at the time of sampling. As early as De Saussure (1804) showed that the composition of the ash of plants varied with the part analysed, with the age of the plant, and with the soil upon which the plants grew. Few years later, Lagatu and Maume (1934), followed by Thomas (1937, 1945) developed the concept of foliar diagnosis, which included a study on the course of nutrition as reflected by its intensity (sum of percentages of NPK) and by its quality (ratio of NPK). Shear et al. (1946) in their use of leaf analysis as a means of determining the nutritional requirements of plants concluded that when all other factors are constant, plant growth is a function of two variables of nutrition, intensity and balance, and maximum growth and yield occur only upon the coincidence of optimum intensity and balance.

The use of foliar diagnosis developed rapidly, at the first in the USA (Hilgeman 1941; Chapman and Brown 1943; Jones et al. 1944). Its use later spread to South Africa (Bathurst 1943), then to Israel (Oppenheimer 1945), and later gradually to other citrus growing countries. As early as 1949, Chapman proposed a tentative leaf nutrient standard for the first time using ‘Valencia’ sweet orange, which were intended for adoption to individual situations and varieties. Determination of the quantity of nutrients present in the whole tree (Juang and Huang 1985) provided the information on the relative amount and distribution of nutrients within the tree with leaves accumulating the highest concentration.

Leaf analysis is advantageous over soil analysis in terms of analysing the concentration of metabolically active nutrients, fixing the fertilizer requirement, verifying the occurrence of nutrient deficiency or any nutrient imbalance, and determining whether or not fertilizers applied are utilised by the plant. Soil analysis on the other hand, has certain advantages over leaf analysis that it can measure the level of immediately available nutrients in the soil (nutrient intensity), the extent to which those will be available to crop/ during the growth period (nutrient capacity), and reliable for evaluating the salinity, alkalinity or even the nutrient toxicity. Soil analysis does help in assessing the fertilizer needs, but it does not help us to evaluate the efficiency or sufficiency of nutrient uptake to ensure optimum growth and productivity. Majority of studies have demonstrated the better correlation of fruit yield and quality with leaf analysis values than soil analysis (Srivastava et al. 2001). However, leaf analysis alone presents certain limitations. The analysis fails to identify the problem of lime-induced chlorosis, evident from absence of correlation between leaf Fe and degree of chlorosis expressed as chlorophyll content (Abadia 1992). Another limitation of leaf analysis is the fact that sampling date is recommended late in the growing season, generally close to harvest. At this point, it is no longer possible to correct nutritional disorders in time to avoid negative impact on fruit yield and quality. Leaf analysis is seldom able to distinguish the metabolic (active) forms of nutrients from non-metabolic (non-active) forms.

1. Sampling Index Leaves: Many studies in the past have thoroughly discussed about the various steps involved in collection of index leaves. The accuracy of foliar analysis depends upon the specificity of sampling with respect to leaf age (Embleton et al.1973a; 1973b; 1973c; Robinson 1980; Obreza et al. 1993), position of leaves on the fruiting versus non-fruiting terminals (Koo and Sites 1956; Harding et al.1962; Embleton et al. 1963; Bradford et al. 1963), sampling size (Steyn 1961; Carpena et al. 1974), cropping pattern (Bould 1963), and the agroclimatic region (Srivastava and Singh 2003). There are clearly two schools of thought with regard to leaf position for sampling. The one school believes that 6-7 month old leaves from non-fruiting terminals are the most reliable source as they are easy to select by shape, colour, and state of maturity. The second school believes that leaves taken from behind the fruit (fruiting terminal) are more reliable due to stabilising effect of fruit (Terblanche and Du Plessis 1992). Nutrients have some preferential ability to accumulate in specific proportion depending upon plant parts and type of rootstock, e.g. Swingle citrumelo has the ability to retain more B in its stems and roots than the sour orange, thus preventing B-transport to leaves (Papadakis et al. 2005).

When only one plant sample is collected from a given location during growing season, such as in plant-nutrient surveys where the results will be used in succeeding crops, the date selected for sampling must, to be effective, be based upon previous experience with the crop. If, the leaf samples are taken early in the season, some of the plants found high in nutrients would become deficient later, whereas if the samples were taken late in the season, some plants found low in nutrients would have been well supplied during most of their growth period and, therefore, would have little chance of responding to fertilizer application. A safe compromise between these two extremes for collecting a single sample during a cropping year would be to collect it in midseason or during the later stages of the grand growth period of the crop.

When the nutrient concentration of a plant has been found by analysis to be below the critical level, information is immediately gained as to what nutrient deficiencies are limiting the growth of the plant at the time of sampling. What is not learned, however, is the cause or the causes for the deficiencies within the plant. Plant analysis alone cannot disclose the reasons for the deficiencies except possibly in those instances in which salt or nutrient excesses hinder the absorption of deficient nutrients. Though a low nutrient concentration in the plant frequently indicates a correspondingly low concentration in the soil, nevertheless, deficiencies may arise even though the nutrient concentration in the soil is high. Investigation usually discloses a limited root development that is frequently associated with an impervious layer, high water table, excessive salt concentrations, toxic metals, or poor aeration. Under these conditions, the remedy would be to remove, whenever possible, the impediment of nutrition rather than to add fertilizers. Regardless of the cause of the failure, plant analysis by itself can only tell what was deficient at the time of sampling and not what caused the deficiency, nor can it suggest the remedy for its correction. These are questions that must be answered by other means at the disposal of the investigator. Not the least of these means is a physical and chemical examination of the soil.

2. Sample Processing, Storage, and Analysis : One of the most exhaustive pieces of work highlighting the problems associated with the preparative phase of leaf samples by Steyn (1959, 1961) indicated that large differences in the final figures could result from: (i.) number of leaves taken from a single plant, (ii.) number of trees sampled, (iii.) time of day during the sample collection, (iv.) change in metabolic activity with loss in dry weight between the time of sampling and drying e.g. samples stored green in sealed polythene bags lost more weight during storage than those dried in the open laboratory, (v.) leaf washing technique, (vi.) temperature and time of oven drying, (vii.) period and storage of ground samples, and (viii.) method of grinding as a contaminating factor.

Processing: There is overwhelming data to show that washing is essential in order to obtain correct values irrespective of the conditions of leaves. The technique of washing leaves has a profound influence on the concentration of Fe, Mn, Cu, and Zn (Jones Jr. 1971). The dirt contamination was satisfactorily removed by washing in dilute acid (0.7 N HCl) or dilute acid plus detergent, but surface residue of a minor element spray containing Cu, Fe, Mn, Mo, or Zn was not completely removed by any of the two washing solutions (Arkley et al.1960). Labanauskas(1966) later tested various leaf washing techniques which involved: (i.) no washing, (ii.) hand-washing in aqueous solution of 0.1% detergent by passing through the fingers and thumb over the total surface of the leaf, (iii.) rinsing in de-ionized water, and (iv.) dipping leaves in 3% HCl for 2 minutes, again rinsing in deionized water. No effect of these washing techniques was observed on the concentration of N, P, K, Ca, and Mg. Other studies (Lee 1986) demonstrated that varying leaf sample handling and preparation techniques produced a significant apparent differences in most of the nutrients on account of difference in respiration rate of leaf samples causing discrepancies in dry weight and concentration of nutrients like N, P, K, and Ca.

Analytical data regarding the nutrient concentration for washed and unwashed citrus leaves revealed a considerable difference (Labanauskas 1979). Washing with acid detergent proved to be most efficient with regard to Fe, Mn, and Zn content. In another study, washing with distilled water and Twin-80 acidulated with 0.1 M HCl proved to be most effective with regard to concentration of macro-and micronutrients (Alvarez-Fernandez et al. 2001). A good procedure for drying of the leaf samples involved blotting of samples from rinsed with de-ionised water, using ash free filter paper sheets, placed in brand new paper bags, and then to be dried in oven at 60^0 – 65^0C to a constant weight (Zekri and Obreza 2003a). Good dried samples are always of much brighter green color than those of incompletely dried ones.

Storage : Utmost care is needed while grinding the samples for analysis. Grinding can contaminate the samples with metals contained in the grinding equipment. The fineness of grinding is important to ensure preparation of samples as homogeneous as possible in particle size (40-60 mesh size), especially for micro-analysis. The ready samples are stored in air tight containers till further analysis. Immediately before weighing a portion of samples for analysis, the powdered tissues are re-dried for 12 hrs in an oven at a temperature of 65^0C (Zekri and Obreza 2003a). Comparing the deterioration in leaf samples analysed for 30 days at every 5 days interval, Recio and Mendez (1986) observed that leaf K content decreased by 14.9% and 20.5% after 5 and 30 days interval in leaf samples deficient in N P K and N with low P K, respectively. While, leaf N and P contents remained unaffected by the length of storage before analysis in either type of samples.

Analytical Methods : The most common decomposition procedures are, wet oxidation and dry ashing (ashed in Muffle Furnace at 550°C for 4-5 hours and then dissolved in 1M HCl) The volatilization loss of N in dry ashing and B in wet oxidation, is most common. Most of the wet-oxidation procedures are based on three principal methods: (i): HNO_3 - H_2SO_4 mixture, (ii) H_2SO_4-H_2O_2 mixture, and (iii) mixtures containing $HClO_4$ with HNO_3 - H_2SO_4 mixture, producing most viable and desirable results (Tolg 1974). A large variety of analytical procedures is available to determine the concentration of various nutrients. However, these analytical approaches are classified into two broad categories. The first approach determines the total leaf nutrient concentration where the freshly prepared homogeneous leaf samples are first digested in di-acid or tri-acid mixture. The acid extracts are then subject to alkaline steam distillation and followed by titrimetirc estimation of N or alternatively, N may be determined using an auto-nitrogen analyser. P is usually determined colorimetrically using the vanadomolybdophosphoric acid method or altenatively using Inductively Coupled Plasma Argon Emission Spectrophotometer (Page et al. 1982). The methods used in analysis of other nutrients consist of : K flame photometrically, Ca and Mg by versene titration or flame photometry, and micronutrients (Fe, Mn, Cu, Zn, B, and Mo) using emission spectrophotometry (Black et al. 1965; Page et al. 1982). The second approach concentrates only on the water extractable portion of different elements (Carpena-Artes 1978), but its reliability is doubtful, e.g. whether water soluble nitrates represent a true reflection of the nitrogen status of citrus trees.

4. Interpretation and Diagnostic Norms : The interpretation of leaf nutrient levels is based on the premise that there is a significant biological relationship between the elemental content in leaf, plant growth, and fruit yield with a purpose to predict fertilizer requirement depending upon site characteristics. This is popularly known as ‘critical value approach’ widely applied in citrus orchards with considerable success. These relationships normally reflect a sigmoidal response curve on which two critical values can be identified. These values for each nutrient are the value below and above which plant performance is reduced (Terblanche and Du Plessis 1992).

***Interpretation Tools* :** A variety of interpretation tools (IT) have shown their application in leaf analysis of citrus. These are: critical nutrient concentration (Terblanche and Du Plessis 1992; Srivastava et al. 1999); nutrient concentration range (Parent and Dafir 1992); nutrient balance using factorial method (Cantarella et al. 1992), Kenworthy's balance index (Kenworthy 1973), Moller - Nielson balance concept (Moller-Nielson and Friis-Nielson 1976); crop logging (Abaev 1977); boundary line concept (Walworth et al. 1986) all suggesting only single value concentration and DRIS, diagnosis and recommendation integrated system considers the nutrient ratio (Walworth and Sumner 1987; Beverly 1987). The utility of these ITs in the past faced many limitations, especially in the context of alternative to identify the nutrient constraint at any growth stages during the season and, therefore, diagnoses found application only to a specified growth stage due to strong influence of leaf age.

Of different ITs, DRIS is claimed to have certain advantages over other conventionally used ITs (Malavolta et al. 1993; Li et al. 1999). The working premises of DRIS (Filho 2004) are based on: (i.) the ratios among nutrients are frequently better indicators of nutrient deficiencies than isolated concentration values; (ii) some nutrient ratios are most important or significant than others; (iii) maximum yields are only reached when important nutrient ratios are near the ideal or optimum values, which are obtained from high yielding selected populations; (iv) as a consequence, the variance of an important nutrient ratio is smaller in a high yielding (reference population) than in a low yielding population, and to the relations of significant nutrient ratios; (v) the DRIS indices can be calculated individually, for each nutrient, using the average nutrient ratio deviation obtained from the comparison with the optimum value of a given nutrient ratio, hence, as pointed by Walworth and Sumner (1987), the ideal value of the DRIS index for each nutrient should be zero. The efforts in the past have successfully established the DRIS norms for 'Valencia' orange in USA (Beverly et al. 1984; Wallace 1990), South Africa (Woods and Villiers 1992), Venezuela (Rodriguez et al. 1997), Brazil (Murraro Filho and Azevedo 2003); 'Verna' lemon in Spain (Cerda et al. 1995); 'Sicilian' lemon in Italy (Creste 1996) and 'Pera' sweet orange in Brazil (Creste and Grassi Filho 1998); acid lime (Varalaxmi and Bhargava 1998), 'Kinnow' mandarin (Hundal and Arora 2001) 'Nagpur' mandarin, 'Khasi' mandarin, and 'Mosambi' sweet orange in India (Srivastava et al. 2001; Srivastava and Singh 2003; 2006b).

***Diagnostic Norms* :** Almost any conclusion can be drawn from the earlier attempts on the development of leaf nutrient diagnostics in the countries like Argentian (Perez 1996), Australia (Jorgensen and Price 1978), Brazil (Quaggio et al. 1998a), China (Koto et al. 1990), France (Marchal et al. 1978), India (Chahill et al. 1991; Srivastava et al. 1999; Srivastava and Singh 2002), Italy (Dettori et al. 1996), Japan (Terblanche and Du Plessis 1992), Turkey (Saatci and Ya Mur 2000), Spain (Hellin et al. 1988), Costa Rica (Alvardo et al. 1994), USA ((Chapman 1949; Koo et al. 1984; Swietlik 1996) etc. employing a variety of diagnostic methods using different aged index leaves from fruiting as well as non-fruiting terminals. Such efforts have generated differential diagnostic capabilities in the absence of commonality in guidelines used in diagnosing the nutrient constraints, e.g. a different set of optimum values are obtained when a specific leaf analysis data are subject to contrasting ITs like multivariate quadratic regression analysis (MQRA) or diagnosis and recommendation integrated system (DRIS) using some commercial citrus cultivars of India (Table 1). DRIS-derived values were further very close to original values from high performance elite orchards than values obtained from MQRA(Wallace 1990; Woods and Villiers 1992; Srivastava and Singh 2003). Alves and Filho (2005) observed that conventional sufficient range approach (SRA) and DRIS were in agreement for nutritional diagnosis of K. While other nutrients like Cu, Mn, and Fe were diagnosed as deficient by DRIS and classified adequate to high by SRA in 'Valencia' sweet orange orchards on three different rootstocks in Sao Paulo, Brazil.

Table 1. Optimum leaf nutrient levels for three commercial citrus cultivars of India using two most common ITs

Nutrients	NM		MSO		KM	
	MQRA	DRIS	MQRA	DRIS	MQRA	DRIS
N(%)	2.2-2.4	1.7-2.8	2.4-2.5	2.0-2.6	2.2-2.5	2.0-2.6
P(%)	0.07-0.10	0.09-0.15	0.13-0.15	0.09-0.17	0.10-0.11	0.09-0.10
K(%)	1.2-1.6	1.0-2.6	1.6-2.3	1.3-1.7	1.9-2.1	0.99-1.9
Ca(%)	1.3-1.5	1.8-3.3	2.6-3.2	1.7-3.0	2.1-2.3	2.0-2.5
Mg(%)	0.48-0.67	0.43-0.92	0.32-0.49	0.32-0.39	0.28-0.38	0.24-0.48
Fe(ppm)	110-132	75-113	132-148	70-137	148-180	85-249
Mn(ppm)	49-43	55-85	52-112	42-87	72-85	42-87.6
Cu(ppm)	8-14	10-18	7-10	7-16	10-19	2-14
Zn(ppm)	18-30	14-30	25-43	12-29	24-39	16-27
Mo(ppm)	-	-	0.34-0.54	0.39-1.1	-	-
B(ppm)	-	-	25-36	13-26	-	-
Yield (kg/tree)	40-54	47-117	87-95	77-138	45-62	32-56

NM = ‘Nagpur’ mandarin, MSO = ‘Mosambi’ sweet orange, KM = ‘Khasi’ mandarin

Source: Srivastava et al. (1999), Srivastava and Singh (2003)

The arguments are often put forward to support the view that deficient, optimum or excessive levels of nutrient concentration cannot be determined by means of absolute figures (critical levels) due to great deal of variation in vegetative activity. Hence, a new concept of the above evolutionary balance of bioelements and the critical area based on the links between nutrients and the balance of all the bioelements, was proposed by Carpena-Artes(1978). According to this concept, the leaf level of any nutrient, for a given moment is determined by the difference between the amount of nutrient which has reached the leaf and from there, the amount transported to other plant organs. Hence, four diagnostic criteria of deficiency area, critical area, normal area, and excess area were suggested for determining nutritional requirement.

Du Plessis (1996) advocated a different leaf nutrient norms based on climatic zones. The norms derived for small fruit area of cool climate like Nelspruit in Mpumalanga province (2.0-2.4% N, 0.95-1.50%K, and N/K ratio of 1.6-2.2) were different to that of large fruit size area of Citrusdal in the Western Cape province(2.1-2.7%N, 0.70-0.90% K and N/K ratio of 3.0-4.5) having warm climate with other nutrients like P(0.11-0.16%), Ca(3.5-5.5%), and Mg(0.30-0.55%) showing no significant difference. Most of the leaf nutrient diagnostics have, therefore, failed to find any universal applicability when tested over space and time under varying conditions. These warranted for developing a cultivar specific nutrient standard to suit regional level growing conditions and to compare the norms developed by different approaches, it will be worthwhile to establish a conversion factor to relate norms which are developed for non-fruiting terminals to that of fruiting terminals and vice-versa.

Leaf analysis is often considered synonymous with tissue analysis, the former involves an analysis for the total nutrient concentration and the latter, an assessment of nutrient concentration of sap squeezed from tissue or analysis carried out by an extraction of either fresh or dried plant tissue. Tissue analysis is carried out mostly in the field by employing a rapid colorimetric analysis on cell sap extracted from plant tissue. These tests are called rapid field tests.

Plant tissue tests in the field are valuable for verifying deficiency symptoms (Chapman and Brown 1950). It is considered a more direct method of evaluating plant nutritional status than soil analysis, but that method must necessarily involve a well defined plant part for analysis (Hallmark and Beverly 1991). Moreover, they help to discover hidden hunger which is not indicated by deficiency symptoms of any other diagnostic method. Additionally, the plant tissue tests can be made with rapid speed and straightway on the growing crop, and results can be, thus, compared in the field. The variation in chlorophyll concentration in Citrus rootstocks for lemon, 'Cravo' (*Citrus limonia* Osbeck) and 'Volkameriana' (*Citrus volkameriana* Ten ex. Pasq) and for mandarin, 'Cleopatra' (*Citrus reshni* Hort. Ex. Tan.) and 'Sunki' (*Citrus sunki* Hort. ex. Tan.) was positively correlated with growth characteristics and leaf N concentration (Marlon et al. 2003).

The sap from plant parts other than leaves is also used for nutritional diagnosis, e.g. stem sap analysis is very useful at early developmental stages of crop like flowering and fruit set. However, the utility of stem sap analysis is limited by seasonal fluctuations more than the conventional leaf analysis. Analysis of stem xylem water can be a valuable tool for detecting short term variation in chloride uptake, since leaf analysis reflects only the cumulative chloride content. Therefore, it does not always give the current transitory mineral uptake status (Raveh and Levy 2005) as opposed to stem sap analysis due to greater sensitivity of stem xylem chloride than leaf tissue chloride (Raveh 2005). Though, sap analysis proved to be very successful in field grown crops, and tissue testing kits have found wide scale use. But in citrus, not much information is available about its utility in field diagnosis of nutritional constraints. e.g., Fe can be determined by a tissue test (Bar-Akvia 1984) in the field using peroxidase activity through development of blue color, an indication of Fe-adequacy.

For the valid use of an enzymatic system as an indicator of activity of certain nutrient element in plant tissue, it is essential for the enzymatic system to be specific for the said element (Hellin et al. 1995). Hence, for these purposes, the choice is almost completely limited to metalloenzymes whose enzymatic activities are directly influenced by the metabolic activity of the nutrients. For example, the use of the peroxidase in the diagnosis of Fe- and Mn- deficiencies (Bar-Akiva 1964) prompted checking the utility of the method for citrus cultivars grown on differentially fertile soils. Parallel to what was observed with peroxidase, catalase, adolase, and aconitase reduced their levels of activity with Fe-deficiency and increased with Mn-deficiency, facilitated to establish the possibility of using these enzymes as viable mean of distinguishing between Fe- and Mn- deficiency producing morphological symptoms of overlapping nature (Bar-Akiva 1961; Garcia et al. 1990). Studies on different aspects of biochemical marker-aided nutrient constraint analysis (Table 2) revealed that the level of specific enzyme activity, hence, provides a rapid and sensitive indicator of deficiencies of both macro- as well as micro-nutrients (Lavon and Goldschmidt 1999; Srivastava and Singh 2006a). This method of nutrient constraint diagnosis did not find much favour amongst citrus researchers because of the high sensitivity (enzymatic activities change over time) of the method, higher cost involved compared to conventional leaf or soil analysis, and the technicalities involved in analysis in addition to an array of sophisticated instrumentation required such as electrophoretic unit, high performance liquid chromatograph, ion exchange chromatograph, refrigerated centrifuge, particle size column, amino acid analyser etc. which require experienced hand.

B. Soil Analysis

The soil analysis method is based on the assumption that the chemical extractants stimulate the root system acquisition of soil nutrients in a comparable manner. The quantity of a nutrient extracted through the soil using a suitable extractant is an index of nutrient actually available to trees. The available portion of nutrient determined by soil analysis is at best an estimation, because it is measured by an extractant that cannot be expected to duplicate the action of plant roots in nature (Zekri and Obreza 2003b). Use of soil testing, for citrus as a guide for fertilizer recommendation is restricted due to lack of calibration for P and K in soils and the crop response (Hanlon et al. 1995). Another limitation of soil analysis based diagnosis is the suitable soil sampling, which is usually to represented by the soil portion explored by the roots (Reuther and Smith 1954).

Utility of soil analysis is largely dependent on soil sampling, soil analysis and interpretation of results. Errors are possible in all three steps, although most errors are generally made during soil sampling because soil variation is insufficiently dealt with and too few samples are taken. The choice of analytical technique in relation to soil property or soil type is another potential source of errors. For interpretation of soil test results, resilience and reversibility are important concepts that reflect the soil to withstand stress and ability to reverse changes brought about by cropping.

Table 2. Biochemical markers associated with different nutrient deficiencies in citrus

Biochemical markers	Increase(+) or decrease (-) in activity/ concentration	Reference
N – deficiency		
- Leaf NH_3-NH_4^+, proline, total sugar	+	Bukhbinder (1990), Lovatt et al. (1992)
- RuBPCase, arginine, nitrate reductase, glutamate dehydrogenase, phosphenol-pyruvate carboxylase	-	Rabe and Lovatt (1984), Osaki et al (1993), Huber and Huber (1996)
P - deficiency		
- Arginine, proline, lysine, histidine, citruline, ornithine, free amino acid	+	Nemec and Meredith (1981), Rabe and Lovatt (1984)
- Ribonuclease, glutamic oxaloacetic transminase, citrate synthetase, acotinase, malic enzyme, phosphenol pyruvate carboxylase, succinate dehydrogenase	-	Chen et al.(1990), Achituv and Bar-Akiva (1978a, 1978b)
K - deficiency		
- Cadaverine, acid invertase, lysine, histidine, L-arginine carboxylase	+	Lavon et al.(1995, 1999), Zheng et al.(1996)
- N-carbamyl putrescine amino hydrolase, pyruvate kinase	-	Besford (1978)
Ca – deficiency		
- Succinate dehydrogenase, nitrate reductase, RuBPCase	-	Chen et al. (1990, 1997)
- Pyruvate kinase	+	Lavon et al. (1988)
Mg - deficiency		
- Acid invertase, alkaline invertase	-, +	Lavon et al.(1999)
Fe – deficiency		
- Peroxidase, adolase, acontinase	-	Garcia et al.(1990), Hellin et al. (1995)
- Citric acid	+	Saatci and Ya Mur (2000)
Mn – deficiency		
- Peroxidase, xylose	+	Bar-Akiva and Lavon (1967, 1968)
- Catalase, phenyalanine, ammonia lyase, tyrosine ammonia lyase, phosphenol oxidase	-	Jeyarajan et al. (1970), Aoba et al.(1982a, 1982b)

Fe & Mn – deficiencies		
- Arginine, asparagine, serine, free amino acid, shikimic acid	-	Thompson (1980), Burnell (1988)
Zn – deficiency		
- Arginine, proline, free amino acid	+	Sharma et al. (1981)
- Carbonic anhydrase, nitrate reductase, indole acetic acid	-	Swietlik (1989), Devi et al. (1996)
B – deficiency		
- Phenyalanine ammonia lyase, sugar borate complex	-	Shkol'nik et al.(1980), Sakal and Singh (1995)
Mo – deficiency		
- Peroxidase, nitrate reductase	-	Triboi (1978), Horesh et al.(1986)

1. Soil Sampling : The accuracy of identifying a soil fertility constraint depends on how well the soil sample represents the soil variability within an orchard and the extent of root distribution. That is why the soil sampling is often, recommended at the time when leaf samples are collected. The horizontal and vertical depth of soil sampling is dependent on the root distribution pattern (Alva and Paramasivam 1998), since the state of nutrition, size, and yield of trees are closely related to the amount of soil explored by the root system. The root spread in citrus, in most of the cases exceeds the spread of branches i.e. citrus roots spread far beyond the area covered by the crown. Both rootstock and scion influence root distribution. Comparison of grapefruit and sweet orange trees on rough lemon indicated that the grapefruit trees had a higher density of fibrous roots in the surface 25 cm, though the roots systems are not static, it may change its distribution with age and tillage treatment (Kaufmann et al. 1972). Of the total roots sampled from the top 60 cm soil layer, 75% of roots were in the 0-15 cm layer and < 10% were in the 30-60 cm layer. More roots were present in the 15-30 cm depth of trees which received either 112 or 168 kg N/ha than that of the trees fertilized with lower N-rates (Zhang et al. 1996). Studies on root distribution of 'Valencia' orange trees on different rootstocks in relation to soil types (Mallee soils) showed that the majority of roots was concentrated in the top 60 cm depth of soil. Trees on Murray sand had twice as many roots as on Barmera sand shallow phase or on Moorook sandy loam below 90 cm (Mikhail and El-Zeftawi 1979).

Soil testing has never been very effective as a guide for fertilization in citrus in central Florida because: (i.) citrus trees are long-lived perennials having roots grown-up and unction at considerable depth in the soil profile (Castle and Krezdorn 1975). (ii.) soil and climatic conditions are very conducive to rapid leaching of the mobile fertilizer nutrients (Buol 1973; Davis and Sakamoto 1976); and (iii.) the buffering capacity of the soils is too low to effectively dampen the antagonistic effects of ion imbalances. It has been shown, for example, that under some conditions, the uptake of Mg by citrus is more strongly affected by the supply of available soil K than by the supply of available soil Mg (Anderson and Albrigo 1972). Changes in soil extraction procedures give little improvement in the correlations between soil and leaf Ca and Mg and soil values from even the best methods, generally involving the milder chemical extractants, account for only 25% of the observed variation in leaf contents (Anderson and Albrigo 1972).

While comparing the utility of soil versus fruit juice analysis, the sensitivity of soil sampling to factors like rooting depth, variable sampling pattern, size of orchard broadly categorised into pedogenetic-induced variability and management-induced variability precludes its wide acceptance as a reliable diagnostic tool for working out the fertilizer requirement. On the other hand, juice analysis involving fruit samples are subject to comparatively less variation e.g. juice analysis is very useful for ascertaining salinity tolerance(Levy and Shalhevet 1990a). However, storage of fruit samples is the biggest limitation as opposed to soil samples or even leaf samples. Likewise, comparing leaf versus juice analysis, the nutrient concentration in leaves changes over time, while matured fruits vary much less but, have some limitations for micronutrient concentration (Gallasch et al. 1984).

2. Analysis and Interpretation

Analysis: Extraction of nutrients and their analysis using different laboratory techniques are two major steps involved in the success of soil analysis. Limited attempts have been made to correlate soil testing extraction procedure and extractable value of any nutrient calibrated to correlate with citrus production levels or fruit quality. The analytical procedures used in soil testing vary considerably among laboratories. Selection of extraction procedure depends on soil physico-chemical properties e.g. Mehlich No. 1(0.05M HCl + 0.0125 M H_2SO_4). Likewise Bray-solution (0.03 M NH_4F in 0.025 M HCl) is popularly used for acid soils and Olsen-P(0.5 M $NaHCO_3$) for neutral or alkaline soils, and adapt different approaches while making recommendations, leading to differences in suggested fertilizer needs. Some of the review articles by Olsen and Sommers (1982) and Thomas (1982) have covered these aspects in detail. The Kjeldahl digestion involving high temperature digestion in concentrated H_2SO_4 in the presence of catalyst and later determining the ammonium concentration depending upon macro - (> 1 g), semimicro - (0.5-1.0 g) or micro - (< 0.5 g sample) analysis. Microkjeldahls can also be carried out with auto-analyzer, specific ion electrode, automated distillation or even by using infrared reflectance as a non-destructive method.

The extraction procedure (0.05 M DTPA, diethylene triamine penta acetic acid + 0.1 M triethenolamine + 0.01M $CaCl_2$) described by Lindsay and Norvell (1969) is most widely used for extraction of Fe, Mn, Cu and Zn. Combination of DTPA-Olsen bicarbonate proposed by Soltanpour and Schwab (1977) produced much better results in a quest to find universal extraction reagent. Mehlich (1982) also proposed Mehlich No. III (0.015 M NH_4F + 0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.013 M HNO_3 + 0.001 M EDTA) as an universal reagent. Hot water soluble-B and ammonium oxalate extratable-Mo are widely used (Black et al. 1965; Page et al. 1982) for these two important mirconutrients. Much work has been done on universal extractants for soil tests to assess micronutrient availability. Many workers (Barber 1984; Cox and Kamprath 1972; Walsh and Beaton 1973) prepared comprehensive reviews of chemical tests for the determination of water-soluble, acid extractable, exchangeable, and complexed or chelated trace elements in soils.

The analytical techniques for determining the concentrations of elements in the extract from a soil sample have changed significantly in the last decade. Wet chemistry procedures were initially used and are still in wide use today (Piper 1942; Chapman and Pratt 1961; Jackson 1958). The first major change came with the introduction of flame emission spectrophotometry for determining K and Na, and to a certain degree Ca and Mg, in soil extracts, a technique that was both easy and fast (Issac and Kerber 1971). Technicon Auto Analyzers were adopted by many soil-testing laboratories for the determination of Ca, Mg, P, and K (Issac and Jones 1970; Flannery and Markus 1971), but they have proven too slow during peak demand periods.

The next major change came when atomic absorption spectophotometry offered the analyst a relatively easy and fast method for determining Ca and Mg and the micronutrients Cu, Fe, Mn, and Zn in soil extracts (Issac and Kerber 1971). However, the determination of B and P is not possible by atomic absorption, and the analysis of K and Na by this technique is unsatisfactory. Although atomic absorption spectrometry enjoys wide acceptance and use, its inability to adequately assay several important elements has turned analysts back to emission spectrometry (Soltanpour et al. 1982). This technique, referred to as ICAP (inductively coupled argon plasma), can be used to determine most of the elements of interest in soil extracts. Besides having multielement capability, this technique has the advantage of excellent sensitivity and high speed. The ICAP analysis technique has stimulated interest in the development and use of universal extraction reagents.

Interpretation of Soil Test Results **:** The interpretation of soil test results has two aspects: (i) an evaluation of result in terms of its relationship to plant grown and (ii.) determination of the amount of lime and/or fertilizers needed to correct a deficiency revealed by the test result, and to meet the crop requirement (Jones 1985). The variability in soil test values within an orchard area from which a composite soil sample is collected, can markedly influence optimum fertilizer rates. The orchards sites with low variability would under-predict the optimum fertilizer rate for maximum economic yields than for the orchard sites with high variability in soil test values. A variety of methods of interpretation have been used from time to time. These include: numerical category to a range of test values, a procedure called indexing (Cope 1972), graphical method-based Cate and Nelson procedure (Cate and Nelson 1965), the sufficiency levels of available nutrients (SLAN) based on regression of soil test value with plant growth

(Melested and Peck 1977), basic cation saturation ratios (BCSR) suggesting best cation ratio (Bear et al. 1945), ionic composition of soil solution-based buffer system (McLean 1982), and diagnosis and recommendation integrated system (DRIS) suited initially for plant analysis interpretation finds good application to interpreting soil test results (Sumner 1982).

3. Soil Property Norms: The inherent difference in soil properties produces differential production response, which eventually determines the soil quality. It is a concept, that describes soil in terms of its capacity to perform three major functions, viz., enhanced productivity, environmental protection, and health. The citrus soil differs from other cultivated soils, since the latter remain fallow for 3 to 6 months every year, and undergo depletion of soil organic matter causing very little addition of organic-C during the fallow phase. On the other hand, biological oxidation of organic matter continues at the same rate in soils under a perennial crop (Sharma and Singh 2001). The quantitative changes over any period must be measured for later use in evaluating the changes in soil quality. Indicators of favorable soil fertility include thickness of the A-horizon, lower bulk density, and higher level of organic C, available N, and P (Sys et al. 1993; Sandor and Furbee 1996). In soil fertility management, the central element is the optimum value, best regarded not as a constant, but as having a range of values within which the highest crop yield is obtained, consistent with the potential varieties, climatic condition, and field management (Medvedev 1990).

The soil optimum values are further influenced by temporal variability (refers to variation in the optimal apparent density during crop growth), and ecotrophic variability (refers to differences in weather condition and soil fertility level). The soil singled out as the best or ideal in terms of productivity, represents the standard by which the other soils are judged. An appraisal of soil suitability criteria may, therefore, help to identify suitable soils, to avoid any risk of sub-optimum production on account of soil-related-constraints. Researches carried out under different soil and climatic conditions have shown varying responses in relation to properties of soil on the performance of citrus orchards (Sanchez et al. 1998).

Soil Type-Depth : Identifying the causes for productivity difference in a 50 ha grapefruit (*Citrus paradisi* Macf.) orchard in the flatwoods of southwestern Florida, (USA), Myhre and Shih (1993) observed that tall high yielding trees grew on the friable Pompano soil (Psammaquents) with good drainage and neutral pH up to 90 cm depth. While, trees grown on Oldsmar soil (Alaquods), had low yields due to poor drainage and very acidic pH (4.5-4.8) in the rooting zone. Yields on Oldsmar soils could be increased by tile draining at shallower depth and by lime application.

The fruit yield on shallowest and least stony soils was 42 % of those obtained on the deepest soils with the same stoniness. The developed regression equation showed an increase in fruit yield at the rate of 0.15 metric tonnes/ha per 10 cm increase in soil depth within soil depth range of 25-200 cm in a red ferrallitic soil (Hernandez et al. 1987). In the Nelspruit RSA area, where citrus trees are grown predominantly on three soil types, (red sand, red sandy loam, and red clay soil), tree size decreased drastically from 42.0 m^3 on red sand soil to 23.0 m^3 on the clay soil (Nel and Bennie 1983).

Salinity: Maas (1992) observed adverse effect of soil salinity on fruit yield which decreased at about 13% for each 1.0 dS/m increase in electrical conductivity of saturated soil extract once the salinity exceeded a threshold EC of 1.4 dS/m. Nunez-Moren and Valdez-Gascon (1994) observed average values of ECe, water soluble Na, Ca, Mg, and exchangeable sodium percentage as 3.8 dS/m, 12, 16, 3.8, and 7.3 me/L in low yielding orchards (48 kg/tree) compared to corresponding values of 1.1 dS/m, 6, 4, 1.2, and 4.6 me/L in high yielding orchards (162 kg/tree).

Soil Fertility Levels: Soil suitability criteria is a dynamic concept. A different criteria is used for the same cultivar, if grown under different agro-climates. For example, the reddish brown soils of the Tripolitanian coastal plain of USSR are considered suitable for citriculture, if the following criteria are met: soil depth > or up to 60 cm, $CaCO_3$ < or up to 8-12 %, EC < or up to 5.0 mmhos/cm, and gypsum < or upto 30% (Shishov and Kapshuk 1984). In Western Georgia, highest fruit yield of 'Satsuma' mandarin (10-12 t/ha) was observed in soils having: 31-49 exchangeable K, 52-54 mg/100g Mg, and 197-223 mg/100 g Ca with Ca: Mg 2.5-3.0, Mg : K_2O 3-4, and Ca : K_2O 8-10 (Beridze 1986). While Ko and Kim (1987) suggested the average values of soils as: pH 5.7, organic matter 8-9 %, and exchangeable K, Ca, Mg, N levels of 1.4, 6.7, 2.3, and 0.2 me/100g soil, respectively, for high yielding 'Satsuma' mandarin orchards in Jeju county of Korea. The orchards established on dark grey colluvial soils registered highest fruit yield of 28.1 metric tonnes/ha and lowest yield of 16.1 metric tonnes/ha on yellow earth soils in central Taiwan. In terms of soil series, the soils in grey yellow colluvial soils had the highest fruit yield of 39.6 metric tonnes/ha and 16.1 metric tonnes/ha in yellow earth colluvial soils (Lay and Wang 1997).

Seasonal changes in the relationships between macronutrients in 'Valencia' orange leaves and soil analytical data in central Florida showed more significant correlations (leaf N to soil P and Mg; leaf P to soil P and Mg; leaf Ca to soil Ca, P, and pH; leaf Mg to soil Mg, Ca, and pH) of soil to leaf values collected in the late spring or early summer than earlier or late and for the surface (0-15 cm) than the subsurface (15-91 cm) soil analyses (Anderson and Albrigo 1977) . Under sub-humid tropical climate of central India, soil available nutrients (N, P, and K) significantly influenced the fruit yield up to depth of 30 cm only. Beyond 30 cm, the correlation between soil fertility levels and fruit yield was poor (Srivastava and Singh 2001). Based on these responses, soil fertility guidelines in relation to optimum fruit yield using different ITs were developed (Table 3).

Table 3. Soil fertility norms for some commercial citrus cultivars of India.

Nutrients	NM		MSO		KM	
(mg/kg)	MQRA	DRIS	MQRA	DRIS	MQRA	DRIS
N	118.4-121.2	94.8-154.8	130.1-142.2	62.5-107.3	222.6	161.0-418.7
P	9.2-10.3	6.6-15.9	9.8-11.4	4.9-8.5	7.2	4.5-8.7
K	178.4-232.5	146.8-311.9	182.4-210.3	85.0-186.3	254.2	82.3-287.5
Ca	-	408.1-616.0	-	-	289.2	148.8-285.4
Mg	-	85.2-163.2	-	-	81.1	31.3-84.4
Fe	12.4-16.2	10.9-25.2	13.2-18.6	1.6-4.7	104.0	39.5-180.9
Mn	8.6-12.2	7.5-23.2	14.6-22.6	3.7-7.6	30.5	27.0-80.3
Cu	2.1-2.3	2.5-5.1	2.16-2.42	0.30-1.75	1.2	0.67-2.90
Zn	0.98-1.10	0.59-1.26	0.98-1.21	0.14-0.43	3.1	2.84-5.14
B	-	-	0.28-0.48	0.17-0.30	-	-
Mo	-	-	0.08-0.10	0.05-0.08	-	-
Yield (kg/tree)	40-54	48-117	87-95	46-76	50	32-56

NM = 'Nagpur' mandarin, MSO = 'Mosambi' sweet orange, KM = 'Khasi' mandarin

Source: Srivastava and Singh (2001, 2006b).

Soil Properties and Fruit Quality **:** Soil properties showed a strong influence on fruit quality parameters (Munshi et al. 1979; Reddy et al. 1991; Zhao et al. 1996). The quality of 'Sathgudi' sweet oranges grown on Inceptisols was observed to be significantly superior to those either on Alfisols or Vertisols (Reddy et al. 1991). Cicca et al. (1988) observed increased incidence of fruit splitting in 'Navelina' orange at higher soil available P at the deepest 40-80 cm soil layer in southern Italy, but the problem reduced with increasing available N in soil. An improvement in water soluble and exchangeable Ca^{2+} in soil as a result of $CaSO_4$ application at the rate of 1440 g/tree (400 kg/ha) in Typic Haplustert soil type, improved the fruit quality parameters such as juice content and total soluble solids of Nagpur mandarin fruits in addition to reduction in juice acidity (Srivastava and Singh 2003).

In well drained volcanic ash soils of Jeju Island of South Korea (pH 6.1, available Zn 2.0 mg/kg, exchangeable K 109.6 mg/kg, and 10.2% organic matter), sweet orange fruits produced better quality in south and east of Island than those from north and west (Moon et al. 1980). Response of soil type on the quality of ‘Satsuma’ mandarin indicated that the daily increase in fruit citric acid concentration was 30% higher for trees grown on a tertiary rock soil than those on granite soil (Matsumoto and Shiraishi 1980).

C. Juice Analysis

Effects of fertilizer treatments on citrus juice yield and other quality parameters have received an intensive investigation. With most citrus fruits, the total soluble solids and citric acid concentrations, the ratio of solids to acid in the juice (brix), and the juice percentage are the indices used in defining quality and maturity standards (Hilgeman et al. 1938). Role of nutrients in influencing the juice quality has necessitated development of juice nutrient standards, much on the lines similar to leaf nutrient norms or soil fertility standards. This has stimulated more research with reference to effect of various orchard practices on fruit juice quality.

1. Fruit Nutrient Removal : A significant amount of nutrients is removed annually by the citrus fruits. Various nutrients are reported to be removed (in kg/ha) in the proportion of : 55.5 N, 51.1 P, 53.7 K, 23.4 S, and 5.1 Mg (Labanauskas and Handy 1972); 89 N, 20 P, 192 K, 10 kg S, and 14 kg Mg (Embleton et al.1973a); 270 N, 60 P, 350 K, 30 S, and 60 Mg (Kemmler and Hobt 1985); 100 N, 60 P, 350 K, 30 S, and 40 Mg (Tandon 1987); 68 N, 3.4 P, and 31 K (Kohli et al. 1997a) in relation to an average fruit yield of 30 tonnes/ha by different citrus cultivars. These observations give an insight about the order in which, different nutrients are preferred by specific citrus cultivar, and the ratio in which different nutrients are removed. Such nutrient removal patterns are to be meted out in order to maintain the sustained supply of the nutrients through soil.

2. Nutrient Value of Citrus Juice : Juice has an excellent nutrient value. The citrus cultivar e.g., ‘Valencia’ orange showed a large variation in the concentration of nutrients viz., K (1245 – 3025 ppm), Na (0.89-43.3 ppm), Fe (0.80-17.5 ppm), Ca (67-150 ppm), P (104-309 ppm), and Mg (82-155 ppm) in juice from the fruits grown in Spain, Brazil, and USA(Cohen 1985; McHard et al. 1980).

3. Merits and Demerits : It would be logical to use fruit juice analysis as a diagnostic of nutrient constraints, considering the purpose of fertilization is to obtain optimum production and maintain fruit quality. As early as Ulrich (1952) suggested that for a variety of crops, fruits are insensitive indicators of plant nutritional status because the vegetative parts of plants showed more variability in nutrient concentration. Later studies (Birdsall et al. 1961; Koo 1963) demonstrated more stable values of macronutrients from juice than leaves due to large effect of age and season on the leaf nutrient composition.

Many studies (Koo 1982; Gallasch et al. 1984) highlighted the advantages and disadvantages of juice analysis in evaluating the nutritional problems. Juice analysis is advantageous over leaf analysis in terms of providing rapid means of assessing the nutrient status, better correlation with fruit quality parameters, easier to collect fruit samples, less time required for sample preparation, no necessity standardising the sampling procedure, and cheaper in cost of analysis. However, some demerits are also associated, such as storage and transport of fruit samples. Application of juice analysis is currently limited to analysis of macronutrients (Gallasch et al. 1984).

4. Juice Nutrient Standards: The time of fruit sampling is clearly defined, namely just before the first fertilizer application. Very limited information is available with regard to juice nutrient standards that can be used as an alternative to leaf analysis. Juice nutrient standards suggested by different workers consist of (in ppm): 233-269N, 81-113P, 1424-1574 < for ‘Washington’ navel (Gallasch et al. 1984); 120-310P, > 1400 K, 65-120 Ca, 95-170 Mg for ‘Satsuma’ mandarin (Brause et al. 1984); and < 30 Na, < 10 NO_3, > 400 PO_4, > 1700 K, < 100 Ca, and > 90 Mg for ‘Valencia’ sweet orange (Hofsommer 1989). It is unlikely that the nutritional status of citrus tree with respect to all essential elements, will be reliably reflected by fruit analysis alone, since fruits are the type of sink as strong as leaves for all the essential nutrients (Terblanche and Du Plessis 1992).

D. Deficiency Linked Morphological Symptoms

This is the most widely used diagnostic method. Often, the diagnosis becomes difficult due to appearance of overlapping morphological symptoms produced by deficiency of nutrients like Fe versus Mn, Fe versus S or N versus S. However, mobility of nutrient is one such factor which undergoes a definite redistribution at the time of citrus plant starts bearing fruits after initial few years of vegetative growth. Accordingly various nutrients are classified as very immobile (B and Ca), very mobile (N, P, K, and Mg), immobile (Fe, Cu, Zn, and Mo), and slightly mobile (S). Such a diversification in nutrient mobility within a plant is the reason, why specific plant parts show the characteristic deficiency symptoms. The symptoms on fruits are noticed for very immobile nutrients like B and Ca. The nutrient deficiency symptoms are translated into metabolic disorders which induce changes in micromorphology of plants before these symptoms are identifiable. The way in which the symptoms develop and manifest on younger or older leaves or the fruits, gives a reliable indication about the cause of nutritional disorders. Both deficiency and excess of nutrients can lead to reduction in crop yield coupled with inferior fruit quality. Differential response of citrus cultivars to various kinds of nutritional stress is more or less common. Mild visible leaf symptoms of some of the essential element deficiencies can be tolerated without a reduction in yield in some citrus varieties, but not in others. Sweet orange trees for example withstood the mild foliage symptoms of Zn-deficiency without a loss in yield, while the lemon trees suffered the yield loss (Embleton et al. 1973c). Some of the studies in the past (Chapman 1968; Embleton et al. 1973a; 1973b; Sweitlik 1989) have already described field utility of nutrient deficiency symptoms in citrus.

Various forms of deficiency symptoms could be summarised as: (i.) stunted or reduced growth of entire plant with plant remaining either green or lacking in normal green luster or the younger leaves being light colored compared to older leaves, (ii.) older leaves showing purple color of leaves which is more intense on the lower side, (iii.) chlorosis of leaves either interveinal or whole of the leaf itself with symptoms either on the younger and/or older leaves or both, (chlorosis can be best defined as any yellowing of leaves that regreens following the application of that suspected nutrient-based salt). (iv.) necrosis on the margins or interveinal areas of leaf or the whole leaf on young or older leaves, and (v.) stunted growth of terminals in form of rosetting, frenching, or smalling of leaves coupled with reduced terminal growth or subsequently death of terminal portion of plants (Jones and Benton 1998). These symptoms are further summarised (Fig.1) from the results of field response experiments, sand culture, and field observations.

Fig. 1 : 1st row (L to R : Indiscriminate yellowing of plant canopy N – deficiency, tip burn – N toxicity, thick peel and expanded hollow central core – P deficiency, eliptical and small sized fruits – K deficiency); 2nd row (L to R : coarse and deformed peel – K toxicity, inverted V-shaped non-chlorotic portion in the chlorotic background – Mg deficiency, accretions due to chlorophyll degradation along the mid-rib and lateral veins – Fe toxicity, multiple micronutrient deficiency (Fe+Zn) characterized by yellowing of leaves, small size and multiple sprouting coupled with interveinal chlorosis); 3rd row (L to R : various expressions of Zn deficiency like interveinal chlorosis without reducing leaf size, rossetting, smalling of leaves, and a interveinal chlorosis in young leaves); 4th row (L to R : Fine network of green veins in the chlorotic background – Mg deficiency, yellow spots – Mo deficiency, vein splitting – B deficiency, gummy secretions from the peduncle – Cu deficiency)

III. CITRUS DECLINE AND NUTRIENT CONSTRAINTS

A. Historical Background

Citrus decline also known as frenching, decay, chlorosis, die-back, neglectosis etc. have been an area of rigorous research in nearly all the citrus growing countries. Nutrient constraint induced decline of citrus orchards is as old as cultivation of citrus. The nutrient mining linked soil fertility depletion in surface (Srivastava and Singh 2004a) and sub-surface (Dass et al. 1998; Reddy et al. 2003), salinity (Bielorai et al. 1988), ion toxicity (Grieve and Walker 1983), and nutritional imbalances (Walker and Douglas 1983) are the major contributory factors to citrus decline. The failure or success of citrus cultivation is claimed to be due to individual or combined effect of several of these factors.

Age of orchard has an ultimate effect on the magnitude of decline in fruit yield after giving consistently good yield for a number of years, e.g. peak production efficiency of Nagpur mandarin orchards in central India was computed to be only 22-25 years, and thereafter a decline in productivity was worked out (Huchche et al. 1999). Survey of 86 Nagpur mandarin orchards in central India (Diware and Kolte 1990) covering 39,261 trees varying in age 7 - 27 years showed highest, 30.4% decline on shallow soils (<45 cm) compared to only 10.2% on deep soils (>135 cm).

Heavy crop load, as it occurs during the ‘on’ year of alternate-bearing cultivars, involves depletion of both carbon and mineral reserves which may culminate under extreme conditions in tree collapse (Stewart et al. 1968; Smith 1976; Golomb and Goldschmidt 1987). Whereas Stewart et al. (1968), assumed that N and K deficiencies are the primary cause of tree collapse. Smith (1976) indicated that root carbohydrate starvation is the triggering event. This view has also been adopted by Monselise and Goldschmidt (1982). The effect of K, Mg, and Ca deficiencies on leaf carbohydrate pools and metabolism was recently investigated by Lavon et al. (1995). K-deficiency resulted in lower starch and higher soluble sugar content, as well as a several-fold increase in β-amylase and acid invertase activities.

B. Morphological Symptoms

Quite often, decline is confused with die-back and most of the times, citrus decline is considered similar to citrus die-back considering no sharp distinction between them exists even today. However, for all practical or operational purposes, the term die-back denotes a lethal condition leading to rapid death of the plant from top downward due to one or more causal factors, whereas the decline refers to a gradual degradation of orchard which may occur due to non-pathogenic factors (Ghosh and Singh 1993). Visual symptoms are variable, often non-specific and unreliable to determine citrus decline arising due to single or multiple nutrient deficiencies.

C. Citrus Decline and Soil Properties

Several investigations have attributed the decline of citrus trees to unfavorable soil conditions (Hernandez et al. 1987; Nunez-Moreno and Valdez-Gascon 1994; Srivastava and Singh 2004a). Comparative studies made on the soil conditions in a young sweet orange orchard with patches of poor growth and in adjacent areas with normal growth revealed that soil conditions in the affected areas had the presence of higher total soluble salts, higher concentration of soluble and exchangeable Na, and lower water soluble Ca and Mg (Milad et al. 1975; Malewar et al. 1983).

1. Soil Physical Properties Related Constraints : Soil physical properties indirectly influence the soil fertility and plant nutrition. Influence of soil physical properties on tree growth of mid-season cultivars (20 year old sour lemon and 25 year old ‘Valencia’ on sweet lemon rootstock with clean cultivation and grassed down, respectively) indicated a much better tree growth under grass on the soil type (30-70 cm depth) having 10 % higher clay content than on the soil type (50-125 cm depth) under clean cultivation (Nel 1980). High sub-surface clay content > 60% at deeper than 30 cm soil depth reduced the flowering intensity in Nagpur mandarin grown on smectite rich black clay soils in central India (Dass et al. 1998) and fruit yield of ‘Valencia’ and grapefruit orchards in Belize (Gutierrez 2002). Poor drainage due to clay rich sub-surface restricting the root development is reported to be the causal factor for low yield of mandarin in Aegean region of Turkey (Kovanci et al. 1978), sweet orange in Yaracuy (Merlo et al. 1990), and Concordia and Enter Rios provinces of Argentina (Swartz et al. 1980).

Soil compaction is an another physical constraint to low citrus yield (Nel and Bennie 1984). Analysis on causes of low yield (25-67 kg/0.67 ha) of mandarin cultivar 'Wenzhoumigan' on beach land in Yueqing county of Zhejiang, China showed that heavy clay texture of soil coupled with non-capillary pores (0.15-0.33%), and highly compacted layer (169 kg/cm) at 10-40 cm depth were responsible for low yield. The efficacy of soil improvement measures assessed from yield increments decreased with treatment involving combined use of ferrous sulphate, alum, sulfur, and gypsum or green manuring and P-fertilization (Lou and Yin 1986). In order to ameliorate problems associated with soil compaction, deep ploughing upto soil depth of 80 cm is necessary to facilitate favorable rooting volume for regenerated roots (Abercrombie and Du Plessis 1995) and improvement in fruit quality (Okada et al. 1994). However, others are of the opinion that such soil management practices often result in pruning of roots, and impart adverse effect on the tree performance (Van Zyl and Van Huyssteen 1987).

2. Soil Fertility Related Constraints : Soil fertility decline is defined as the decline in chemical soil fertility or a decrease in the levels of soil organic C, pH, CEC, and plant available nutrients. Soil fertility decline thus includes nutrient depletion or nutrient decline (larger removal than addition of nutrients), nutrient mining (large removal of nutrients and no inputs), acidification (decline in pH and/or increase in exchangeable Al), the loss of organic matter, and an increase in toxic elements (e.g. Al., Mn). The decline in a soil fertility parameter in relation to the pool is closely related to the resilience (the ability of the soil to recover from a period of stress) of soil.

Soil pH : Soil pH is one of the properties that governs the nutrient availability. The performance of 'Balady' lime, 'Cleopatra' mandarin, and sour orange seedlings evaluated at different soil pH values showed 40.1% reduction in growth at soil pH 8.0 than at soil pH 6.0 (Shawky et al. 1980). Canopy of 'Satsuma' mandarin at soil pH 4.0 was observed as half of trees growing at soil pH 5.0, and attributed low soil pH due to heavy N-fertilization for such a differential response (Yuda 1985). Quite often phytotoxicity of nutrients also limits the growth and yield in which soil pH plays an important role, e.g. Cu-phytotoxicity. On the basis of the relative dry matter weights of the seedling tops, a 20% reduction in dry matter weight occurred at about 60 to 68 mg/kg leaf Cu in seedlings grown on soils with pH ≤ 6.5. In contrast, a 20% reduction in root weight occurred at 62 to 271 mg/kg Cu in the roots of seedlings grown at soil pH range of 5.7 - 6.5. The roots can accumulate greater concentrations of Cu when grown at higher pH than at lower pH soil for a given degree of growth suppression (Alva et al. 1995). However, the effect of Cu on the growth of Hamlin orange trees was more pronounced at soil pH range of 5.5-6.0 than at higher or lower soil pH regimes (Alva et al.1995).

Salinity: Soil salinity is a long standing and chronic problem in citriculture, especially in semiarid regions, where saline water is largely used as a source of irrigation. Salinity due to the geological origin of soils occurs less frequently. Salinity is one of the main factors limiting crop productivity (Bernstein and Hayward 1958), but few of the approximately 300 scientific articles on plant responses to salinity published yearly (Flowers and Yeo 1995) focus on fruit trees. One reason is that, fruit trees are generally salt sensitive and, therefore, have a limited potential to be grown in salt affected soils. The exposure of citrus plants to high salt concentration at the root zone markedly alters the uptake, transport, and distribution of mineral elements in the plants. The tissue mineral composition may not reflect the presence of excess salts in the growth medium, at moderate levels of salinity (El-Gazzer et al. 1979). Citrus trees are quite sensitive to excess salts (Bielorai et al. 1988; Srivastava and Lallan Ram 2000). The effect of salt stress on the imbalance in mineral composition is more evident in the root than in the leaf tissue (Syvertsen and Yelenosky 1988; Ruiz et al. 1997), since such effect is rootstock dependent inheritance property (Syvertsen and Yelenosky 1988; Alva et al. 1991; Banuls and Primo-Millo 1992; Al-Yassin 2004). However, fruit quality remains un-affected due to soil salinity (Levy et al. 1979; Nieves et al. 1991).

Most of the salt tolerance observations in citrus are based on leaf analysis for Cl or Na (Grieve and Walker 1983; Bell et al. 1997). There are some disadvantages in using leaves for assessment of salt accumulation. The accumulation of Na or Cl is dependent on leaf age since it is often seen, a rootstock screened earlier as tolerant to salt shows some susceptibility at later stages. Leaf analysis, hence, may not be indicative of Na or Cl uptake by the roots. Salt tolerance is an inheritable quantitative character for citrus, and is of great importance in identifying and screening citrus rootstocks against their reaction to salinity (Singh et al. 1997), besides breeding rootstocks for salinity tolerance. The physiological parameters, like root hydraulic conductivity (Zekri and Parsons 1989a) and root cation exchange capacity

(Srivastava et al. 1998b) in addition to juice analysis (Levy and Shalhevet 1990b) are equally effective in screening citrus rootstocks against salinity.

Calcareousness : Lime-induced chlorosis is known to be one of the oldest forms of decline due to immobilisation of available micronutrients. Presence of $CaCO_3$ in soil is classified into pedogenic and non-pedogenic forms, the former being more active, hence not desirable from nutrient availability point of view. Although, $CaCO_3$ rich nodules are common in smectite-dominant Vertisols of central India (Srivastava and Singh 2001a; 2002a), no significant difference was observed with respect to $CaCO_3$ under healthy trees (28.0-142.0 g/kg) versus declining trees (22.0-112.0 g/kg). Soil $CaCO_3$ content under healthy trees registered comparatively higher values due to presence of non-pedogenic (geogenic) $CaCO_3$ over declining tree (Table 4). Strong association of $CaCO_3$ nodules with micronutrient-containing mineral (nontronite, suponite, and suconite), which in due course of time, released the trapped nutrients under the influence of argillo-pedoturbation, and improved the available pool of nutrients, thereby acting as a stimulant to better performance of trees.

Table 4. Comparison of soil physico-chemical properties under healthy and diseased sweet orange orchards of central India

Tree	pH	EC	$CaCO_3$	Exchangeable cations (me/100 g)							
		dS/m	(%)	Ca^{2+}	Mg^{2+}	K^+	Na^+				
Healthy	8.0	0.16	7.3	33.8	12.6	1.2	8.0				
Diseased	7.9	0.18	7.3	29.2	13.6	1.3	6.4				
Significance	NS	NS	NS	3.1	NS	NS	0.98				
	----------------------Soil available nutrients (mg/kg)--------------------										
	N	P	K	Ca	Mg	Fe	Mn	Cu	Zn	B	Mo
Healthy	126.0	13.2	173.9	0.19	112.7	10.6	8.2	2.8	22.6	0.41	0.11
Diseased	110.3	10.5	151.0	0.12	108.5	7.4	5.9	2.8	16.1	0.28	0.09
Significance	10.2	2.4	10.2	0.04	NS	1.1	0.90	NS	5.2	0.04	NS
	------- Total leaf nutrients (%) --------					------------Total leaf nutrients (ppm)------------					
	N	P	K	Ca	Mg	Fe	Mn	Cu	Zn	B	Mo
Healthy	2.01	0.13	1.58	2.59	0.32	95.6	63.5	5.9	22.1	29.8	0.34
Diseased	1.83	0.09	1.73	2.21	0.30	75.4	53.7	5.5	17.7	21.2	0.30
Significance	0.11	0.03	0.24	0.38	NS	10.1	9.8	NS	4.1	2.8	NS

Source: Srivastava and Singh (2004a)

It was also noted that the dividing line between chlorotic and nonchlorotic soils was about 2.5-3% $CaCO_3$, with active calcium (0.2 N ammonium oxalate extractable) significantly higher in chlorosis producing soils in Arizona (McGeorge 1949). While for Kinnow mandarin grown in sandy loam soils in northwest India, this level was suggested to be 10%(Randhwa et al. 1966).

The use of salt tolerant rootstock holds a greater potential to combat the adverse effect of salinity or calcareousness in soil. Limited studies are available to suggest a suitable rootstocks which can withstand high $CaCO_3$ in soil since such rootstocks have some ability to lower rhizosphere soil pH. Earlier studies (Cooper and Olson 1951; Cooper and Peynado 1954) showed that citrus rootstock exhibited varied degree of chlorosis under field conditions on calcareous soils. Later studies revealed that under certain conditions, sour orange was still prone to chlorosis (Wallihan and Garber 1968; Levy 1984) with 'Washington Navel' orange as the scion (Levy and Mendel 1982). While, Hamze and Nimah (1982) observed symptoms of lime-induced chlorosis on sour orange rootstock on the soil containing 88%

$CaCO_3$. Similar chlorosis symptoms appeared on trifoliate orange on soils at 88% or 30% $CaCO_3$ at different soil moisture regimes. Maxwell and Wutscher (1976) found tangelo and tangor rootstocks intolerant on calcareous soils. Both 'Kunenbo' and 'Cleopatra' mandarin rootstocks were observed to be more tolerant on calcareous soil than 14 other rootstock of grapefruit (Wutscher *et al*. 1970). An updated listing of citrus rootstocks tolerating various calcareous soil conditions was later prepared by Wutscher (1979).

Studies on tolerance of six rootstock seedlings against calcareousness (rough lemon, cleopatra mandarin, Rangpur lime, carrizo, troyer citrange, and trifoliate orange) suggested cleopatra as most tolerant rootstock (El-Otmani 1996). In countries where *Poncirus trifoliata* and rough lemon rootstocks are commercially used, they are exposed to intolerance on calcareous soils (Castle 1987). These rootstocks might face twin problem with regard to salinity as well as calcareousness.

Nutrient Constraints **:** The occurrence of nutrient constraints in citrus orchards is an inter-continental problem (Moon et al. 1980; Caetano et al. 1984; El-Fouly et al. 1984; Hernandez et al. 1987; Hellin et al. 1988; Razeto et al. 1988; Swietlik 1989; Chundawat et al. 1991; Ghosh and Singh 1993; Li et al. 1999; Srivastava et al. 2003; Srivastava and Singh 2004b).

Cation-anion ratio and water soluble nutrients in soil were proposed to be often associated with decline in orchard productivity multiple nutrient deficiencies. Fruit yield of 'Valencia' orange was observed to be higher (104 kg/tree) at soil pH 7.0 and 2.7 me Ca 10 cm^{-3} compared to yield of trees (4.0 kg/tree) at soil pH 4.0 and 0.2 me Ca 100^{-3}(Anderson 1971). Comparison of soil properties under etiolated and normal citrus trees in China (Cheng and Zeng 1991) showed significantly higher pH, exchangeable Ca^{2+}, and Mg^{2+} (7.7,146.1, and 110.9 mg/kg, respectively) under etiolated trees than corresponding values (5.3, 514.1, and 82.9 mg/kg) in the soils of normal trees. Mean exchangeable-Ca^{2+} was observed to be higher (33.8 me/100 g) under healthy trees (Table 4) compared to declining 'Nagpur' mandarin trees (29.2 me/100 g) established on Entisol, Inceptisol, and Vertisol soil orders.

There are certain secondary transformation of nutrients within the citrus trees following the occurrence of blight evident from higher K and lower Fe, Mn, and Zn in the rhizosphere soil of blight affected than those of healthy trees (Pavan and Wutscher 1993). Zinc accumulation in trunk phloem is used as the diagnostic symptom of the predecline stage of blight. Higher Zn levels in the bark than in woods is normal (Wutscher and Hardesty 1979). Zinc accumulation may be mediated by a Zn-binding factor (ZBF), since metal apparently moves through the phloem in complexed forms (Syvertsen and Albrigo 1984). The abundance of this zinc binding protein increased 2-5 folds and considered responsible for sequestration of Zn removing it from routine metabolic processes of blight affected trees (Taylor et al. 1996).

The decline stage follows with development of amorphous plugging in xylem vessels of the inner wood and further Zn accumulation in the outer wood. Bark Zn content was much higher above the bud union than below in blight affected trees on rough lemon (*Citrus limon* Burm.) or trifoliate orange (*Poncirus trifolita* Raf.) rootstock (Albrigo and Young 1981). Altered Zn distribution may be associated with subsequent drought like symptoms. Xylem plugging apparently results in water stress, which is manifested as partial and finally full canopy wilt (Timmer et al. 1992). The changes in symptom ontogeny and physiology associated with the development of progression of citrus blight (Albrigo et al. 1986; Albrigo 1984) also include elevated Zn, N, and Mn and lower B in trunk phloem tissue of blight affected trees as a result of continuous water deficits or the less of canopy and root systems (Albrigo 1984; Williams and Albrigo 1984). These symptoms follow trunk phloem and outer wood Zn accumulation.

Nitrogen accumulation in trunk wood, bark and leaf tissue also is associated with the decline stage of citrus blight (Albrigo 1984). Other alterations in the metabolism of decline-stage trees include elevations of wood pH (Wutscher 1981) and the levelof wood phenolics (Wiersma and Van Goor 1979) with increases in scion bark and leaf proline (Street and Peterson 1982). In addition, carbonic anhydrase and IAA oxidase, both Zn requiring enzymes activities are decreased in declining trees (Bausher 1979; 1982). Decline-stage symptoms are considered secondary to the earliest known symptom associated with citrus blight – trunk phloem Zn accumulation (Albrigo et al. 1986; Albrigo and Young 1981).

IV. NUTRIENT CONSTRAINTS REMEDIATION

There are two basic philosophies of fertilizer management, one aims at fertilizing the soil and the other at fertilizing the crop (Jones Jr. 1985).

A. Fertilizer Requirement : A Complex Problem

Effect of nutrients on plant growth and development has been studied for over 350 years since the experiments of van Helmont in 1648 (Epstein 1972). Exciting progress has been made in the past to develop and improve diagnostic techniques of identifying nutritional constraints and accordingly, the fertilizer management strategies have changed from time to time. Multiplicity of methods and techniques currently available for determining nutrient requirement emphasizes the importance attributed to an awareness of fertilizer requirements.

Fertilizer programs for citrus are determined by many approaches. These are: surveys, growers' experience, following the fertilization program of high yielding orchards, replacing the amount of nutrients removed in fruits, deficiency symptoms, applying results from sand, soil culture, and field experiments, and soil/leaf analysis. Each one of these has certain advantages and limitations. Some of the difficulties in developing sound recommendation for fertilizer program may be traced in the history of developments dedicated towards determining nutrient requirements. All these studies however, aimed towards the balanced plant nutrition, a fundamental concept of any nutrition program. Fertilizer recommendation using integrated nutrient management (INM) approach embodies a strategy for the economic use of fertilizers, taking into account a number of modifying factors (Fig. 2). Two important modifying factors are soil type (texture and pH) and crop requirement, upon which, the role of INM-based components viz., organic manures, biofertilizers, and inorganic chemical fertilizers vary, and collectively fulfill the twin requirement as nutrient source and soil amendment as well.

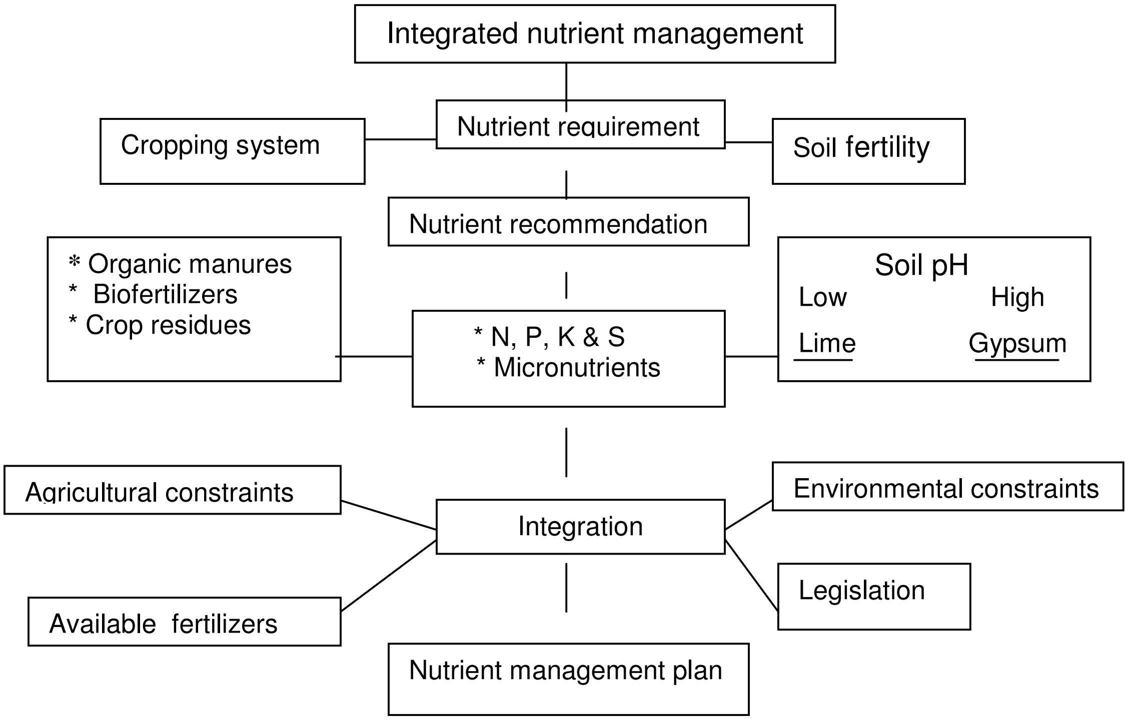

Fig.2. Schematic plan for integrated nutrient management

There are three approaches to fertilizer recommendations that are widely used: the deficiency correction philosophy (originates from nutrient constraints based crop response through nutrient additions 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 (emphasises the 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 the plants over time). An optimum supply of nutrients is, therefore, 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.

The fertilizer requirement of citrus depends whether the purpose is to grow the crop (pre-bearing stage) or feed the crop (bearing stage). Based on these objectives, 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 changes in nutrient regime within the tree may significantly influence the amount of fertilizers to be applied to maintain optimum productivity.

As early as Macy (1936) related the nutrient concentration and yield response of plants to three zones of nutrition; a zone of minimum concentration, in which the nutrient concentration remains constant but yield increases; zone of poverty adjustment, in which the nutrient concentration and yield both increase simultaneously; and a zone of luxury consumption, in which the nutrient concentration increases without favorable yield response. The critical concentration separates sharply the zone of luxury consumption from the zone of poverty adjustment. Citrus, like most other plants, performs along a yield response curve. Small amount of fertilizer makes huge yield increases in the beginning, but the increases drop off subsequently, as the potential of the trees is reached. Theoretically, as per the law of diminishing returns, doubling the amount of fertilizer, the yield response will be 50% closer to the orchards' maximum potential yield.

Most of such fertilizer response studies were conducted many years ago. Is it safe to assume, they are still valid today in the pretext of closer spacings, latest irrigation technique like automated fertigation/micro-irrigation, changes in soil conditions, and more productive trees. They are probably still good, because fertilization program for bearing trees is addressed in terms of yield expectancy. For example, studies carried out by He et al. (2003) recommended 130-208 kg N/ha/year to maintain the concentration of N in 6-month-old spring flush leaves at 2.2-2.3% with an average fruit yield of grapefruit 65-70 tonnes/ha/year. Nearly thirty year old studies (Reitz and Hunziker 1961; Smith et al. 1969) showed maximum yield of grapefruit at 160-170 kg N/ha/year. The higher dose of N in recent studies could be due to increased planting density (from 45-50 to 130-270 trees/ha) and yield from (45-50 to 65-70 tonnes/ha/year). But, if these values are calculated on per tree basis, the values in 1960s (0.9-1.2 kg N/tree) are much higher than recent studies (0.50-0.80 kg N/tree) due to higher fertilizer use efficiency obtained by irrigation systems and BMPs. The records which have accumulated over a period of years are worth a great deal since the actual cause and effect relationships between leaf analysis, fertilizer applied, and fruit production can be efficiently correlated (Jackson 1992). Predictive equation relating leaf nutrient composition to fruit yield is more effective than soil available nutrients to fruit yield (Srivastava et al. 2001). No simple leaf to soil analysis correlation was sufficient for developing a predictive equation for the leaf content of any macronutrient based on a single soil analysis (Anderson and Albrigo 1977).

Citrus nutrient management can be separated into four major components according to Obreza (2003). These are: monitoring, program development, application, and evaluation. Monitoring can be qualitative (visual observations of orchard performance in terms of growth and yield), or quantitative (laboratory-based analysis of soil or leaf samples). In the program development, the factors like type of fertilizer sources, the rate, timing, and frequency are considered. The application phase concentrates on methods of fertilizer application e.g. basin application, foliar spray or fertigation etc. Following fertilizer application, the evaluation step determines the crop response through improvement in tree growth, fruit yield, and quality. Nutrient management can become a complex task, if all the factors affecting the efficiency of fertilizer use are considered. Therefore, relative sensitivity of citrus to various nutritional factors is of utmost importance. The sensitivity of citrus trees to shortage or excess of individual nutrients differs greatly. For example, Mn-deficiency does not affect the production as much as N-deficiency or excess of B affects fruit quality more than an excess of Mg. Likewise, related to soil fertility changes, a decreasing level of exchangeable K may be less of a problem than a large decrease in organic carbon because K may be replaced by weathering mineral or inorganic fertilization, whereas improving organic carbon to the original level is cumbersome. DRIS-based leaf or soil analysis in relation to growth or yield performance can provide the information on the relative importance of different nutrients.

Nutrient management program for citrus trees is often based on nutrient removal of fruits (Quaggio et al. 1996). The knowledge of the nutrient distribution in trees is important to establish sound nutrient management programs for citrus production. Earlier studies (Smith 1966a; Chapman 1968) discussed the mineral composition of citrus trees published between the 1930s and the 1960s. These authors reported results of several chemical analysis of important components of citrus tree biomass, which allowed a broad understanding of amounts of proportion and distribution of nutrients in the various compartments of the plant. The distribution of the total tree dry weight (%) was observed as: fruit 30.3, leaf 9.7, twig 26.1, trunk 6.3, and root 27.8. Calcium made up the greatest amount of nutrient in the citrus tree (273.8 g/tree), followed by N (234.7 g/tree), and K (181.5 g/tree). Other macronutrients collectively comprised about 11% of the total nutrient content of trees. The contents of various nutrients in fruits (kg/ton) were: N 1.20, K 1.54, P 0.18, Ca 0.57, Mg 0.12, S 0.09, B 1.63 x 10^{-3}, Cu 0.39 x 10^{-3}, Fe 2.1 x 10^{-3}, Mn 0.39 x 10^{-3}, and Zn 0.40 x 10^{-3}. Total contents of N, K, and P in the orchard corresponded to 66.5, 52.0, and 8.3 kg/ha, respectively, which were equivalent to the amounts applied annually by fertilization (Mattos et al. 2003). There is an agreement that calcium, nitrogen, and potassium are the dominant constituents of citrus tree biomass. While, phosphorus, magnesium, and sulfur represent a smaller proportion (~10%) followed by micronutrients (<1%). However, the proportion of individual nutrients may vary among different cultivars and tree age depending upon horticultural practices (Golomb and Goldschmidt 1987; Feigembaum et al. 1987). Such a large pool of nutrients present in the structural frame work of trees represent a large storage which is carried from year to year, and provides nutrients for fruit production during deficiency of applied nutrients (Kato 1986; Feigembaum et al. 1987; Legaz et al. 1995).

B. Expert Systems for Fertilization Program

A fertilizer program for the bearing orchard basically consists of replacing what is removed by the crop, and supplying what is needed to replace leaves lost due to old age, insects, diseases or pruning. Little is required beyond these basic needs, since extra fertilizer is likely to produce only extra growth which is subsequently required to be pruned off and increase the likelihood of ground water pollution. This prompted to reassess the fertilizer practices and evolve computer based decision support systems that can be readily integrated into production system. In an attempt to tailor best management practices (BMPs) to specific production conditions, research has also focused on modeling biological processes to assess citrus nutrient requirement and to incorporate information into computer-based decision support systems (Bustan et al. 1999). Various models like quadratic plateau model (Obreza et al. 1993; Srivastava and Singh 2001b; 2002a; 2003b), DRIS-based norms as discussed earlier, DRIS derived FTOVAL (Sautoy 1992; Woods and De Villiers 1992), simulation models (Jones 1998), fertilization program model (Gallasch 1992), and two stochastic dynamic optimisation models (Feinerman and Voet 1995) suggested different methods of arriving at sound citrus fertilization program under diverse growing conditions. These decision support systems can provide information on site specific irrigation scheduling, nutrient requirement, seasonal variation in nutrient uptake, and nutrient budgetting through annual orchard specific nutrient recommendations; eventually to reduce production cost and negative environmental impacts.

Expert system for citrus fertilization (SEFEAG) proposed by Resina et al. (1992) is an advanced prototype aimed to study the citrus nutritional problems and maximising the effect of fertilizers. The system identifies the causes of nutrient excess or deficiency on the basis of information collected in the field (visual analysis) and using data on orchard history, values of leaf and soil analysis obtained from interfaced data bank or from interactive interviews. In a subsequent publication, Basile et al (1992) described the data base required for citrus fertilization which can be used in SEFEAG consists of cultivar features, production characteristics, cultural techniques, technological standards, and results of leaf/soil/water analysis. With this data bank using SEFEAG, it is possible to improve fertilizer management for individual farm to establish yield and quality standards for each cultivar in different areas to compare and evaluate the relationship between cultural techniques and orchard performance in various locations. Chiriatti and Plant (1996) described a prototype case based reasoning (CBR) system for fertilizer application management, adopting the case based planning technique and a planning system in cooking domain. Although, not yet in a form suitable for field implementation, the prototype provides an insight into how CBR system can be used to provide decision support in nutrient management program.

C. Foliar Fertilization

Plants sometimes grow at rates that are faster than the ability of their roots to absorb and translocate mineral nutrients to the leaves or developing fruits. Foliar sprays are useful to maintain optimum nutrient concentration in the plant during the growing cycle by optimising the movement of nutrients. Foliar fertilization means the epigean application of plant nutrient, which a plant needs for its nutrition and growth i.e. the non-root feeding or extra radical feeding. Historically, a problem of absorption of water by leaves was described in 1676 but was disputed until demonstrated this possibility experimentally in 1930s'. Different aspects of foliar nutrition have been reviewed previously (Boynton 1954; Wittwer and Teubner 1959; Jyoung and Wittwer 1965; Haynes and Goh 1977; Kannan 1980).

The foliar fertilization is better than conventional soil fertilization under the conditions, e.g., (i.) acute shortage of nutrient supply, (ii.) nutrients either due to their total absence or due to trace elements, are immobilized on account of unfavorable soil conditions, (iii.) nutrient imbalances i.e. having an unfavorable influence on root absorption for an optimal growth, and (iv.) restricted nutrient uptake through the plant roots. The other advantages with foliar application are : high effectiveness, rapid plant response, convenience in application, and elimination of toxicity symptoms induced by excessive soil accumulation of a given element. On the other hand, the common disadvantage of foliar application is associated with its temporary response, necessitating repeated applications without any residual effect into next cropping season.

Foliar application provides not only a means to apply nutrients at a particular stage in the growth cycle, but it also permits acting remedial action to be taken soon after diagnosis of a deficiency; soil applied nutrients would not be as quick acting. The foliar fertilization causes a plant to pump more sugars and other exudates from its roots into the rhizosphere. Beneficial microbial populations in the root zone are stimulated by the increased availability of these exudates. In turn, this enhanced biological activity and increased the availability of nutrients (Swietlik and Faust 1984). Some of the advanced foliar fertilization technologies like use of electrostatic sprayers (impart a charge to the spray particles and cause them to adhere more readily to plants) and sonic bloom (uses sound to increase the leaves' absorption capacity of nutrients) have recently come into practice.

1. Efficacy of Foliar Sprays : 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 – nometabolic cuticular penetration. It 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 excesses 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 (Boyton 1954).

The transport of ions within plant tissues and organs involves three processes viz., movement in xylem; movement in phloem; and storage, accumulation, and immobilization. The chelating ligands are most important in the control of cation translocation in plants. However, numerous other factors such as pH, the oxidation-reduction state, competing cations, hydrolysis, polymerisation, and the formation of insoluble salts (e.g. phosphate, oxalate etc.) govern metal mobility within plant tissues. These factors account for differential concentration of nutrients due to selectivity behaviour of leaves arising either because the transport properties of each cell type allow them to absorb only particular nutrients from the transpiration stream or because each nutrient moves along a different pathway in leaf and so is only available to certain cell types (Karley et al. 2000).

The health of the plant is important in any form of fertilization. The foliar fertilizers can perform their action through foliar sprays with utmost efficiency only when they are sprayed at optimal time (phenological phase), right site, and in correct application rate with uniformity in distribution. As a third organ of the plant after shoot, leaves differ from the roots, that besides leaves being the principal site for photosynthesis and transpiration, they do not have an acid producing mechanism as do roots. The uptake of nutrients is further influenced by a number of interacting factors, of which only a part are known to date. These factors account for a greater variability in foliar absorption of nutrients and are, therefore, responsible in part for the variable response of foliar sprays.

Urea is being considered the most suitable form of foliar N (Swietlik and Faust, 1984) because of its unique physico-chemical properties, including nonpolarity, rapid absorption, low phytotoxicity, and high solubility in both oil and water (Wittwer et al. 1963; Yamada et al. 1965; Knoche et al. 1994). Cuticle plays an important role in absorption of foliar applied nutrients. Reducing the urea solution pH from 8.0 to 4.0, decreased the amount of urea penetrating the cuticle (Orbovic et al. 2001). Cuticles are 10-20 times more permeable to urea than inorganic ions (Yamada et al. 1965). Addition of nitrogen compounds to the sprays can, hence, enhance the nutrient uptake. Foliar sprays of urea (28-31 kg N/ha) 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), and only 5% KNO_3 in ‘Valencia’ orange (Koo et al. 1984) demonstrated that only two nutrients, N through urea or low biuret urea and K as KNO_3 or K_2SO_4 are 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). Citrus production has been maintained by applying 3-6 foliar applications of urea per year implying that 16% to 33% of the annual requirement of citrus could be supplied with a single foliar application (Embleton and Jones 1974). As much as 70% to 80% of a 5% urea (23.3 g N/liter) solution was absorbed within 24 hours (Impey and Jones 1960) and up to 57% of the applied ^{15}N urea (1.77% N) within 48 hours (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 old 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 nonbearing 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 hours. On an average, only 3% and 8% of $K^{15}NO_3$ was taken up after 1 and 48 hours, 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 hours 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).

Better efficiency of foliar applied nutrients can be obtained only when there is a maximum concentration of root absorbed nutrients. For example, Swietlik and Zhang (1994) observed foliar sprays of zinc less effective than Zn applications to the roots in alleviating severe Zn-deficiency, because foliar absorbed Zn was not translocated from the top to the roots. The study further suggested the involvement of two mechanisms operating at two tiers of structural organisations: one in the roots and the other in the shoots. An unequal amounts of a given nutrient absorbed by a crop from a deficient soil are often related not only to different nutrient requirements within the vegetative tissues, but to the kind and extent of root development (Swietlik 2002).

High cuticular affinity also exists between various micronutrients viz., Mn, Cu, and Zn, which decreased in the following order: Cu>Zn>Mn. Copper reduced the cuticular retention of Zn, revealing high selectivity of Cu over Zn (Chamel and Gambonnet 1982). This is very important when multi-nutrient spray is used. If for certain nutrients, foliar application at an early growth stage is recommended, it is necessary to reach a compromise between early application and allowing the crop to attain a leaf area large enough for the better absorption of applied nutrients. For example, maximum accumulation of K in leaf takes place by the end of fruit set stage, thereafter the rate of nutrient accumulation by leaf is considerably slow (Srivastava et al. 1998a). Therefore, foliar application of nutrients must be restricted up to the period as long as wax deposition on leaf cuticle has concentrated enough to restrict any foliar absorption of nutrients.

Foliar sprays of urea have been reported to enhance the number of flower buds, flowers per inflorescence, and yields under California winter conditins (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) and Nutriphite (6.1 l/ha 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 (Albrigo 1999). A large variation exists with regard to foliar recommendation of micronutrients containing inorganic salts as well as synthetic chelates (Table 5).

D. Soil Fertilization

This is still the most accepted and widely used method of fertilization. The main organ for absorbing water and nutrients by a plant is its roots. Average concentrations of micronutrients (mg/kg) in the fibrous roots of 'Valencia' orange grown in sand culture reported by Smith et al. (1954) were: B 25, Cu 157, Fe 1783, Mn 257, and Zn 462 mg/kg. Climate and soil related factors such as low temperature, excessive moisture, 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.

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.

Roots impose nutrient demand depending upon the sink strength, in form of fruits and newly emerging vegetative growth, which eventually dictates 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

Table 5. Foliars spray of recommended various micronutrients across different countries

Macronutrient	Crop/citrus spp	Country	Source

Fe-polyflavonoid (1%)	'Verna' lemon		Fernandez-Lopez et al. (1993)
$FeSO_4$ (0.5%)	'Valencia' Orange	Spain	Primo et al. (1970)
$FeSO_4$ (2.5% as trunk injection)	'Verna' lemon	Spain	Carpena et al.(1968)
Fe - Mn - Zn (1.2% each)	'Washington' navel	Egypt	Maksoud and Khalil (1995)
Fe(0.75%) - Mn (0.50%) - Zn (0.75%)	'Washington' navel	Egypt	Hassan (1995)
$FeSO_4$ (1%) – $ZnSO_4$(0.5%)	'Kinnow' mandarin	India	Dixit et al. (1977)
$FeSO_4$ (0.25%) - $MnSO_4$ (0.05%) – $CuSO_4$ (0.25%) - $ZnSO_4$ (0.05%) - $MgSO_4$ (0.05%)	'Mosambi' sweet orange	India	Desai et al. (1991)
$MnSO_4$ (0.3%)	'Satsuma' mandarin	Japan	Koto and Takeshita (1957)
Mn - Zn (0.30-0.50%)	'Valencia' orange	USA	Alva and Tucker (1992)
$MnSO_4$ – $ZnSO_4$ (0.15%)	'Thompson' Navel		Razeto et al.(1988)
$MnSO_4$ - $ZnSO_4$ (0.45% each)	'Valencia' orange	USA	Labanauskas et al. (1972)
$MnSO_4$ - $ZnSO_4$ (0.50% each)	'Coorg' mandarin	India	Subramanian (1960)
$MnSO_4$ (0.12%) – $ZnSO_4$ (0.15%)	'Sicilian' lemon	Italy	Alcarez et al. (1986)
$CuSO_4$ (0.2%)	Sweet orange and mandarin		Majorana (1960)
$ZnSO_4$ (0.7%)	'Valencia' Orange	Spain	Carrasco et al. (1969)
$ZnSO_4$ (0.4%)	'Malta' sweet orange	India	Sandhu et al. (1970)
$ZnSO_4$ (0.5%)	'Kinnow' mandarin	India	Nair and Mukherjee (1970)
$ZnSO_4$ (0.6%) - 2,4-D (20 ppm)	'Kagzi' lime	India	Singh and Misra (1986)
$ZnSO_4$ – $CuSO_4$ (0.20% each)	'Kinnow' mandarin	India	Sharma (1990)
$ZnSO_4$ (0.5%) - K_2SO_4 (4%)	'Kagzi 'lime	India	Singh et al.(1989)
$ZnSO_4$ (0.30%) - $CuSO_4$ (0.25%)	'Succary' and 'Balady' orange		Bacha (1975)
Zn - Cu - K (0.25% each)	'Wilking' mandarin	India	Singh and Chohan (1982)
Zn-EDTA (0.5%)	'Mosambi' sweet orange	India	Dube and Saxena (1971)
Zn-EDTA – Mn-EDTA (1%)	Lemon	Egypt	Rawash et al.(1983)
Zn-EDTA (0.10%)	'Washington' navel	Egypt	El-Gazzar et al.(1979)
Zn EDTA (0.4%) - Cu-EDTA(0.2%)	'Eureka' Lemon	India	Sharma et al. (1990)
$ZnSO_4$ (0.5%) –$MnSO_4$ (0.5%) - $FeSO_4$ (0.25%) – $CuSO_4$ (0.25%)	'Mosambi' Sweet orange	India	Desai et al. (1991)
$ZnSO_4$ (0.5%) – $CuSO_4$ (0.3%) –	Kagzi lime	India	Singh et al. (1993).
Borax (0.3%)	'Valencia' orange	Venezuela	Laborem (1977)
B (0.1%) – Zn (0.1%)	'Satsuma' mandarin	Georgia	Talakvadze (1973)
Borax (0.2%) – $MgSO_4$ (0.2%) – $ZnSO_4$ (0.1%)	'Jiaogan' mandarin	China	Wang (1999)

Ammonium molybdate (0.1%)	'Clementine' mandarin	France	Brusca and Haas (1956), Blandel and Blanc (1975)
Ammonium molybdate (0.50%)	'Satsuma' mandarin	China	Huang and Wang (1991)
Ammonium molybdate (0.45%)	'Valencia' orange	USA	Leonard (1952)

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 were 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 fruit from young trees than in fruit 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 applications (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).

1. Macronutrient Requirement : Response of nitrogen 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/day 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 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 on the medium fertility soil produced a yield of 40.5 kg/plant and 35.9 kg/plant with 1.03 kg N/plant 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 6) suggest 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 is extremely limited. The response of Ca and Mg application is common as an amendment in citrus orchards established on soils of varying acidities. Lime (upto 12 tonnes/ha) and phosphogypsum (upto 4 tonnes/ha) 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; Quaggio et al. 1998b). Other amendments like gypsum (Anderson 1968), sulphur (Rasmussen and Smith 1959)

Table 6. Soil application of various macronutrients recommended across citrus growing countries

Dose	Cultivar	Country	References
1200 N – 600 P g/tree	'Persian' lime	Cuba	Hernandez (1983).
600 N – 150 P - 600 K g/tree	'Clementine'	Algeria	Dris (1997)
800 N - 500 P - 600 K g/tree	'Pera' sweet orange	Brazil	Cantarella et al. (1992)
22.5-25 N - 5-12.5 P – 10-12.5 K g/tree	'Satsuma' mandarin	China	Wang (1985)

1500 N - 250 P - 1250 K - 1100 Mg - 100 Zn g/tree	'Satsuma' mandarin	China	Yin et al. (1998)
500 N – 100 K g/tree	'Mosambi' orange	India	Sharma et al. (1993)
500 N –100 P - 40 0 K g/tree	'Mosambi' orange	India	Ghosh (1990).
750 N - 200 P, - 500 K g/tree	'Balady' lime	Egypt	Ahmed et al. (1988)
475 N – 320 P- 355 K g/tree	'Satsuma' mandarin	Turkey	Koseoglu (1990).
125 N - 175 P 100 K g/tree	'Satsuma' mandarin	China	Hong and Chung (1979)
160 N - 320 P - 480 K g/tree	'Valencia' late orange	Cuba	Hernandez (1981)
600 N - 135 P - 285 K g/tree	'Navel' orange and 'Balady' mandarin	Egypt	El-Hagah et al.(1983)
1500 N - 400 P – 750 K g/tree	'Balady' lime	Egypt	Maatouk et al. (1988)
100 N - 200 P - 300 K kg/ha	'Valencia' orange		Goepfert et al. (1987)
475 N - 320 P - 355 K g/tree	'Satsuma' mandarin	Turkey	Koseglu et al. (1995)
240 g N - 40 g P - 100 K g/ tree	'Dancy' mandarin	Spain	Pedrera et al. (1988)
120 N - 150 P - 75 S - 6 Cu - 0.8 Mo - 5.0 Zn g/tree	'Neck' orange	Korea	Lim et al. (1993)
500 N – 500 P – 100 K g/tree	'Marsh' grapefruit	Greece	Androulakis (1992)
1002 N - 580 P – 550 K g/tree	'Satsuma' mandarin	China	Liu et al. (1994)
700 N – 250 P – 100 K – 120 Mg - 50 Zn g /tree	'Jincheng' orange	China	Yin et al. (1988)
1400 N –1008 P – 1100 K g/tree	Acid lime	India	Chundawat et al.1991)

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. Koo (1971) in two long term trials testing sources and rates of Mg on 'Marsh' grapefruit and 'Valencia' orange, reported that application of 1.5 tonnes/MgO/ha increased the yield by 12.6% and total soluble solids by 14.7% over low rate of 0.60 tonne MgO/ha. Dolomite application at the much lower rates, 400 kg/ha/year produced an additional fruit yield 75 kg/ha in 'Satsuma' mandarin in 6 years of experiment compared to application at 200 kg/ha/year (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 slowly solubilizing nutrients extensively tested all over the citrus growing countries only for a few years, especially as a method of reducing nitrate leaching (Khalaf and Koo 1983; Ferguson et al. 1988; Obereza et al. 1999; Paramasivam and Alva 1997; Schumann et al. 2003; Wang and Alva 1996). Most of these studies conducted on young trees were short term experiments focussed mainly the effect of several CRFs 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 besides (Khalaf and Koo 1983; Koo 1988) 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 (Rouse and Obreza 2003).

These CRFs performed better when applied once per year at 220 kg N/ha than water-soluble fertilizer applied three times per year at 180 kg N/ha. These observations suggest that provided

economics are favourable, 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).

2. Micronutrient Requirement : Soil application of micronutrients, especially inorganic salts is usually not so effective. The researchers even today are not unanimous about the efficacy of soil versus foliar fertilization with reference to micronutrients. Elevating Zn concentration only in the tops of Zn-deficient plants with foliar sprays partially restored the normal root growth, but clearly was not as effective as the roots absorbing Zn directly from high Zn concentration solutions (Swietlik and Zhang 1994). The micronutrient-based Zn chelater complexes are poorly or not at all absorbed by plant roots, as demonstrated through water culture studies (Chaney 1988; Swietlik and Zhang 1994). While, under field conditions, however, the addition of Zn micronutrient-chelate may elevate the amount of free nutrients in the soil solution due to adsorption and exchange properties of minerals present in soil. Soil sapplication of micronutrient, e.g., Zn from $ZnSO_4$ is fixed in the surface soil, while the chelated-Zn remain soluble and get distributed evenly throughout the soil, as evident from 46-times higher uptake of Zn from Zn-EDTA than $ZnSO_4$ on sandy soils (Parker et al. 1995). The chelates like Fe-EDTA in acid soils and Fe-EDDHA in 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 7) 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. $ZnSO_4$ - K_2SO_4 (0.5% foliar spray) - K_2O as K_2SO_4 (210 g/tree soil application) for ‘Kinnow’ mandarin(Singh et al. 1989) and $ZnSO_4$ - $FeSO_4$ - $MnSO_4$ (50 g/tree each soil application) - (0.50% foliar application) for ‘Sathgudi’ sweet orange (Devi et al. 1996).

Table 7. Soil application of various micronutrients recommended across citrus growing countries

Dose	Cultivar	Country	References
$FeSO_4$ (11.2 kg 1000 sq. feet)	‘Trifoliate’ orange	California	Armstrong (1957)
Fe-EDTA (10 g/tree)	‘Lisbon’ lemon	Israel	Helllin *et al.* (1987)
Fe citrate (2.6- 6 mg/kg) - $MnSO_4$ (1.3-3 mg/kg)	‘Satsuma’ mandarin	China	Liu and Nan (1996)
Fe-EDTA (10 g/tree)	‘Valencia’ orange , Trifoliate orange	Spain, USA	Primo *et al.* (1970), Khadr (1965)
Fe-EDTA (6 g/tree)	‘Satsuma’ mandarin	Japan	Matsuda (1968)
Fe – Mn - Zn-EDTA (292 g + 292 g + 315 g/ha)	‘Valencia’ orange	USA	Alva and Tucker (1992)
Fe-EDDHA - Zn-EDTA (35 g/tree	Trifoliate orange	India	Bakshi et al. (1973)

each)			
$MnSO_4$ (483 g/tree) + $ZnSO_4$ (303.8 g/tree)	‘Valencia’ orange	Cuba	Garcia – Alvarez et al. (1983)
$MnSO_4$ (2.2 kg/tree) + $CaCl_2$ (1.3 kg/tree)	‘Valencia’ orange	USA	Leonard and Stewart (1960)
$ZnSO_4$(100 g/tree)	‘Sathgudi’ orange	India	Devi et al. (1996)
Zn-aldehyde (4-12 kg/ha)	‘Satsuma’ mandarin	Georgia, SSR	Mdwaradze (1981)
- Zn-EDTA (30 g/tree)	‘Rio Blood’ cv grapefruit	USA	Swietlik (1996)
$ZnSO_4$ (810 g/tree soil application) - $MnSO_4$ (630 g tree)	Lemon	USA	Embleton et al.(1966)
Zn-EDTA 2.1 g/m^2	‘Valencia’ orange	USA	Anderson (1984)
Zn (3 g) - B (3 g) - Mo (1.5 g/tree)	‘Valencia’ orange	USA	Egorashvili et al. (1991)
$ZnSO_4$(500 g/tree)	Sweet orange	India	Khera et al. (1985)
Borax (1kg/ha)	‘Coorg’ mandarin	India	Srivastava et al. (1977)
Borax (100 g/tree)	‘Eureka’ lemon	Egypt	Khalidy et al. (1966)

E. Fertigation

Low water - (WUE) and fertilizer-use-efficiency (FUE) are amongst the major production related constraints (Germana 1992; Srivastava and Singh 2003). Flood irrigation in tree basin is widely used in citrus orchards, but it has several drawbacks in terms of losses through conveyance, percolation, evaporation, and distribution, 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 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 low temperature deficit stress, e.g. central India. The lack of uniformity in moisture distribution within the trees’ rhizosphere due to variation in sub-soil properties can adversely affect the development of desired fruit size (Shirgure et al. 2001a; 2001b). 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).

Fruit yield of Nagpur mandarin with different micro-irrigation systems on Vertic Ustochrept was significantly higher (48.2-58.9 kg/tree) over basin irrigation (32.3 kg/tree) with corresponding WUE of 0.19-0.24 versus 0.109 t/ha/cm and leaf N content of 2.38-2.42% versus 2.01-2.12% (Shirgure et al. 2001b; 2003). Fertigation (application of nutrients through 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). Besides the better mobility of nutrients, fertigation has been shown to have several advantages over broadcast application of granular fertilizers (Willis et al. 1991) with respect to growth response (Koo 1979), nutrient uptake (Koo 1980), effective placement of nutrients and flexibility in application frequency (Ferguson and Davies 1989), development of uniform root distribution in wetted zone, an important pre-requisite for better FUE (Alva and Syvertsen 1991; Zhang et al. 1996), fruit yield (Koo and McKornack 1965), and improvement in fruit quality (Bowman 1996).

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 Intriglio et al. (1992) while comparing a single annual application of NPK to continuous fertigated application. 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). However, 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 support 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).

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 ground surface and 53% canopy area. These observations suggest the importance of canopy coverage for high nutrient uptake efficiency and higher yield. Response of six year-old 'Hamlin' orange to fertigation frequency using 324 to 464 g N/tree, showed nitrogen uptake efficiencies 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 (Syvertsen and Jifon 2001). While, Alva et al. (1998) 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) 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 (CRT), 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 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. 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) 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), FRT (15 applications/year), and WSG (3 applications/year) 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/year produced a significantly higher 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% depletion of AWC with 600 g N + 200 g P + 100 g K/tree/year in 14-yr-old Nagpur mandarin (*Citrus reticulata* Blanco) on an alkaline calcareous Lithic Ustochrept soil type (Shirgure et al. 2003; 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% is 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. All these studies suggest that fertigation is better than conventional basin or flood irrigation with broadcast method of fertilizer application.

F. Open Hydroponics

Hydroponics is a technology for growing plants in nutrient solutions (water and fertilizers) with and without the use of an artificial medium (e.g. sand, gravel, vermiculite, rockwool, peat moss, sawdust) to provide mechanical support (Schippers 1978). Hydroponic systems are further categorised as open (i.e. once the nutrient solution is delivered to the plant roots, it is not reused) or closed (i.e. surplus solution is recovered, replenished, and recycled)

Open hydroponics (OH) is a management practice to address low fertility gravel base soils and saline water. A significant area of citrus is currently grown under OH which aims to increase productivity with quality by continuously applying a balanced nutrient mixture through the irrigation systems, limiting the root zone by restricting the number of drippers/tree, and maintaining the soil moisture near field capacity. The emphasis under this technique is given on achieving a small rooting system that provides the ability to manipulate and control plants for more efficient nutrient and water uptake through all stages of the productive cycle, since the trees are supplied with a complete and balanced nutrient solution. The buffered nutrient solution maintains the root volume at a constant pH making liming or acidification of the soil unnecessary including the planting application of phosphates. Concentrated nutrient solution is introduced into water stream by pumps that are controlled by pH sensors while observing the electrical conductivity of the solution. The technique of formulation, adjustment, and balancing of the nutrient solution together with their composition is based on irrigation water analysis. The nutrient uptake can be maximised, if the ratio of ions in the solution matches with scion/stock requirements.

Martinez open hydroponics technology (MOHT) was developed by Prof. Rafael Martinez Valero from the University of Miguel Hernandez in Alicante, Spain and introduced into Australia in 1999, which was very successful in other countries like, South Africa, Chile, Argentina, Morocco and USA. Martinez et al. (2004) in Spain evaluated the performance of ‘Nova’, ‘Marisol’, and ‘Dalite’ mandarins at density of 1000 plants/ha under MOHT system. The average yield in sixth year was 60-75 tonnes/ha, which is much higher than many conventionally managed orchards.

Various advantages of OH include high-density, maximum crop yield, a virtual indifference to ambient temperature and seasonality, more efficient use of water and fertilizers, minimal use of land area, and suitability for mechanization and disease control. However, the major superiority of hydroponics, as compared with growth of plants in soil is the isolation of crop from the underlying soil, which often has problems associated with disease, salinity, or poor structure and drainage. While, the disadvantages of hydroponics are the high costs of capital and energy inputs relative to conventional open field agriculture, and high degree of competence in plant science and engineering skills required for successful operations (Hanger 1982). The system is entirely water based, it is possible to fully automate a hydroponic system. So if the grower is absent for an extended period of time, the plants will not suffer. The water is typically reused, as opposed to traditional farming methods where much water is lost through evaporation or runoff. Hence, in less space, more plants can be accommodated under OH system. More information on critical issues like capability of manipulate the soil solution as a restricted root zone versus conventional drip irrigation root zone, buffering capacity of soil manipulating specific nutrient ratios at different physiological stages, evaluating orchard productivity-energy relationship through ionic balanced nutrient solution, planting density etc. are further required before OH system under citrus is adopted on a commercially large scale.

Bravdo et al. (1992) in Israel compared the response of ‘Shamouti’ orange under restricted root zone practices, a sprinkler versus drip irrigation treatment with three fertilizer rates, maintained at high moisture status (8-12 Kpa) as a part of intensive OH program. A significant increase in yield in the restricted root zone drip irrigation treatment was observed with the highest rate of fertilizer application, 400 kg N/ha. Similar promising results were obtained by Kruger et al. (2000) in South Africa where OH system increased the yield of ‘Valencia’ orange and ‘Clementine’ orange by 19% and 25%, respectively, using 16% less water with 25-31% higher returns compared to micro-irrigation with broadcast method of fertilizer application as control.

The principles of OH have some potential benefits in conventional production practices like intensive fertigation programs (IFP). IFP is a fertigation program that has similar principles to OH, but is less intensive than OH. Both use a nutrient solution containing various macro- and micronutrients (ionic balance is more important in IFP than OH), proportional injection of the nutrients into the water supply, pH adjustment of the irrigation water, and a high level of irrigation scheduling and monitoring. The most obvious difference is that IFP uses a larger conventional root zone volume and a refill point that is set lower than OH. The practical implication of using a conventional root zone is that the physical and chemical properties of the soil are more utilised. This can lower the application rates of some of the macronutrients, e.g. Ca, Mg, and K. The majority of growers using IFP would irrigate only once a day to maintain soil moisture at a good level (generally not exceeding 50% readily available water), whilst OH would be focussing on maintaining soil moisture levels near field capacity. IFP is an intensive form of fertigation, whilst OH uses fertigation as apart of a hydroponic management strategy. Nutrient application rates in majority of OH and IFP in citrus can be about 20% to 50% higher than conventional practices due to higher productivity levels and a lower nutrient bank in the soil. Therefore, OH and IFP use a more intensive nutrition program that may push the trees into a higher level of vigor and productivity requiring higher nutrient application rates to maintain production.

G. Organic Soil Fertility Management

Renewed and intensified efforts are in progress to grow citrus organically ever since the depleting soil fertility causing citrus decline has warranted concern to citrus researchers. The occurrence of multiple nutrient deficiencies has the major force in citrus belts with low production, especially in southeast Asian countries. There are some citrus growers who annually add large amount of organic manures to maintain soil fertility in the context of leaching losses of applied inorganic fertilizers and consequently, the ground water pollution. Besides fertilization or manuring, certain indirect methods of restoring soil fertility in form of soil conservation practices like trench planting (Lu et al. 1977), terrace planting (Vasalmidze 1969), contour planting (Brown 1963), and soil ridging (Coetzee 1995) also helped in raising the productivity of hillside citrus orchards.

Organic farming and low input sustainable agriculture (LISA) program are both the part of an alternative agricultural movement that promotes biological interactions and other cultural practices in lieu of agricultural chemicals (U.S. Dept. of Agriculture 1991). Formulated federal definition specifies organically grown citrus as: (i.) citrus must be produced for three years prior to harvest without the use of artificial radiation, synthetic pesticides, synthetic plant or soil amendments, or synthetically compounded fertilizers, (ii.) no residue of synthetic pesticides greater than 1% of the tolerance limit of guidelines established by the U.S. Environmental Protection Agency or the U.S. Food and Drug Administration (Congressional Record 1990).

1. Soil Microbial Distribution : Review of work done during 1975 - 1998 (Kalita et al. 1996; Bhattacharya et al.1999) showed the presence of *Bacillus polymyxa, B. subtilis, Aspergillus terreous,* and *Trichoderma viridi* as phosphate solubilizers in citrus growing soils of India, having phosphate solubilising capacity of 13.3 - 81.7% (Kohli et al. 1997b). Population density of *Azotobacter*, ammonifiers, and phosphate solubilising bacteria was higher in rhizosphere (0.4-16.5 x 10^4, 0.5-95.0x10^5, and 0.9-78.0x10^4/g soil) than non-rhizosphere zone (0.3-10.5 x 10^4, 0.5-35.0 x 10^5 and 0.9-38.2 x 10^4/g soil, respectively), and influenced in fruit yield substantially (Kohli et al. 1997b; Paliwal et al. 1999). Mycorrhiza species predominantly belonging to genus viz., *Glomus mosseae*, *G. clarum, G. caledonium, G. intraradices, Gigaspora,and Scutellospora* are commonly observed in citrus orchards (Camprubi and Calvet 1996; Ishii and Kadoya 1996).

2. Organic Manuring Versus Inorganic Fertilization : One of the basic principles of soil fertility management in organic citrus is that plant nutrition depends on biologically- derived nutrients, instead of using readily soluble and less available forms of nutrients such as those in bulky organic materials are used (Ramesh et al. 2005). Organic manures in comparison to inorganic fertilizers are often claimed to be superior on four counts (Sankaram 1996). These are: (i) decreased storage losses and high starch content after storage due to low moisture content, (ii) higher ascorbic acid content, better taste, flavor, resistance to insect pests, and diseases in addition to higher biological value of protein, (iii) introduction of beneficial microorganisms due to suppression of soil borne plant pathogens by organic amendments, and (iv.) buildup and stability in soil structure, better air-water relation, retention and regulated supply of nutrients. Shelf life and fruit quality of citrus are claimed arguably better in organically grown citrus (Huchche et al. 1998; Srivastava et al. 2002). Many studies in the past have not supported this perception, and warrant for an indepth long term experiment to provide a sound scientific data base in support of above claims.

Application of farmyard manure (FYM) either alone or in combination with NPK improved the leaf area (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 in 'Nagpur' mandarin (Huchche et al. 1998) in comparison to NPK alone. Combined application of organic manure with chemical fertilizer is still a popular mode of fertilization. Highest fruit yield and improved quality were obtained with 25 kg FYM with 400 g N - 150 g P - 300 g K/plant in 'Khasi' mandarin on acid red soils (Ghosh and Besra 1997), 15 kg neem cake with 800 g N - 300 g P_2O_5 - 600 g K_2O/tree/year in 'Mosambi' sweet orange (Tiwari et al. 1997),and 90 kg organic manure – 0.60 kg urea 0.80 – 1.00 kg complex fertilizers in 'Satsuma' mandarin (Xong et al. 1997). Similarly, other studies (Fisher 1992; Huang et al. 1995) explained the promising role of chicken manure in citrus manuring program with reference to both fruit yield and quality. Response of different rootstocks (sour orange, Swingle citrumelo,Troyer citrange, and cleopatra mandarin) seedling grown on a mixture of peat, vermicullite, and sand showed an increase in root and shoot dry weight by 15% and 21%, respectively, with treatment of 0.5% and 1% root solution as bio-stimulant containing humic acids, marine algae extracts, plant metabolite, and vitamin-B (Swietlik 1991).

3. Cover Crops : Role of wide range of cover crops in citrus orchards is very well documented (Jones and Embleton 1973; Anderson 1980). The cover crops like purple vetch (*Vicia atropurpurea*) and sweet colver (*Melilotus indica*) produced net gains of nitrogen to the tune of 375 kg/ha (Chapman et al. 1949). Luo et al. (1992) based on 8 yers of experimentation showed yellow clover (*Melitotus officinalis*) as a promising green manure crop which can produce 7.5-12.0 tonnes/ha green biomass adding(kg/ha) 3.7-59 N, 4-6 P, and 23-37 K into soil. Likewise, application of 20 cm thick grass mulch in a nonirrigated orchard of 13-15 year-old 'Satsuma' mandarin for 3-years improved the organic mater N, P, and K by 68%, 67%, 86% and 107%, respectively (Jiang et al. 1977). Huang (1998) based on 20 year old of experimentation in hillside citrus orchards on red soil at 275-900 m altitude showed that most suitable green manure crops include Indian cowpea (*Vigna radiata*) and Chinese milk vetch (*Astragulus sinicus*).

4. Vermicompost Usage : Vermicompost is a stable, consolidated, and nutrient rich compost derived from recycling of organic wastes using specialized technique of earthworm culture on a bio-organic farming concept. Various research groups are working to establish the role of vermicompost, and devise ways of adopting natural farming using eco-friendly soil fauna. One such alternative is the production and utilisation of composted organic wastes achieved by earthworms.

Charles Darwin, in his masterpiece treatise on formation of vegetable mould through action of worms, called earthworms 'Natures Plough' due to their utility as living plough. The native species of earthworm namely *Lampito mauritil, Perionyx excavatus, P. arbicola, Dracvida wilsii, Eisenia foetida,* and *Eudrilus eugenieae* are commonly used in vermiculture (Sarkar 1994). The vermicompost formed by these earthworms showed a large variation in nutrient value of compost upon maturity (Talashilkar et al. 1999). Earthworm burrowed lines and casts serve as an excellent media for harbouring N-fixing bacteria and active enzymes *viz.,* protease, amylase, lipase, cellulase etc., to aid in disintegration of organic matter (Loquet et al. 1997).

Stability of soil aggregates due to vermicompost treatment is of great physical importance for improved soil-water-nutrient-plant relationship. Improvement in soil properties especially available N, permeability, structure in form of water stable aggregates due to stabilization of soil particles by polysaccharide gums produced by bacteria present in earthworms' intestine, and hydraulic properties (Friend and Chan 1995) due to creation of permanent burrows of earthworms are well documented. Considerable increase in available K extracted from the wormcasts over non-ingested soil due to partial conversion of non-exchangeable K into exchangeable form supports their role in soil-K transformation (Rao et al. 1997).

5. Microbial Biofertilizers : Microbial fertilizers are biofertilizers or microbial inoculants defined as preparations containing live or latent cells of efficient strains of nitrogen fixing, phosphate solubilising or cellulotytic microorganisms to augment the nutrient availability in an assimilable form. The biofertilizers are cheaper and less prone to cause pollution than chemical fertilizers which are based on renewable energy sources. One possible way of increasing nutrient content of the organic residues is the microbial enrichment technique with cellulose decomposers. Response of microbial biofertilization is comparatively unpredictable due to their biological origin and susceptibility to various abiotic stresses. But, considering the vital role of microbes in maintenance and buildup of soil fertility, their utility is worth considering in organic citrus (Srivastava et al. 2002), and have the potential of being introduced in citrus soil (Dubey et al. 1999).

6. Mycorrhizal Associations : Fossil records indicated that VAM fungi infected the roots of *Aglaophyton* major, as early as 400 million years ago, known as Devonian period when plants invaded the land. Mycorrhizae are symbiotic association between fungi and roots of higher plants, in which both members normally benefit from the association. The endomycorrhizae association fungal hyphae enter the intracellular space, and often disintegrate to enrich soil fertility is commonly observed in citrus (Nemec 1992). Known effects of VAM fungi are: (i.) promotion in adsorption of minerals, especially P; (ii.) stimulation in growth; and (iii.) enhancement in resistance against environmental stresses (Ishii and Kadoya 1996).

Growth : Citrus is infected by several kinds of VAM fungi and considered highly dependent on them (Ishii 1994) known as mycorrhizal dependence expressed as dry weight ratio between mycorrhized and non-mycorrhized plants, is common amongst citrus rootstocks (Camprubi and Calvet 1996). On high-P orchard soils, less mycorrhizal dependent (MD) species have lower rate of root colonization than more MD-species (Graham et al. 1997). Mycorrhizal inoculation has shown substantial improvement in various vegetative growth parameters (Cheng et al. 1997; Zyl 1996) and plant carbohydrate reserve(Nemec 1992).

Plant nutrition: Mycorrhizae are helpful to improve the uptake of diffusion limited nutrients such as P, Ca, Zn, Cu, Mn, and Fe by the host plants (Treeby 1992; Onkarayya and Mohandas 1993; Graham et al. 1996), on account of their ability to dissolve and promote absorption of these nutrients. 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 nutrient uptake, especially noticeable in soils of low fertility. Exact mechanism involved is still not clear, whether the endophyte is directly involved in nutrient uptake and supply to the host, or it is an indirect effect of change in root growth habit.

Soil fertility variations have profound implications on mycorrhizal efficiency. On basis of analysis of 26 citrus orchard soils in California, Menge et al (1982) observed maximum growth of citrus through mycorrhizal inoculation, where soil had < 34 mg/kg Olsen - P, 1.2 mg/kg Zn, 27 mg/kg Mn, and 3% organic matter. While, Dixon et al. (1989) suggested that foliar application of boron stimulated the efficacy of mycorrhizal inoculation. Selection of suitable fungal species and native soil-P level are, hence, important for tapping the efficiency of VAM fungi in citriculture.

H. 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 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.

The conventional long term fertilizer trials (Tiwari 2002) revealed that: (i.) omission of limiting macro- or micronutrient leads 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 big 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.

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 applications (Schumann et al. 2003; Zaman et al. 2005).

1. Variable Rate Fertilization : It is one of the most effective techniques for rationale use of fertilizers executed by matching the fertilizer rate with tree requirement on a per tree size basis. Site specific management of 17-year old 'Valencia' grove (2980 trees) in Florida using automated sensor system equipped with differential global positioning system and variable rate delivery of fertilizers (135-170 kg N/ha/year) on a tree size basis (0-240 m^3/tree), achieved a 38-40% saving in granular fertilizers cost. While, conventional uniform application rate of 270 kg N/ha/year showed that trees with excess nitrogen (>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 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 with corresponding fertilizer does (g/tree) 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)

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 size classes and a median size of 82 m^3/tree. At a uniform fertilization rate of 240 kg N/ha/year, 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, and constituted 62% of the grove. Under such conditions, variable rate fertilization can, therefore, save production costs, 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/year. For comparison purposes, the eastern half of the grove received the full uniform rate of 240 kg N/ha/year. No fertilizer was allocated by spreader to skips or resets 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)

V. SUMMARY AND CONCLUSIONS

1. General Review

Diagnosis of nutrient constraints and their management are the two pillars of an efficient fertilizer management program. Maximising quality production through constraints- based use of nutrients is a well established fact that assumes a greater significance in fertilizer responsive perennial fruit crop like citrus. A large number of diagnostic tools, namely leaf analysis, soil testing, juice analysis, and biochemical markers-aided-analysis are under continuous scrutiny, test, recurrent use, and subsequent refinement. The nutrient diagnostics that have emerged through worldover research on different commercial citrus cultivars have lacked considerably in their universal applicability due to difference in interpretation tools used in developing the nutrient diagnostic norms, besides being influenced by many other factors in the outcome of the interpretation. A diagnostic tool is considered best for both diagnostic as well as prognostic testing that minimizes the influence of these over-riding factors, and produce uniformity in diagnosis when spaced over time. Out of different diagnostic methods in practice, only leaf analysis complimented by soil analysis, has made some headway. Geo-referenced soil sampling has proved to be an effective tool in defining soil variability within an orchard. Once the critical soil properties are identified, the procedural steps can be evolved to address the inconsistency in fertilization response.

The utility of conventional leaf analysis as a diagnostic tool is often cut short due to strong influence of leaf age (crop development stage). The interpretation tools used in the past such as critical nutrient concentration and sufficient range system developed by using index leaves are applicable only to specified developmental stage of crop. The researches on DRIS with citrus as test crop have shown some distinct advantages over conventional leaf analysis-based interpretation tools in order to make diagnosis possible at any stage of crop development without loosing much the precision in application of norms under diverse growing conditions. The remediation of nutrient constraints has now found a new look in terms of automated fertigation, organic cultivation using a combination of bulky organic manures, and microbial biofertilizers, site specific nutrient management as a part of precision citriculture, all to be integrated to develop a more effective INM strategy. But above all these changes, still the major challenge lies on the relationship between inconsistency in response of fertilization and modulating the quality production, because of site specific nature of yield response studies.

2. Prospects for Future Research

Some of the issues are still difficult to answer even today in concrete terms, unless supported by an additional research for better conceptual understanding about the diagnosis and management of nutrient constraints in citrus. In this regard, ideally we need to develop the polypeptide- based warning system using biochemical markers to facilitate round-the-year nutritional care of crop through a better use of precision precision oriented informatics keeping in mind the orchard efficiency as an ultimate index of productivity. To fulfill this, studies on biochemical response in relation to varying nutrient supply systems especially under multi-nutrient deficiencies and establishing the causal relationship between the nutrient deficiency in root system and to be able to coordinate changes in shoot system, are very much imperative reactions that are seemingly most sensitive to a nutrient deficiency.

Amongst different nutrients, Zn has attracted worldwide investigation from various angles. 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.

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, frequent low concentration fertigation events, multiple applications, and variable rate application technology in order to improve FUE.

However, using newly emerging techniques of nutrient management like open hydroponics with restricted root zone and site specific management, concreted efforts would be required to develop yield monitors in the light of adequacy level of plant nutrition.

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