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Microirrigation and fertigation in citrus (*Citrus* spp.): chronological advances

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Abstract

Citrus (*Citrus* spp.) belongs to an evergreen tree category, requires some kind of stress , either soil water deficit stress or low temperature stress for induction of flowering, depending upon agro-pedology of growing conditions. Soil physical properties participate to a greater extent in regulating the success of flowering , fruit setting intensity and yield, coupled with desirable quality traits compared to chemical properties with regard to fertilizers- and water-use-efficiency. Hence, water management via micro-irrigation and fertigation play a pivotal roles in production sustainability alongside orchard longevity. A number of studies have established varying savings (25-35%) on both fertilizers and irrigation water compared to overly tilted use of basin irrigation methods. Computation on stagewise nutrient and water application scheduling without compromising the recommended doses of fertilizers and irrigation has further aided in developing precision citriculture with reduced water footprints and improved water-and nutrient-use-efficiency. However, carbon footprint emphasizing soil-plant-environment inclusive studies in relation to coupling of irrigation and fertilization is still not a preferred research agenda , in addition to development of 4R (right amount of fertilizers at right growth stage in right form and right placement) 4W (right amount of water at right growth stage in right form and right placement, depending upon zone of feeder root concentration) strategy to economise both fertilizers and water use . Initial success on sensor-based sub-surface fertigation linking IOTs and machine learning, though has produced some encouraging results, but a long way in waiting before such developments are computerized at farm level from operation point of view.

Key words: Citrus, Irrigation, Fertilization, Water-use-efficiency, Nutrient-use efficiency, Fruit yield, Quality, Orchard longevity

Citrus (*Citrus* spp.) are cultivated between 40°N and 40°S, up to 1800 m altitude in the tropics and up to 750 m altitude in the subtropics. Citrus is the third largest grown fruit in India, originated in wet tropics in Southeast Asia, but large-scale commercial production is confined in the subtropics under irrigation (Srivastava *et al.*, 2000; Singh and Srivastava, 2004). The most commonly cultivated citrus species in India are : *Citrus reticulata* (mandarin), *C. sinensis* (sweet orange), *C. aurantifolia* (acid lime), *C. aurantium* (sour or Seville orange), *C. grandis* (pummelo, shaddock), *C. limon* (lemon), *C. medica* (citron), and *C. paradisi* (grapefruit). The optimum mean daily temperature for growth ranges between 23°C and 30°C, markedly reduced above 38°C and below 13°C. Active root growth occurs when soil temperatures are higher than 12 °C. Citrus is grown on soils that are sufficiently aerated and deep to allow tap roots to penetrate to the desired depths (1-2 m). Light to medium textured soils, free from stagnant water and sticky impervious layers are preferred (Srivastava and Singh, 2001a, 2008), avoiding the areas with high water table (Srivastava and Singh, 1997, 2002a) . Soil physical structure is of greater importance than the chemical properties, provided sufficient magnesium and minor elements such as zinc, copper and manganese are present in an available form, with soils with pH between 5.0 and 8.0 are preferred (Srivastava and Kohli, 1999 ; Srivastava and Singh, 2001b) .

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Water as a basic component of plant cell tissue controls the growth and development of citrus trees through the water absorbed from the soil. Nutrients present in the soil are dissolved in water, taken up by the tree, and supplied to all parts of plant through translocation (Srivastava and Singh, 2004) . Hence, an adequate water supply during the growth stage has a significant influence on plant development, fruit quality and yield. In most citrus-growing areas, rainfall is unevenly distributed at different parts of the year, with marked dry and wet seasons (Srivastava and Singh, 2002b). To stabilize fruit production and quality, it is necessary to supply adequate irrigation in the dry season, and proper drainage during the wet season (Srivastava and Singh, 1999) in order to accomplish the water-use-efficiency and water productivity linking quality production of citrus. Therefore, it is important to provide the right amount of water and fertilizers at different growth stages not only enhance the growth of citrus trees, but also to improve the yield and fruit quality (Shirgure *et al.*, 2002a , 2002b). Amid these developments, recent studies (Meshram *et al.*, 2025a;2025b) highlighted the application of sensors in monitoring the irrigation and role of sub-surface fertigation on Indian Vertisols. In this background information , we attempted to take stock of the developments that have taken place with regard to micro-irrigation and fertigation emphasizing citrus performance in both vegetative reproductive phases.

Vegetative Growth Citrus

Citrus species are small, evergreen shrubs or trees. In the subtropics, shoot growth occurs in a series of discrete flushes initiated by a rise air temperature (>12.5^{0}C) or, in the tropics, where the flushes are less discrete, by the availability of water (Davies and Albrigo, 1999). Seasonal variations in vegetative growth of Hamlin sweet orange in subtropical Brazil (22.5^{0}S) have been described by Ramos and Santos (2010), whilst the influence of water on growth and development of young trees is illustrated by experiments in Florida and Spain. Irrigation, at up to four-to-six day intervals in Hamlin sweet orange (*C. sinensis*) grafted on sour orange rootstock (*C. aurantium*) during first year after planting on a sandy soil, enhanced many components of vegetative growth, including leaf area, canopy volume and trunk cross-sectional area. (Marler and Davies, 1989). Similar results were obtained in Spain with eight-year-old Clementina de Nules mandarin trees (*C. Clementina* grafted on to Carrizo citrange rootstock) by Ginestar and Castel (1996). Withholding irrigation in the spring showed no effect on shoot extension in the first (spring) flush, but water stress in the summer (14 June to late-July /early-August) reduced shoot growth in second (summer) flush or even stopped in co-occurring. Water stress in the late-summer/early-autumn had a similar effect, but trees irrigated at this time, having previously been drought-affected, produced an abundant second (summer) flush composed mainly of flowers. The chronological studies are narrated as below :

- Shoot growth occurs in district flushed initiated by a rise in temperature (subtropics) or availability of water (tropics) (Jones *et al.*, 1985).
- Water stress can delay the initiation of the summer and autumn flushes. Shoot and root growth alternate (Jones *et al.*, 1985; Bevington and Castle, 1985; Syvertsen and Llyod, 1994). Although, citrus cultivars are evergreen, leaves are shed throughout the year and continual leaf replacement occurs as the trees grow. The age at which a leaf drops is variable, but is usually between nine and 24 months leaves of all sizes are shed generally in the months immediately following blossoming (Kriedemann and Barrs, 1981).
- Canopy development and stem growth are both restricted by water stress (Kriedemann and Barrs, 1981).
- Water stress during periods of vigorous vegetative growth should be avoided (Doorenbos and Kassam, 1979). There is evidence of a direct causal link between stimulation of ethylene production by water stress and citrus leaf abscission (Kriedemann and Barrs, 1981).
- There is a poor correlation between trunk size and canopy development . Sun-exposed leaves represent only about 20% of the total leaf area of an orange tree canopy.
- The internal canopy does not receive more than 10% of the total photosynthetic photon flux density received at the canopy surface. Citrus leaves can reach temperatures of around 42^{0}C in the summer (Ribeiro and Machado, 2007).
- Excess vegetative growth can reduce fruit yields (Srivastava *et al.*, 2000).

Flowering in Citrus

In Citrus. a stress period appears to be essential for flowering. The duration of the stress period determines the amount of flowers produced (Srivastava *et al.,* 2000) . The stress period, preferably of 1-2 months duration, can be induced either by low temperatures in winter (abut 10^{0}C) in the subtropics and in the tropics by a period of water deficit (monthly rainfall or irrigation 50 -60 mm). The flower-bud initiation occurs during this stress period when vegetative growth is minimum. Water deficits can have, however, some harmful effects for long-term crop production as compared to when dormancy is caused by a cold period. Once the stress period is ended, an adequate water supply is necessary because prolonged water deficits will not only delay flowering but also lead to over-production of flowers (Srivastava and Singh, 2008). This can result in lower yields during the next season and possibly in subsequent seasons to a biennial fruit-bearing cycle. For lemons, water deficits in summer are commonly used to start off-season flowering for year-round production. The flowering period is very sensitive to water deficits. Water deficits directly reduce fruit set; also during this period nutrition, especially nitrogen, is essential and adequate water is necessary to make the nutrients available to the crop. Moreover, water deficit during fruit setting reduces yield by causing a heavy June or December fruit drop (Srivastava *et al.*, 2003).

Iglesias *et al.* (2010) have recently published an overview on the physiology of flowering and fruiting in Citrus. According to this report, it takes two- to -five years from planning for a citrus tree to reach a stage when it can produce flowers. In subtropical areas, flowering takes place after a period of bud quiescence as a result of exposure to low temperature in winter. In the tropics and in areas with a dry season, rehydration after a period of water stress triggers the flowering process. The inflorescence may be leafless flower-bud only or leafy (vegetative and flower bud both present on the same shoot) the degree of fruit setting is dependent on the type of inflorescences formed. In general, leafless inflorescences emerge first and contain a bouquet of flowers with a low likelihood of setting fruit (Srivastava *et al.*, 2000). By contrast, flowers in leafy inflorescences are commonly associated with a better fruit setting (the fewer the number of flowers on a stem the higher the proportion that form fruits). In seeded cultivars, pollination (mainly by bees) and fertilization are necessary to initiate fruit development, but not in the seedless cultivars (mainly by bees), fertilization is necessary to initiate fruit development (Iglesias *et al.,* 2010). The practical aspects of evaluating the intensity of flowering in citrus has been studied by Ribeiro *et al.* (2008). Citrus trees bloom profusely (e.g. for sweet orange as many as 2,50, 000 flowers /tree can be formed). This number is considerably reduced by the abscission of flower buds , with some important studies as highlighted as below:

- Rest period is necessary for induction of flowering to take place, can be provided by low temperature in the subtropics or by drought in tropics. Too much stress can result in the production of too many flowers, may lead to biennial bearing (Doorenbos and Kassam, 1979 ; Srivastava *et al.*, 2000).
- Rain/irrigation after drought induces flowering, undesirable in midseason (Smajstrla, 1993). In some parts of the subtropics, the 'rest period' is induced by two successive months with mean air temperatures, presumably at 10^0C or less and in the tropics by water stress (monthly rainfall less than 50-60 mm).
- Allowing a water deficit to occur in the summer is commonly used to initiate flowering for year-round fruit production in lemons (Doorenbos and Kassam, 1979).
- Water stress during flowering increases shedding of flower buds and flowers before fruit is set. These effects are due to weakening of the (two) pre-formed abscission zones at the points of attachment (Jones *et al.*, 1985).
- Water stress during the fruit expansion phase affects final fruit size (but can increase the content of the total soluble solids (TSS) and acids) (Doorenbos and Kassam, 1979).

Crop Water Requirement

Citrus trees are evergreens and thus transpire throughout the year. Water requirement for high production vary with climate, ground cover, clean cultivation or no weed control, species and rootstock. The water requirements for grapefruit are somewhat higher than for the other citrus species, with total water requirements varying between 900 and 1200 mm per year (Srivastava and Singh, 2008). As a perennial crop the response of citrus to water supply at a particular period of development will depend greatly on the level of water supply prior to that period during the same growing season and also the level of water supply during previous growing seasons. New vegetative growth in any year is influenced by residual effects of growth in previous seasons. The vegetative growth of young trees determines their final tree size and future fruit-bearing capacity (Srivastava and Singh, 2001b). While, for mature trees, the growth vigour determines the replacement rate of fruit-bearing branches. Any effect of water deficit on root and leaf development may impair the number and size of fruits later in the season. Water deficits must be avoided when vegetative growth is most rapid. Prior to flowering and fruit setting, however, too vigorous, luxurious growth may impair production of high quality fruit (Shirgure *et al.*, 2003a, 2003b, 2004).

The water-balance method was used by Garcia Petillo and Castel (2007) in southern Uruguay (34^0 39'S 56^0 46' W; alt. 30 m), in a three-year-period, to measure the actual water use (ET) by mature orange trees (*C. sinensis* cv. Valencia) grafted on the trifoliate rootstock (*C. trifoliata*). In a carefully monitored trial, annual water used averaged 767 mm from drip-irrigated trees and 620 mm from rain-fed trees spaced 6 x 4 m with 416 trees ha^{-1} (crop cover increased from 30 to 50% during the course of the experiment). Seasonal potential evapo-transpiration rates (ETc) increased from 1.3 mm d^{-1} in the winter to 2.8 mm d^{-1} (spring) to 3.0 mm d^{-1} (summer) before declining to 1.0 mm d^{-1} in the autumn. These values are similar to those recorded in Florida, Valencia (Spain) and in less and areas of Israel, but less than those reported from Texas, Arizona, South Africa and Iran (Garcia Petillo and Castel, 2007), where reference-crop evapo-transpiration rates (ET_0) were estimated from a USWB Class A evaporation pan with an appropriate pan factor (Allen *et al.,*1998).

In southern Brazil, Marin and Angelocci (2011) monitored the water use of seven-year-old irrigated (with under-tree micro-sprinklers) acid lime trees (*C. latifolia,* grafted on to *C. limonia* rootstock) over a (dry) winter and a (wet) summer season. In dry year, including cold/frost protection) were within the SFWMD permitted levels (300-560 mm, which excluded irrigation for cold protection), and that the simulated estimates were generally less than the values for individual districts, which in turn were reasonable. Similarly, Wheaton *et al.* (2006) used a water- balance approach to simulate the effects of a selection of variables. In particular the 'allowable' depletion of available water at different growth stages, on the annual irrigation requirements of a Hamlin orange orchard (*C. sinensis* grafted on to *Carrizo citrange* rootstock) planted on a free draining sandy soil in Lake county, Florida (USA).

Table 1: Crop water requirements and Kc of Citrus cultivars. (ET_o is the reference crop evapotranspiration, ETc is the potential evapotranspiration from a citrus orchard and Kc is the crop coefficient (K_c=ET_c/ET_o). T is transpiration. '?' means value uncertain. (units in mm d^{-1})

Parameter	Spring	Summer	Autumn	Winter
Uruguay (orange)[a]				
ET_o	3.5	5.0	1.3	1.5
ET_c	2.8	3.0	1.0	1.3
K_c	0.80	0.60	0.77	0.87
Brazil (lime)[b]				
ET_o	-	4.5	-	2.5
ET_c		2.5		0.6
K_c	-	0.65?	-	0.24
Italy (clementine)[c]				
ET_c	-	6-8	-	
K_c	1.0-1.2	Up to 1.2	0.8	
Spain (clementine)[d]				
ET_c	2.1		2.6	
K_c	0.43		0.44	
T/ET_o	0.25		0.30	

Source : Marin and Angelocci (2011), Rana *et al.* (2005), Villalobos *et al.* (2009)

Quantifying water requirements of an orchard crop like citrus is not that easy to compare the results of measurements taken under different conditions and with different methods. However, it appears to be accepted that low stomatal/canopy conductance restricts water use of Citrus spp. compared with other crops. Recently reported research, summarized in Table 1 indicated that potential water use (ET) by mature orange trees in the subtropics ranges from 1.0 (autumn) to 3.0 mm d^{-1} (summer, maximum ET_c = 3.3 mm d^{-1}, which is equivalent to 80 litres/ tree/ day).

The corresponding K_c values are 0.77 (autumn) and 0.60 (summer). For seven-year-old lime trees in Brazil, ET_c (summer) = 2.5 mm d^{-1} (Kc = 0.65) and ET_c (winter) = 0.6 mm d^{-1} (Kc=0.24, a low value due to dry inter-row vegetation). In contrast, ET_c rates for clementine reached 6-8 mm d^{-1} in Italy with a correspondingly high crop coefficient (up to 1.2). In Spain, the equivalent kc values were much lower at c. 0.4. For comparison, Kridemann and Barrs (1981) had earlier cited values for (the equivalent ot) K_c=0.7 (summer) and 0.6 (autumn) in south Australia, as well as seasonal K_c mean values of 0.83 (in Arizona) and 0.68 (in Israel). Given the variability in some of the results reported, and until more is known about citrus water requirements, the approach proposed by Allen *et al.* (1998) seems reasonable.

Irrigation Scheduling in Citrus

Basically, citrus trees do not exhibit visible symptoms of water stress until most of the available soil moisture has been depleted. Consequently, extensive research in the citrus production areas has led to the recommendation that water be applied at one-third depletion during January through June and at two-thirds depletion over the remainder of the year. Irrigation scheduling requires great caution. Citrus trees demand good soil aeration and over-irrigation is highly detrimental, particularly to young trees. Too frequent and heavy irrigations may affect root development and yield and lead to leaching of nutrients. In recent years, a diversity of methods has been used to measure the actual water use of Citrus. These methods include the water-balance approach (with orange) in subtropical southern Uruguay, and the aerodynamic method in Brazil (lime), Italy (clementine) and Spain (clementine). The sap-flow technique has been used to estimate transpiration in Brazil and Italy. Evaporation modeling with multiple linear regression as well as artificial neural network was studied for citrus crops (Shirgure *et al.*, 2001a, 2001b, 2001c, 2001d).

Depletion of available soil moisture can be measured indirectly as a mathematical computation which correlates Class "A" pan evaporation data with evapotranspiration (ET_o). Given that citrus requires about 45 to 50 inches of water annually, evapo-transpiration models that are based on 60-80% of pan evaporation (the crop coefficient, as it is called) indicated a close correlation with total amount of water. However, classic work in citrus growing parts of the USA, predicted citrus water use with actual use as measured by neutron probe, revealed that the models were fairly accurate in spring and fall months, but overestimated the amounts needed in winter and underestimated the amounts needed in the summer. When these findings were applied to conditions in India, it was determined that the citrus coefficient should be adjusted for the winter and the summer periods. The irrigation scheduling and microirrigation systems were also studied in Nagpur mandarin (Shirgure *et al.,* 2004d, 2014; Shirgure and Srivastava, 2014a). The Kc values for different growth stages with no vegetative ground cover is further highlighted (Table 2).

As early as Hashemi and Gerber (1967) attempted correlation between actual evapo-transpiration and potential evapo-transpiration computed with Penman's model. Koo (1968) advised Florida citrus growers to maintain soil moisture at 55 to 65% of field capacity from bloom the young fruit exceeds 1 inch in diameter. Retiz (1968) estimated the water requirement of citrus at 40-45 inch/year. Richards and Warnke (1968) studied

Table 2: Stage- wise crop coefficients used for irrigation water management in Nagpur mandarin

	Stages of Development				
Crop characteristic	**Initial**	**Crop development**	**Mid-season**	**Late**	**Total**
Stage length, days	60	90	120	95	365
Depletion Coefficient, p	-	-	-	-	0.5
Root Depth, m	-	-	-	-	1.2
Crop Coefficient, Kc Citrus with ground cover					
70 % canopy	0.7	>>	0.65	0.70	-
50 % canopy	0.65	>>	0.60	0.65	-
20 % canopy	0.5	>>	0.45	0.55	-
Yield Response Factor, Ky	-	-	-	-	0.8-1.1

Source: Shirgure and Srivastava (2014b)

the irrigation systems to lemon and irrigation at 60 centibar(cb) and extrapolations to 150 cb resulted in no measured differential response in tree growth and fruit yield under coastal conditions. Leyden (1977) reported that 610 mm irrigation water applied via a drip system at 0, 200, 300 and 400 liters/tree gave the significant difference in total yield and fruit size distribution. Toledo (1980) showed that irrigation at 65% field capacity caused drought injury symptoms, excessive defoliation, less water consumption. Best results were obtained with irrigation at 85% filed capacity. Evapotranspiration ranged from 3.78 to 4.42 mm/day and 1.46 to 1.3 mm/day for 85% and 65% field capacity irrigation, respectively. Kelin (1983) compared drip irrigation scheduling according to soil water potential to class A pan evaporation in different horticultural crops using a crop factor and concluded that 12-23% water could be conserved by using the irrigation scheduling based on soil water potentials.

Moreshet *et al.* (1988) compared the 100% and 40% of soil volume irrigation in '*Shamouti*' orange and found that partially irrigated plot was 66% of the fully irrigated one. Transpiration from the trees of partially irrigated plots was 72% of that of the fully irrigated plot and evaporation from soil surface was 58%. Fruit TSS and acid contents were higher in partially irrigated plots. Smajstrala *et al.* (1986) found that greatest yield was obtained using spray-jet trickle irrigation. Yield increases were not linear with volume of root zone irrigated but ranged from 39% for the drip irrigation treatments which irrigated 5-10% of the area beneath the tree canopies to 64% for 2-spray jet per tree, which irrigated 50.7% of the areas beneath the tree canopies. Du Plessis (1985) obtained the highest yields (190 kg/tree) and the largest average fruit size with irrigation at a crop factor of 0.9 on a 3-day cycle, with thin consumption micro-irrigation gave better results than drip irrigation. Smajstrala *et al.* (1986) and Shirgure *et al.* (2001c, 2001d) concluded that the tree growth of young Valencia orange was greatest when irrigations were scheduled at 20 cb for no-grass and 40 cb for the grass treatments. Barbera and Carimin (1986) studied different levels of water stress on yield and quality of lemon tree and found that yield was lower in most stressed plot. The number of flowers/m^3 of canopy was higher in most stressed treatment, indicating a relationship between severity of stress and flowering response. The daily water requirement of bearing Nagpur mandarin and acid lime is further estimated (Table 3).

Du Plessis (1985) with a mature 'Valencia' orange trees and field experiment showed that water use pattern over the entire season reaching a maximum of 87 liters/day$^-$ in January, with 690 liters irrigation when tensiometer reaching fell to -50kpa gave the highest net income. Use

Table 3 : Daily water requirement of Nagpur mandarin acid lime (Liters /day/ tree)

Month	Young tree (20 % ground cover)		Middle grown tree (50 % ground cover)		Mature tree (70 % ground Cover)	
	Nagpur mandarin	**Acid lime**	**Nagpur mandarin**	**Acid lime**	**Nagpur mandarin**	**Acid lime**
January	14.96	10.96	44.22	40.22	71.44	67.44
February	20.15	16.15	59.40	53.40	96.18	91.18
March	26.17	21.17	78.48	74.48	126.50	122.50
April	29.16	25.16	87.48	83.48	142.88	138.88
May	33.98	30.98	101.94	97.94	165.91	155.91
June	21.73	20.73	66.42	57.42	109.89	92.89
July	18.27	14.27	55.80	51.80	92.38	88.38
August	13.95	11.95	42.45	38.45	70.25	64.25
September	14.96	10.96	45.63	41.63	75.49	69.49
October	16.87	12.87	51.56	48.56	91.90	71.90
November	14.97	11.97	44.88	40.88	73.80	68.80
December	11.25	8.25	34.88	29.88	56.97	52.97

Source: Shirgure *et al.* (2002b , 2003b , 2004a) of tensiometer rather than evaporation pan scheduling could save 2000 m^3 water/ha annually. Sanehez Blenco *et al.* (1989) compared five flood irrigation treatments with daily drip irrigation at 0.475 Epan and concluded that drip irrigation gave higher yields as compared to flood irrigated plants. Castel and Buj (1990) carried out trials on mature Satstuma average trees grafted on sour orange rootstocks. Plants were irrigated with 60% of the estimated ET losses from a class A-pan and 80% of the control throughout the year.

The preliminary studies on the effect of soil management system on soil moisture in Sweet orange orchard was initiated by Randhawa *et al.* (1960). He also emphasized on irrigation aspects in citriculture in India. Makhija *et al.* (1986) obtained water need for 6- year-old Kinnow mandarin varying from 539 to 1276 mm depending upon the level of irrigation with average consumptive use of water in 2 years as 61.5 cm. Mageed *et al.* (1988) carried the research on influence of irrigation and nitrogen on water use and growth of Kinnow mandarin receiving 4 levels of irrigation and three levels of nitrogen (0,115 or 230 kg N/tree). The consumptive use varied from 66.7 cm to132.5 cm. Ghadekar *et al.* (1989) estimated that the consumptive use of Nagpur mandarin by modified Penman equation using 40 years air temperature, Relative humidity, wind velocity and Solar relation data. Under clean cultivation the water requirement of young, middle age and mature trees was observed as 651.9, 849.0 and 997.3 mm/year, respectively. An equation for daily water use was proposed and it can be used for drip irrigation. Ray and Sharma (1990) studied the response of young Kinnow mandarin to irrigation. Irrigation was scheduled at -0.05, -0.1, -0.2, -0.4 and -0.8 MPa soil water potential 0.8 IW/CPE ratio and irrigation to replenish estimated crop ET. The highest bio-mass per plant was obtained when irrigation was scheduled at -0.05 MPa SWP and 18-19 irrigations were required.

Shirgure *et al.* (2000, 2004a, 2004b, 2004c) initiated the irrigation scheduling based on depletion of available water content and fraction of open pan evaporation in acid lime in pre-bearing stage. Studies were also done to see the effect of different soil moisture regimes with irrigation scheduling based on available soil moisture depletion and open pan evaporation on soil moisture distribution and evapotranspiration in acid lime. He concluded that evapotranspiration varied from 213.6 mm to 875.6 mm in various irrigation schedules. It was also found that the change in soil moisture distribution in the root zone of acid lime plants varied from 195.9 mm to 321.3 mm with different irrigation schedules (Shirgure and Srivastava , 2014a, 2014b , 2014c).

Irrigation Methods in Citrus

The common methods of applying water to orchards are basin, border strip, furrow, sprinkler and drip irrigation. Ring basin is generally followed in early establishment phase of fruit trees. Microirrigation to citrus is common in developed countries (Singh and Srivastava, 2004). Drip and microjet irrigation has advantage over surface irrigation methods, for more uniform and complete wetting of the soil surface and adoption on sloppy terrain. The most common surface irrigation methods are furrow irrigation (several furrows between the tree rows), check irrigation (basins containing one or more trees) or flood irrigation (where citrus trees are planted on beds or ridges). Because of uneven water distribution and difficulty of applying small amounts of water the importance of surface irrigation for citrus is decreasing. Sprinkler irrigation may provide a more uniform distribution of water and the possibility of applying exact depth of required water (Shirgure and Srivastava, 2014, 2015). With the drip or micro-jet systems, water savings may be obtained because water is applied only to root zone, leaving the remaining part of soil dry. Sprinkler irrigation is also frequently used for frost protection.

Faton (1970) observed better tree growth and yield, less weed growth, evaporation and leaching with 16 gallons water applied through drip to each 4-years old lime trees at two weeks interval compared to 320gallon water in flood irrigation. Fritz (1970) observed that all applied water is transferred directly to root zone of plants and 20-50 % water saving is reported depending on soil and climate. Raciti and Sckderi (1977) compared drip irrigation with basin and found that the fruits under drip system ware more acidic with lower maturity ratio. Ronday *et al.* (1977) observed better tree growth and less water consumption in 'Valencia' orange under drip irrigation in sandy soil. Sucderi and Raciti (1978) compared basin irrigation with different combination of drip irrigation and measured number, weight, quality of fruits in Valencia orange. Slack *et al.* (1978) demonstrated that trickle irrigation on young orange trees used 5,400 liters of water compared to 23,400 liters of water per tree for dragline.

Microirrigation Systems

With proper design and operation, drip systems provide adequate soil moisture for optimal growth and production while using only about 12-15 inches of water/ acre/ year. Such savings result from better water use efficiency, negligible evaporation and deep percolation losses, and water is applied to only a limited soil surface area, under which the absorptive root system of the tree is concentrated (Shirgure *et al.,* 2001c, 2001d). However, one drawback to drip irrigation in India with regard to citrus is that in years of adequate rainfall, the roots grow far beyond the drip-irrigated zone of soil. However, such roots necessarily die during subsequent extended dry spells such as have occurred several times over the last few years. The other drawback is that drip systems provide no cold protection for the orchard. Some growers operate the system too long thereby water logging the wetted zone where the roots are concentrated and pushing water too deeply into the soil profile. Regardless of the type of irrigation system and other production inputs, final productivity, fruit size and fruit quality can only be as good as the management of supplemental irrigation in the citrus orchard. The automatic drip irrigation scheduling using hybrid station controller is studied in Nagpur mandarin (Shirgure and Srivastava, 2014, 2015). Raciti and Barbargallo (1982) reported that the yields of lemon was more with localized irrigation amounting to 227.23 q/ha and 213.2 q/ha for basin irrigation. Ozsan *et al.* (1983) compared furrow, under tree, over tree and drip irrigation in lemons. amounts of water applied were greatest (1286 mm) with under-tree method and least (207 mm) with drip irrigation system. Yield was more with over tree sprinkling and least with furrow.

Water-use-efficiency was high in drip irrigation. Cevik and Yazar (1985;1987) demonstrated that a new irrigation system, i.e. Bubbler irrigation for the orchards. He observed that under tree sprinkling and drip irrigation had the best pomological effects. Amounts of water applied per tree for over sprinkling, under sprinkling and drip irrigation were observed as 22.01, 17.04 and 10.33 m^3/season, respectively . Capra and Nicosia (1987) studied flooding, sprinkler, and sub-irrigation with sprays and concluded that the rates of water application affects the rate of growth of fruit diameter. Robinson and Alberts (1983) compared under canopy sprinkler and drip irrigation systems in crop like banana and found that the drip irrigation is superior to under canopy sprinklers. Increased tree growth and yield were recorded in young Valencia orange under drip irrigation method with emitter placed at distance of 1 meter from the trunk (Azzena, *et al.,* 1988). Greive (1988) concluded that under tree micro-sprinklers increased yield by 12% and reduced water application by 9.3% compared to conventional full ground cover. Intrigliolo and Raciti (1989) demonstrated that water saving with sub-surface irrigation was 32% over the traditional basin irrigation. The yield was higher but fruit quality was not much different. Marler and Davies (1989;1990) studied the effect of micro-sprinkler irrigation scheduling on growth of young 'Hamlin' orange trees and found that growth was not affected by pattern of irrigation, suggesting that 90% emitters are enough for root system. Zekri and Parsons (1989) studied drip, micro-sprinkler and overhead sprinkler irrigation at two water application rate and found that fruit size and tree canopy area were 9 -20% greater in the overhead sprinkler treatments.

Citrus orchards can be irrigated in many different ways. For example, In Florida, solid-set sprinkler systems, rainguns, flood and subsurface methods have all been used. Specific types of micro- irrigation systems include drip (trickle) and micro- sprinklers (under- tree) these systems allow small quantities of water to be applied at frequent intervals, usually to only part of the root zone. In Swaziland, largely because of the opportunities it offers for labor saving, water saving and power saving, micro- irrigation (particularly drip) has replaced under-tree drag- line sprinkler systems (Pyle, 1985). In areas prone to frosts (e.g. Florida), micro- sprinklers can also provide some protection against frost damage to young trees (Rieger *et al.,* 1986). of nutrients in soluble form, together with water, directly into the root zone. Good irrigation management is necessary to minimise leaching of nutrients. Shirgure *et al.* (2001d) initiated the research work on evaluation of microirrigation systems in acid lime and a comparison was done with that of basin (ring) method of irrigation. Shirgure *et al.* (2003a) studied the effect of dripper 8 Lph, micro-jet 300^0, micro-jet 180^0 and basin irrigation method on water use and growth of acid lime and found that micro-jet 300^0 recorded higher growth than rest of the systems. The studies on the efficacy of these micro-irrigation systems and basin irrigation on fruit quality and soil fertility changes in bearing acid lime revealed that the micro-irrigation systems and that too micro-jets are best suited for the sustainable production of good quality acid lime (Shirgure *et al.,* 2002b, 2003a, 2003b).

An advanced form of this method of irrigation was developed in Spain and has since been commercialized in several countries, including Australia, South Africa and the USA. Known as open hydroponics, citrus trees are planted at a high density (> 750 trees/ ha) and irrigated (with drip) by short- duration, low- volume pulses throughout daylight hours with fertilizer injected into the water (expect on rainy days). In this way, water and nutrients are readily available within the wetted soil volume, where a mat of roots develop (Falivene, 2005). After two years' commercial experience in Florida with what is called the advanced citrus production system, the observed benefits included early production of high-quality fruit (at 24 months) with the opportunity to achieve potential yields when the trees mature. As there is a limited reserve of available water in the (restricted) root zone, especially in sandy soils, the system is vulnerable to breakdowns.

Good management is essential. Looking to the future, there are opportunities to extend the system to very high -density citrus production under cover. Microjet or micro-sprinkler irrigation systems utilize only one emitter per tree, usually situated on a riser or stake to hold the emitter upright in place. Emitters are available with outputs of 16 -100 liters or more per hour. Most will wet an area up to 7-8 feet from the emitter, thereby producing a wetted surface area equal to or slightly greater than the canopy area of a mature tree (Shirgure *et al.,* 2000 , 2001c , 2004c).

Fertigation in Citrus

Fertigation, the application of soluble fertilizers through micro-irrigation systems, has been used in citrus production since the 1960s. Originally, fertigation was used in arid regions to improve solubility of fertilizers in the root zone and increase uptake efficiently by fruit trees. Without rainfall or irrigation, dry fertilizers often remained on the soil surface and nutrients were lost due to leaching or volatilization. Currently fertigation is being used in many citrus growing regions including Israel, the Mediterranean region, South Africa, and the United States. Nevertheless, many regions in our country still use dry fertilizers due to tradition, lack of fertigation equipment, technique, uneven topography or poor quality irrigation water (Panigrahi and Srivastava , 2017). In humid regions with high rainfall, roots are more widely distributed over the orchard floor and the root concentrating effect of fertigation is less pronounced (Shirgure *et al.,* 2004d,; 2014). Fertigation systems are easily automated and provide an effective delivery system for water and fertilizer. Once the tanks, injectors and back flow valves have been purchased and the irrigation is in place, many citrus trees can be fertigated at the touch of a switch. A wide range of application frequencies are available, ranging from daily to monthly, and can be adjusted easily without additional costs for fertilizer spreaders or labor. A properly maintained and managed fertigation system in addition is an effective means of irrigating. Thus, citrus tree water relations are also often improved when using fertigation.

Fertigation response in citrus

The influence of fertigation on growth, yields and fruit quality of citrus trees has been studied for more than 30 years, with differing, sometimes contradictory findings. Results differ based on climate, soil type, root distribution and possibly tree age. Fertigation is an effective method of fertilizing in arid climates such as Israel (Dasberg *et al.*, 1983; Jeyabaskaran *et al.*, 2021). Fertilizer levels in soil are maintained at constant levels of 35-60 mg/kg throughout the irrigation period. Studies suggest that optimum nitrogen rate for mature Shamouti orange trees is about 170 kg ha^{-1}year^{-1}. Higher nitrogen (N) rates increased yields but decreased external fruit quality by delaying peel colour development and increasing peel thickness. However, juice quality, specifically total soluble solids, was not affected by nitrogen rate. The reduction in fresh fruit quality and increased costs for the additional nitrogen were probably not economically warranted. Similarly, research from Spain with navel oranges showed that daily fertigation significantly increased yields over application of dry fertilizer twice/year (Legaz *et al.*, 1981). Optimum nitrogen rate was 0.75 kg tree^{-1}yr^{-1}.

High N rates increased fruit weight and number but also increased peel thickness and decreased juice content. In this instance, fertilizer was applied using 8 dripperstree^{-1} to insured adequate root zone coverage that is an important factor in any fertigation program. Fertigation does not always increase tree growth and yields over application of dry materials. Therefore, general recommendations concerning its effects cannot be made. Studies from South Africa found no difference in growth of young Valencia orange trees during the first 4 years after planting when using fertigation (6 times year^{-1}) vs. dry application (4 times per year) at the same nitrogen rates (Bester *et al.*, 1977). Fertigation effects on tree performance are even less pronounced in humid subtropical areas such as Florida and Texas. In contrast to Spanish and Israeli findings, growth of 1-2 year-old 'Hamlin' orange trees was similar for fertigated and dry applications over a range of nitrogen rates (Willis *et al.*,1990).

The research related to injection of fertilizers through the drip irrigation systems was started by Smith *et al.* (1979). Koo (1981) appraised the potential advantage of micro-irrigation systems and its usefulness to fertigation. Bielorai *et al.* (1984) advocated use of fertigation technology in citrus as it resulted in higher production of good quality Shamouti oranges, comparing N fertigation at 100, 170 and 310 kg/ha with broadcast application at 170 kg/ha through irrigation system. Average yields for 4-years were recorded as 62, 73 and 82 tons/ha with 100, 170 and 310 kg N/ha, through fertigation. Koo and Smajstrala (1984) supplied 15% and 30% of crop N and K requirements through fertigation and rest through conventional method to Valencia orange. Partial fertigation of N and K resulted in lower N contents of leaves. TSS and acid concentration in juice was also reduced but yield was not affected. Haynes (1985) discussed the principles of fertilizer use for trickle irrigated crops. Haynes (1986) also studied the comparison of fertigation with broadcast applications of urea on levels of available soil nutrients and on growth and yield of trickle irrigated peppers. He found that growth and yields were greatest at the low rate of N applied as fertigation or as a combination of broadcast plus fertigation.

Fouche and Bester (1990) tried various fertilizer combinations through fertigation on 13-year-old Navel oranges. Fertigation was given with a soluble fertilizer 'Triosol' (3:1:5) + 350 gm urea by broadcast, fertigation of N and K with broadcast of single super phosphate and NPK through broadcast. Highest yields was obtained with fertigation of NPK through Triosol or by complete broadcasting of NPK fertilizers. No significant differences were observed as fruit size, acidity, percent juice content and TSS among treatments. Beridze (1987) conducted a rial on 5- year- old lemon tree and fertilized 150 kg N + 120 Kg P_2O_5 + 90 Kg K_2O/ha as basal dressing. The highest yield of 6.6 ton/ha was obtained from trees fertilized with basal dressing + 250 Kg peat/tree as a mulch + FYM at 25 tons/ha. Ferguson *et al.* (1990) studied the fertigation as growth of 'Sunburst' tangerine trees. Two years old *C. reticulata x C. paradisi* cv. Sunburst was fertilized with 0.66 or 1.32 lb N/tree during 1988-89 and it was 0.52 or 1.05 lb N/tree during 1990. Leaf analysis showed that low to deficient concentrations of N, K, Mn and Zn with both N treatments. Zekri and Koo (1994) tried micronutrients through fertigation with different sources of various rates. Inorganic forms (NO_3 and SO_4) were ineffective in evaluating micro element levels in oranges. But, chelated sources of Fe, Mn, Zn and Cu were very effective and their rates of application were comparable with rates through foliar applications.

Neilsen *et al.* (1993) studied that fertigation with calcium ammonium nitrate showed increased vigour and leaf Ca concentration but decreased leaf Mg and Mn compared to trees fertigated with urea or ammonium nitrate (NH_4NO_3) in apple trees. Fertigation with P increased early tree vigour, leaf and fruit P concentration and decreased leaf Mn. Syvertsen and Smith (1996) studied the nitrogen uptake efficiency and leaching losses from Lysimeter grown trees fertilized at three nitrogen rates. He concluded that Average N uptake efficiency decreased with increased N application rates, overall canopy volume and leaf N concentration increased with N rate, but there was no effect of N rate on fibrous root dry weight.

Irrigation at 20 % depletion of available water content and fertilizer treatment of 500 g N + 140 g P_2O_5 + 70 g K_2O/tree individually were observed to be optimum irrigation and fertilizer requirement, respectively. Combined application of these two treatments produced significantly higher magnitude of fruit yield m^{-3} of canopy in addition to higher N, P and K status, and other fruit quality indices (Shirgure *et al.* 2004d; Srivastava *et al.,* 2003). The fruit yield (26.1 kg/tree), fruit weight (135.1 g), total soluble solids in fruits and juice percentage (47.32%) were higher with irrigation scheduled at 20 % and 500N-140P_20_5-70K_2O gplant^{-1} fertigation (Shirgure *et al.,* 2001c). The incremental height (0.40 - 0.60 m), stock girth (4.07 - 4.26 cm) and canopy volume (6.93 m^3) of bearing acid lime was more in irrigation scheduled at 30% depletion of available water content with 500:140:70 fertigation. The combined effect of irrigation at 30 % depletion of available water content and fertigation with 500N:140 P_20_5:70 K_2Og/ tree gave better growth and yield of acid lime. The juice percent and acidity with irrigation scheduled at 30 % depletion of available water content and 500:140:70 fertigation was more (42.5% and 7.0%) as compared to other treatments (Shirgure *et al.*, 2004c, 2004d), with developed fertigation schedule for Nagpur mandarin further highlighted (Table 4). The highest TSS/acidity ratio was observed with K fertigation with 40 g K_2O/plant at 30-days interval (10.0).

Table 4: Fertigation schedule for Nagpur mandarin crop (Spring bloom) grown on deep black soils of central India

Month	N g/plant	P_2O_5 g/plant	K_2O g/plant	$ZnSO_4$ g/plant	$FeSO_4$ g/plant	$MnSO_4$ g/plant	Borax g/plant
October	60	-	-	-	-	-	-
November	60	-	-	-	-	-	-
December	Stress period						
January	60	30	15	50	50	50	25
February	60	30	15	50	50	50	25
March	60	30	15	50	50	50	25
April	60	30	15	50	50	50	25
May	60	30	15	-	-	-	-
June	60	30	15	-	-	-	-
Jul-Sept	-	-	-	-	-	-	-
Total	480	180	90	200	200	200	100

* Fertigation dose for bearing Nagpur mandarin is 480N:180P_2O_5:90K_2O g/tree/year
* Urea phosphate (18:44:0), urea (46:0:0) and potassium nitrate (13:0:46) were used to meet nutrient requirement
*No fertigation schedule adopted in July-Sept due to rains.
Source : Shirgure *et al.* (2014a)

Fertigation with 40 g K_2O/plant at 30-days interval using sulphate of potash fertilizer through micro-irrigation proved to be very effective for better fruit yield and quality of Nagpur mandarin (Shirgure and Srivastava, 2013b). Therefore, use of micro-irrigation and K- fertigation technique will be a sustainable solution for increasing the productivity as well as fruit quality of Nagpur mandarin orchards (Shirgure and Srivastava, 2013a , 2013b).

CONCLUSION AND FUTURE STRATEGIES

Citrus is hence perceived as highly water-responsive fruit tree crop. Despite many breakthroughs in microirrigation and fertigation , their adaptability in citrus orchards, especially under changing climate (Barlas and Srivastava, 2026; Srivastava *et al.*, 2026) is still below the satisfaction, thereby jeopardizing the progress gained in these accomplishments. No doubt , the area under microirrigation is consistently on rise, especially under fruit trees with citrus no exception. By a simple guesstimate, quality yield has been observed to improve by 25-30% with saving on chemical fertilizers by 30-35% over conventionally used basin irrigation coupled with basal method of fertilizer application. The future strategies need to be addressed in terms of : i.development of sub-surface micro-irrigation systems for better water use in citrus along with macro and micro-nutrient fertigation in citrus cultivars; ii.automation for the micro-irrigation system as well as fertigation system in citrus; iii.irrigation scheduling with infrared thermometry and crop water stress index; iv. citriculture under regulated deficit irrigation and pulse irrigation systems as well as partial root wetting concepts under high-density planting; v. artificial intelligence and machine learning-based irrigation management and requirement of nutrient types as per crop phenology as a part of fertigation .

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