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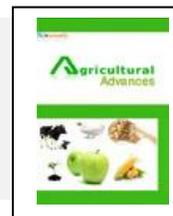


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Review article

Nutrient-water interaction in citrus: recent developments

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ABSTRACT

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Water along with fertilizer use efficiency and commercial citriculture grow in tandem for global trade and tariff. Optimising water and fertilizer requirement through micro-irrigation and fertigation constitute an important component of nutrient -water interaction in citrus. Our past studies involving four treatments, viz., 4 L h⁻¹ dripper (pressure compensating, 4 plant⁻¹), microjet 300° (Rayjet, 2 plant⁻¹), microjet 180° (Ejet, 2 plant⁻¹), and basin (ring) irrigation on a Vertic Ustochrept soil showed significantly ($P < 0.05$) higher fruit yield (48.23-58.93 kg tree⁻¹) with micro-irrigation systems over basin irrigation (32.30 kg tree⁻¹) with corresponding water use efficiency of 0.194-0.238 t ha⁻¹ cm⁻¹. While long term fertigation studies showed that irrigation at 20 % depletion of available water content and fertilizer treatment of 500 g N + 140 g P + 70 g K tree⁻¹ year⁻¹ (against conventional optimum fertilizer dose of 600 g N + 200 g P + 100 g K tree⁻¹ year⁻¹) proved to be an optimum irrigation and fertilizer requirement, respectively, with corresponding reduction in water and fertilizer requirement by 40-50% and 30-40%. Combined application of these two treatments produced significantly higher magnitude of fruit yield m⁻³ of canopy (tree efficiency) in addition to higher leaf nutrient composition and fruit quality indices. With the more addition of sensor- based irrigation and automised variable rate application technique coupled with multiple channel delivery systems, the water- and nutrient -use efficiency will play more pivotal role in commercial citriculture, in the wake of escalating cost of both the commodities.

1. Introduction

Annual nutrient needs of a crop are defined as the amount of nutrients consumed along the year by the plant, which are supposed to be enough for a correct plant development and fruit production. Its determination includes the needs of both new developing organs (reproductive and vegetative) and old permanent organs growth consumption. This demand does not include annual old leaves requirements because these leaves, at the beginning of a new fertilization program, translocate mobile nutrients to different new organs, before its abscission.

In citrus, many years ago, quantitative determinations of nutrients consumptions were determined through chemical analysis of young or aerial plant tissues (Smith, 1966). However, these data did not properly reflect the annual nutritional needs of the plant since neither elements accumulated in perennial tissues (roots, trunk and older branches) nor the nutrients supplied by the storage tissues (internal remobilization) can be determined without extracting plants from soil. Later on, Legaz and Primo-Millo (1988) and Martínez-Alcántara et al. (2011) determined the total amount taken up by a citrus tree along one-year vegetative cycle by means of sequential destructive harvests of trees of different ages (2-, 6- and 12-years-old) along the cycle. In the case of N, these data were obtained by supplying nitrogen heavy isotope (^{15}N) in an inert soil-free medium (sand) or in soil. Annual nutrients requirement shown that some nutrients are provided by the reserves of old leaves, except for Fe, which is scarcely mobile in the plant and its translocation from old leaves to new developing organs can be considered negligible. The difference between new and old organs nutrient demand and that covered by old leaves reserves represents net annual needs for citrus tree.

Citrus is predominantly grown in tropical and subtropical areas of world at 40o latitude of either north or south of equator (Burke, 1967, Shirgure et al., 2000b; 2002a). Flood irrigation in tree basin is widely used in citrus orchards, especially in south-asian countries (Shirgure et al., 2012b). 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., 2012a; Shirgure, 2013a). 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 (Srivastava et al., 2003). 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; 2004). 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).

Many efforts have been made in the past to devise ways and means to enhance fruit yield with combined use of irrigation and fertilizer being far superior to conventional broadcast method of fertilization (Zhang et al., 1996; Shirgure et al., 2001a; 2001b). Bowman (1996) compared the effect of conventional fertilization by broadcasting granular material and a combination broadcast/fertigation on mature grapefruit cv Ruby Red trees established on Flatwood soils of Florida, USA. Conventional fertilization consisted of broadcast application, 3- times a year (January/February, May/June, and October/November), while combination fertigation treatment received 33% of annual N and K in February/March followed by remainder applied as fertigation at 2-weeks interval beginning in April. The total soluble solid (cumulative of 4 years) in combination broadcast/fertigation was much higher (10.9 tons ha⁻¹) compared to conventional fertilization (10.1 tons ha⁻¹). In many citrus growing areas, low water use efficiency (WUE) and fertilizer use efficiency (FUE) are amongst the major production related constraints (Germana, 1994; Srivastava and Singh, 1999; 2002a; 2003). Of the many components influencing the use efficiency of applied fertilizers, application timing, method, and rate play an important role in affecting fruit yield and quality.

2. Micro-irrigation

Micro-irrigation systems, viz., drip irrigation, under-tree sprinklers, micro-sprinklers, and micro-jets have been reported to be highly effective in commercial citrus cultivars like Valencia orange (Azzena et al., 1988), Navel orange (Fouche and Bester, 1986), Hamlin orange (Marler and Davis, 1990), Satsuma mandarin (Peng Young Hong and Rabe, 1999), Clementine (Castel, 1994) and lemon (Cevik et al., 1987). Earlier studies in India comparing drip with flood irrigation in Nagpur mandarin (Autkar et al., 1989; Shirgure et al., 2001d), sweet orange (Kumar and Bhojappa, 1994), and acid lime (Shirgure et al., 2001f, 2002b) showed better performance using drip irrigation. Micro-irrigation systems are commonly used in citrus orchards throughout the world. These results have shown some distinct transformations. There is now a gradual shift in method of irrigation from furrow irrigation-overhead sprinkler irrigation systems to under-tree sprinkling systems like micro-jets (Rondey et al., 1977; Dasberg, 1995).

Basin irrigation for citrus trees is usually used in countries like India, Pakistan, Thailand etc. in south Asia (Ghosh and Singh, 1993; Shirgure and Srivastava, 2012), Argentina (Castel et al., 1989), Australia (Simpson, 1978), Turkey (Tuzucu et al., 1997), Italy (Capra and Nicosia, 1987), South Africa (Plessis, 1985). When basin irrigation is used in northwest and central India, temporary excess soil moisture condition occurs as well as the leaching of applied nutrients below the effective rootzone (Castel et al., 1994; Shirgure et al., 2001a; 2004a). This problem is further confounded by the swelling and shrinking of montmorillonitic clay soils of central India where Nagpur mandarin (*Citrus reticulata* Blanco) is grown so extensively. Therefore, a strategy which allows judicious use of water as well as nutrients in concurrence with plant demand is likely to impart an improvement in citrus production besides fruit quality. Fruit yield of Nagpur mandarin with different micro-irrigation systems on Vertic Ustochrept was significantly higher (48.23-58.93 kg tree⁻¹) over basin irrigation (32.3 kg tree⁻¹) with corresponding WUE of 0.19-0.24 versus 0.109 t ha⁻¹cm⁻¹ and leaf N content of 2.38-2.42% versus 2.01-2.12% (Shirgure et al., 2003a).

The highest fruit yield of mandarin was recorded with irrigation system of micro-jet 1800 (Fanjet) (2/plant) irrigation system (40.33 t/ha) followed by irrigation with 2700 micro-jet (Rayjet) (2/plant) (39.89 t/ha), whereas the lowest fruit yield was observed in irrigation with 3000 Ray type micro-jet (2/plant) (35.10 t/ha). The highest TSS (10.12o Brix) and juice content (43.05 %) was found in micro-jet 1800 (Fanjet) and micro-jet 3000 (Rayjet) respectively (Shirgure et al., 2003a). The Nagpur mandarin fruit yield was highest (30.91 tones/ha) with irrigation on alternate day 120 minutes three times, followed by irrigation scheduled with 90 minutes interval two times daily (30.11 tones/ha). Fruit weight (154.7 g), TSS (10.22 OBrix) and juice percent (40.77%) was found with automatic irrigation at alternate day with 120 minute three times. The automatic drip irrigation scheduling can be better substitute for manual drip irrigation operation and enhancing the water use efficiency (Shirgure and Srivastava, 2012).

3. Fertigation

It is the most effective and convenient means of maintaining optimum fertility level and water supply

Table 1

Response of different irrigation systems on fruit yield, water use efficiency and leaf nutrient composition in Nagpur mandarin (Pooled data 1999-2003).

Treatments	Fruit yield (kg plant ⁻¹)	Water use efficiency (t ha ⁻¹ cm ⁻¹)	Leaf nutrient composition (%)			Fruit quality (%)		
			N	P	K	TSS	Juice	Acidity
Dripper 4 L h ⁻¹ (4 plant ⁻¹)	48.23	0.194	2.080	0.115	1.750	9.10	48.80	0.80
Microjet 300° (2 plant ⁻¹)	55.96	0.225	2.220	0.127	1.850	9.23	50.87	0.78
Microjet 180° (2 plant ⁻¹)	58.93	0.238	2.240	0.142	1.900	9.12	50.47	0.75
Basin (ring) irrigation	32.3	0.109	1.870	0.117	1.730	8.55	47.71	0.85
LSD (P=0.05)	2.91	0.33	0.12	0.01	0.08	0.11	0.37	0.08

Source: Shirgure et al., (2001d and 2003a).

according to the specific requirement of each crop. In the area of scarce water resource and insufficient rainfall, fertigation offers the best and sometimes the only way of ensuring the nutrients enter the root zone of acid lime

(Shirgure et al., 1999; 2001c). 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 (Shirgure 2013b). 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), fruit yield (Koo and McKornack, 1965), and improvement in fruit quality (Bowman, 1996). 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 nutrient, in fertigated production systems, resulted in confining most of the roots within surface soil (Alva and Syvertsen, 1991; Zhang et al., 1998).

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. 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⁻¹, 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⁻¹ (Syvertsen and Jifon, 2001). While, Alva and Paramasivam (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. The investigations on pre-bearing Acid lime (*Citrus aurantifolia* Swingle) during 1995-97 having fertigation with 60%, 80% and 100% N of the recommended doses were compared to the band placement (100% N) method of fertilizer application. The percentage increase in plant height, plant girth and canopy volume was maximum with 100 % N fertigation followed by with 80 % N fertigation. The percentage increase in leaf Nitrogen content was more in case of 80 % N fertigation (27.47 %) followed by 100 % N fertigation (24.32 %) , 60 % N fertigation (20.23 %) and band placement (7.5 %). This study clearly indicates the advantage of N fertigation over the conventional method of fertilizer application (Shirgure et al., 1999). Alva et al. (2003) studied the comparative response of 32 months-old non-bearing 'Hamlin' orange trees on a Candler fine sand (Typic Quartzipsammments) 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 trees which received the higher fertilizer rates were 82.3, 70.2, and 41.4 g tree⁻¹ for the FRT, CRF, and WSG sources, respectively. The corresponding values for the low- fertilizer rate treatments were 38.6, 50.4, and 28.4 g tree⁻¹. However, the proportion of total N partitioned to leaves was greater for WSG than for the CRF and FRT sources at both the fertilizer rates. Similar observations were made through the response of 25 yr-old 'Hamlin' orange in Highland county with varying N rates (112-180 kg ha⁻¹) and fertilizer management practices (WSG, CRF and FRT). Spring flush leaf N content increased with increasing N rates decreased in the order of FRT > WSG > CRF (Paramasivam et al., 2000). Other studies by He et al. (2003) involving CRF (1 application year⁻¹), FRT (15 applications year⁻¹), and WSG (3 applications-1year) showed no response of fertilizer sources either on fruit yield of grapefruit or leaf nutrient composition on Arenic Glossaqualf soil.

It is the result of these important breakthroughs, that fertigation is now increasingly gaining importance as a popular method of fertilizing citrus trees. According to Lekchiri (1983), the phosphorus and potassium requirements of citrus trees are relatively high. But, soil conditions and restricted root colonization may limit the availability and uptake of soil nutrients. To overcome these difficulties, two alternatives can be adapted. These are: i. using micro-irrigation system, fertilizer application using fertigation or by placement in furrow parallel to the dripping ramp where the soil is moist, thereby, improving the mobilities of P and K and enriching the soil where

roots are concentrated to improve fertilizer uptake efficiency, and ii. application of fertilizers by placement in the zone receiving water, to improve the mobility of P and especially of K upto a depth of 60 cm. Besides the mobility of nutrients, fertigation has several advantages over broadcasted granular fertilizers (Willis et al., 1990; 1991) including effective placement of nutrients and flexibility in application frequency (Ferguson and Davies, 1989), in addition to development of uniform root distribution (an important pre-requisite for better fertilizer use efficiency) under fertigation (Zhang et al., 1996). Fouche and Bester (1987) tried various fertilizer combinations through fertigations on 13 year old Navel oranges. Fertigation was supplemented with: i. soluble fertilizer 'Trisol' (3:1:5) + 350 g urea by broadcast, ii. fertigation of N and K with broadcast of single superphosphate and iii. N P K through broadcast application. Highest yield was obtained with fertigation of N, P and K through Trisol or by complete broadcasting of N P K fertilizers. No significant differences were observed with regard to fruit quality parameters viz., fruit size, acidity, juice content and TSS when compared within treatments.

Table 2

Response of fertigation on fruit yield, quality and leaf nutrient composition in Nagpur mandarin (Pooled data of 2001-06).

Treatments			Fruit yield (kg tree-1)	Fruit quality (%)			Leaf nutrient content (%)				
Main plot	Sub plot			TSS	Acidity	Juice	N	P	K		
Irrigation at 10 % AWC depletion	N	P	K								
	600	200	100	40.70	9.04	0.77	49.94	2.24	0.13	2.09	
	500	140	70	43.80	8.55	0.79	50.00	2.19	0.14	2.08	
20 % AWC depletion	400	80	40	51.10	8.49	0.78	49.57	2.09	0.12	1.94	
	600	200	100	43.60	9.21	0.79	51.38	2.28	0.16	2.16	
	500	140	70	58.60	9.54	0.67	53.47	2.47	0.19	2.33	
30 % AWC depletion	400	80	40	61.00	9.45	0.77	51.36	2.27	0.16	2.08	
	600	200	100	43.00	8.16	0.81	49.81	2.22	0.13	1.99	
	500	140	70	49.80	8.61	0.77	49.90	2.19	0.13	2.03	
40 % AWC depletion	400	80	40	58.70	8.31	0.80	49.57	2.12	0.11	1.91	
	600	200	100	42.10	8.54	0.77	52.17	2.12	0.14	2.05	
	500	140	70	45.10	8.85	0.78	48.91	2.12	0.11	1.78	
		400	80	40	54.8	8.50	0.77	48.21	2.16	0.10	1.66
		Irrigation levels (I)		2.04	1.17	0.03	1.64	0.11	0.03	0.15	
CD (P=0.05)		Fertigation levels (F)		3.86	0.12	NS	0.97	0.06	0.02	0.08	
		Interaction I x F		6.77	0.48	NS	2.29	0.16	0.06	0.21	

Source: Shirgure et al., 2001b.

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). Earlier studies 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. Irrigation at 20% depletion of available water content (AWC) combined with fertilizer treatment of 500 g N + 140 g P + 70 g K tree-1year-1 produced a significantly higher fruit yield m³ canopy in addition to higher nutrient status and fruit quality (Table 2) compared to other treatments involving irrigation either 10% depletion or 30% depletion of AWC with 600 g N + 200 g P + 100 g K-1tree-1year in 14-year-old Nagpur mandarin (*Citrus reticulata* Blanco) on an alkaline calcareous Lithic Ustochrept soil type (Shirgure et al., 2001b; 2001c; Srivastava et al., 2003). Irrigation at 30% depletion of available water content (AWC) combined with fertilizer treatment of 500 g N + 140 g P + 70 g K tree-1year-1 produced a significantly higher fruit yield m³ canopy in addition to higher nutrient status and fruit quality compared to other treatments involving irrigation either 10% depletion or 20% depletion of AWC with 600 g N + 200 g P + 100 g K-1tree-1year in 10-year-old acid lime (*Citrus aurantifolia* Swingle) on an alkaline calcareous Lithic Ustochrept soil type (Shirgure et al., 2003b; 2004b).

4. Nutrient use efficiency and fertigation

The purpose of fertilization is to increase the natural fertility of the soil in order to improve the nutritional status of crop plants. Citrus trees demand high-amounts of fertilizers, unfortunately, farmers have applied excessive dosages of nutrients because of poor fertilizing criteria and slight enhances found in fruit yield when increasing the dosages. This has resulted deterioration in the commercial quality of the fruit (Chapman 1968), a reduction in the profitability of the citrus crops (Wild 1992) and a NO₃- displacement, mainly, to deeper soil layers. In this case, many studies have shown direct relationships between this addition of N in areas of intensive agriculture and the alarming increase of NO₃- concentration in groundwater (Singh and Kanehiro 1969, Bingham et al. 1971, Burkart and Stoner, 2002, Babiker et al., 2004, de Paz and Ramos, 2004).

Nowadays, efforts are being directed to understand the large number of processes in which nutrients are involved in the plant-soil system, like irrigation management, application frequency, timing of application, as well as soil processes, in order to reduce rates and thus losses, which may result in surface and ground water pollution, maintaining crop productivity. This section compiles the results of several studies carried out by different authors with the aim of reevaluating current fertilization programs. This information is necessary to deeply understand nutrient use efficiency and thus advance towards Best Management Practices for citrus crops.

Nitrogen Fertigation : In citrus orchards, irrigation systems directly affects N absorbed from fertilizer (N_{aff}) by the entire tree and the amount retained in soil or leached in drainage. Quiñones et al. (2005) obtained higher N recovery percentages in Navelina using drip irrigation (73 %) than under flood irrigation (63%). This data are similar to those of Syvertsen and Smith (1996) who found nitrogen use efficiency (NUE) value for lysimeter-grown citrus trees on the order of 61 to 68%. Further improvement of NUE by citrus with fertigation compared with dry granular fertilizer was reported by Dasberg et al. (1988), Alva and Paramasivam (1998), Alva et al. (1998) and Alva et al. (2003). Li et al. (2004) studied the influence of fertigation strategies on N distribution in soil profile with drip irrigation. For a given volume of water applied, increasing the application rate allows more water to distribute in the horizontal direction, as in drip irrigation, while decreasing the rate leads to more water in vertical direction and, therefore, nitrate leaching could be higher. In this line, Quiñones et al. (2007) showed that the percentages retained in soil profile as NO₃--N were significantly higher for the flood irrigated (around 38% of the N retain) than for the drip irrigated trees (8%). Nevertheless, no significant differences appeared in the amount of organic-15N for both irrigation systems. Citrus trees demand high-amounts of nitrogenous compounds as nitrogen (N) has a greater influence on growth and production than other nutrients (Smith, 1966).

Frequency of N application also affects N distribution in plant-soil-leaching system. More frequent application of dilute N solutions double NUE compared with less frequent application of more concentrated N solutions (Scholberg et al., 2002; Quiñones et al., 2005). In another study, Alva et al. (2006) demonstrated a slight increase in N uptake efficiency as a result of better management practices associated with N placement, timing of application, and optimal irrigation scheduling when comparing fertigation (FRT-15 N applications) versus water soluble granular (WSG-4 N applications). Also increases in NUE were obtained by other authors expressed as increment in fruit yield. Boman (1996) reported a greater NUE (9% greater fruit yield) in grapefruit trees receiving a combination of one dry granular broadcast application (33% of the annual rate) and 18 fertigations at 2-week intervals compared to trees that received 3 applications of dry fertilizer. Alva et al. (2003) evaluated different combinations of irrigation and nitrogen management. In young trees, Morgan et al. (2009) founded higher yields when compared controlled-released fertilizer and fertigation applied 30 times annually with dry granular fertilizer and fertigation applied 4 times.

Greater N recovery by whole tree in trees fertilized with potassium nitrate (40.1 and 37.0% in sand and loam soil, respectively) than those under ammonium fertilization (37.9 and 33.9% in sandy and loamy soil, respectively) was found. Use of nitrification inhibitors (NI) could also affect NUE. Nitrate-N fertilizers are absorbed more efficiently than ammonium-N by citrus plants, however ammonium fertilizers are recommended during the rainfall period. The addition of NI to ammonium-N fertilizers increases NUE (16%), resulting in lower N-NO₃- content in the soil (10%) and in water drainage (36%).

4.1. Phosphorus fertigation

Unlike nitrogen, phosphorus has been less studied because, in general, the soils have enough phosphorus. In practice, the main important question the citrus growers could ask is whether there is enough available P in the soil solution to ensure a proper plant development (Kafkafi and Tarchitzky, 2011). In non-irrigated conditions,

phosphorus shows very low mobility into the soil profile (Malavolta and Violate Neto, 1989), and therefore losses by leaching of this element are negligible (Coelho, 1973). High fertigation frequency ameliorates this situation, since there is a continuous forced mass flow, which goes from the surface into the soil. Increased saturation of P fixation sites in the soil due to high frequency and application rate results in higher amounts of P released to solution, which combined with the forced flow of water into the soil, facilitates the distribution and the consequent increased levels of P (Duenhas et al., 2002). In this sense, P application through drip irrigation can increase the movement of this nutrient in the soil profile, compared to the conventional application; moreover the use of phosphoric acid provides increased mobility of soil P when compared to superphosphate (Vivanco, 1996; Zanini et al., 2002). Anyway, phosphate rapidly reacts with Ca in basic soils and with Fe and Al in acid soils, being the distance travelled by applied P quite limited, even in sandy soils, as compared with the water (Ben Gal and Dudley, 2003). The low availability of P in the bulk soil limits hence plant uptake. In this sense, the efficiency of absorption of P can vary the order of 10%, for furrow irrigation system and up to 35% for irrigation (Papadopoulos, 2001), because about 80% of the P becomes immobile and unavailable for plant uptake due to adsorption, precipitation, or conversion to the organic form (Holford, 1997).

In Florida, citrus orchards traditionally receive about 40 kg phosphorus ha⁻¹ at planting, followed by applications of up to 100 Kg per ha and year until they enter the fruit-bearing years after the age of four. From then onwards, citrus receive 20-50 kg ha⁻¹ and year (Tucker et al., 1990). However, according to Obreza, (1990) there is a lack of fertilizer response in citrus trees newly planted in sandy soils. Similarly, adult citrus trees rarely respond to P fertilizer (Smith, 1966), except when planted on soils with extreme P fixation capacity. In this sense, Cantarella et al. (1992) and Quaggio et al. (1998) observed positive yield responses of Valencia oranges and lemons to annual P fertilizer rates up to 62 kg ha⁻¹ on a high P-fixing Brazilian soil. On the contrary, Alva et al. (2003) found negligible effects of fertilization source (granular, controlled release formulation or liquid) and rates on citrus trees P content grown in a sandy soil.

4.2. Potassium fertigation

Citrus trees remove large amounts of potassium (K) compared with other nutrients; moreover, K enhances fruit set and thus yield, as well as affects fresh fruit qualities. Potassium deficiency reduces fruit number and size, increases fruit creasing, plugging and drop, and decreases juice soluble solids, acid and vitamin C content. Potassium is present as component of rocks and soil (fixed position) or an exchangeable cation on all clay particles. Since the rate of K release from fixed position is slower than the rate of K demand by plants, additions of K in fertilizers are needed to normal plant development. This is especially important when drip irrigation is used, since the volume of soil occupied by the active root is small and not all the soil volume contributes K to the growing plant (Kafkafi and Tarchitzky, 2011). In soils containing appreciable amounts of organic matter or clay, mobility of K can be limited because the positive charge of K ion enables it to be held by the soils' negatively-charged cation exchange complex. However, in sandy soils, with very low concentrations of clay or organic matter, the ability to hold K against leaching can be almost non-existent (Obreza, 2003). According to this situation, and considering that citrus trees use large quantities of K, in a typical citrus fertilization program K is applied at relatively high rates. Potassium is applied at a K₂O rate equal to the N rate; however this rate is increased by 25% when leaf K is consistently below optimum and especially in calcareous soils (Obreza, 2003; Obreza and Morgan 2011). The efficiency of absorption of K can vary the order of 60% for furrow irrigation system and up to 90% for fertigation (Papadopoulos, 2001). The effect of K-doses on yield and fruit quality of the Nagpur mandarin was studied during 2009-2012 and results showed that the highest fruit yield (26.67 tonnes/ha) with 50 g K₂O/plant potassium sulphate (Table 3) followed by in K-fertigation with 40 g K₂O/plant dose (25.52 tonnes/ha) (Shirgure et al. 2012).

The research results showed the highest response of the fruit yield (31.13 t/ha) with treatment potash fertigation using mono potassium phosphate followed by in fertigation with potassium nitrate (29.4 t/ha) (Table 4). The total soluble solids was highest (10.49 OBrix) in K fertigation with mono potassium phosphate followed by fertigation with potassium sulphate (10.48 OBrix). Highest juice content (38.76 %) and low acidity (0.77 %) was found in K fertigation with mono potassium phosphate. The highest TSS to acidity ratio (sweetness indicator) was observed in Mono potassium Phosphate (13.6) followed by Potassium sulphate (13.1) (Shirgure and Srivastava, 2013).

Table 3

Effect of K-dose on yield and fruit quality of the Nagpur mandarin (Pooled: 2009-2012).

Treatments	No. of fruits	Yield t/ha	Average				
			wt. of fruit g	TSS OBrix	Juice %	Acidity %	TSS/acid Ratio
K1	489	21.39	155.85	9.60	37.88	1.13	9.5
K2	519	23.33	159.53	9.63	38.74	1.12	8.6
K3	567	25.52	163.30	9.61	37.15	0.96	10.0
K4	580	26.67	164.37	9.74	39.72	0.86	11.32
LSD (P = 0.05)	28	1.83	1.94	0.04	0.32	NS	----

K1 - Fertigation with 20 g K₂O/plant/month, K2- Fertigation with 30 g K₂O/plant/month.K3- Fertigation with 40 g K₂O/plant/month and K4- Fertigation with 50 g K₂O/plant/month.**Table 4**

Effect of different K sources on yield and fruit quality of Nagpur mandarin (Pooled : 2009-2012)

Treatment	No. of fruits	Yield t/ha	Average wt.		TSS OBrix	Juice %	Acidity %	TSS/acid ratio
			of fruit g					
F1	590	24.32	154.96		10.07	37.16	0.85	11.8
F2	668	29.40	155.28		10.44	38.05	0.84	12.4
F3	625	26.77	155.33		10.48	37.55	0.80	13.1
F4	697	31.13	156.24		10.49	38.76	0.77	13.6
LSD (P = 0.05)	31	1.72	0.03		2.81	0.52	NS	----

F1 -fertigation with potassium chloride, F2- fertigation with potassium nitrate.

F3- fertigation with sulphate of potash and F4- fertigation with mono potassium phosphate.

5. Future trends

Nowadays, techniques and managements of agricultural production are directed towards the need to conserve resources, energy and a commitment to the environment. In this sense, fertigation has raised as a valuable tool in recent years so that has spread around the world in all agricultural areas, field and horticultural crops. This has led to an increase in fertilizer and water use efficiency. In the future, fertigation should continue to replace traditional flood irrigation.

Citrus are mainly grown in arid and semiarid region; in these areas, like in many regions of the world, the lack of water or lack of good water is a growing concern for the development of relevant agriculture since water is the most limiting factor for crop production. Furthermore, climatic conditions are characterized by low rainfall (400-600 mm year⁻¹) and irregular spatial and temporal distribution. On the other hand, the world's population has undergone an exponential growth, which has led to soaring food demand and, therefore, high natural-resource exploitation. Therefore, future trends in fertigation should be addressed to use another source of irrigation water like recycled sewage or/and desalination water.

In this context, improved water use efficiency (WUE), using different strategies, is also a key concept to solve this water scarcity. So nowadays, efforts are being focussed on developing not only alternative irrigation methods but also new water management methods in order to reduce water dosages while maintaining maximum tree growth, without significantly affecting yield. In drip irrigation systems, subsurface drip irrigation (SDI), where is applied below the soil surface, using buried drip tapes, is being part of modern agriculture. Current commercial and grower interest levels indicate that future use of SDI systems will continue to increase.

Improvement of WUE can be also achieved by means of DI. In this sense, it is possible to increase efficiency under different irrigation management methods based on regulated deficit-irrigation (RDI) programmes. These RDI strategies are defined as a practise where the total water provided for the plant (irrigation plus effective rainfall) is below to the crop's water needs in order to reduce ET_c, and hence save water, while simultaneously minimizing or eliminating negative impacts of stress on fruit yield or quality. However, these principles of scheduling fertigation are still far from factual basis since they do not take into account the nature and properties of the rhizosphere soil. In this regard, use of available water content has shown a definite edge over the other methods of scheduling fertigation.

Lastly, nutrient use efficiency can be meliorated by using nitrification inhibitors or plant growth-promoting bio-effectors. Nitrification inhibitors restrict the microbial conversion of ammonium to nitrate that it is mobile in soils and therefore leached. Thus, nitrification inhibitors have potential to reduce nitrate leaching. Bio-effectors or bio-stimulant is a term that is used to describe microorganisms and active natural compounds involved in plant growth which, not being a plant nutrient or pesticide, but in some manner have a positive impact on plant health. The biostimulant may increase chlorophyll efficiency and production, enhance metabolism, increase antioxidants, enhance nutrient availability and increase the water holding capacity of the soil. In addition to all these, precise soil sampling, whether to take samples from below drippers or in between drippers or mixing soil samples from both the sites and finally, drawing a representative soil samples, find a greater intervention while evaluating nutrient-water interaction in citrus.

The efficiency of the fertigation, either macro-nutrients or micro-nutrients can be further improved in a rhizosphere zone pre-treated with microbial consortium so that the available pool of nutrients is elevated. The intervention of automated technologies using variable rate application with further enhance the fertilizer use efficiency. However, the biggest constraint still lies with regard to options about fertilizer sources. Although, use of soluble fertilizers have undoubtedly aided in improving the efficacy of the fertigation, but in the context of the cost of the production, a much needed customisation in total fertilizer requirement using the conventional fertilizers is the call of the day. In this regard, the concerted effort would lead to develop a complete rationale of fertilizer use in citrus.

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