Journal of Integrative Agriculture 2017, 16(5): 1184–1194

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RESEARCH ARTICLE

Water and nutrient management effects on water use and yield of drip irrigated citrus in vertisol under a sub-humid region

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Abstract

Scarcity of water and nutrients in orchards are the major causes of low productivity and decline of citrus in tropics. With a hypothesis that the optimal amount of water and nutrients application through drip irrigation (DI) could save substantial irrigation and fertilizers comparative to that under traditional basin irrigation (BI) with band placement of fertilizer (BPF), this study was conducted in citrus in vertisol of central India. Three DI regimes: I_1, I_2 and I_3 scheduled at 50% class-A pan evaporation rate (E_p), 75% E_p, and 100% E_p along with three fertilizer doses: F_1, F_2 and F_3 at 50% recommended dose of fertilizer (RDF, N:P_2O_5:K_2O=600 g:200 g:100 g), 75% of RDF and 100% of RDF were applied to mandarin plants respectively. BI with band placement of fertilizer (BPF) at 100% RDF was taken for comparison. All the drip-fertigation treatments (except I_1F_1) produced higher plant growth and fruit yield, with better quality fruits compared with BI+BPF. The highest fruit yield (16.39 t ha^{-1}), water use efficiency (3.9 kg m^{-3}) and fertilizer use efficiency (87.3 kg kg^{-1}) were observed in I_2F_2. The concentrations of N, K and Fe in leaves were significantly higher in I_2F_2 compared to other treatments. The leaf photosynthesis, stomatal conductance (G_s) and transpiration were the highest in I_3F_3. However, leaf water use efficiency (LWUE, photosynthesis/transpiration) was the highest in I_2F_2. The overall results of this study demonstrated that the application of optimum quantity of water and fertilizers (I_2F_2) through DI could be a productive and water efficient option in citrus production in vertisol.

Keywords: drip irrigation, fertigation, citrus, fruit yield, fruit quality, economics of production

1. Introduction

Availability of water is one of the major constraints in crop production. Due to higher water demand for drinking and industrial uses, the share of agriculture in available water is going to be reduced. The higher crop production to feed the increased population with reduced water availability becomes a challenge to researchers and managers of water sectors in crop production. One of the options to produce more crops with drop of water is judicious utilization of available water with efficient irrigation system like drip irrigation (DI) and optimum irrigation scheduling (Ghosh 2007). Moreover, the application of fertilizers through DI, called fertigation may enhance fertilizer use efficiency (FUE) in crops.

Citrus is the widely cultivated fruit crop in world (CCRI 2015). Globally, the crop is grown in 146 countries which is the highest in number as per as any fruit crop is grown. As a perennial evergreen tree, citrus requires water and nutrients throughout the year for higher orchard efficiency

Received 27 August, 2016 Accepted 21 October, 2016
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doi: 10.1016/S2095-3119(16)61500-9

(Davies and Albrigo 1994). The shortage of water and nutrients in any stage of the crop reduces the yield and quality of the fruits drastically. In other hand, water scarcity is a major problem in most of the citrus grown regions of the world. The use of water and fertilizers under traditional surface irrigation (flooding, basin and furrow irrigation) is a common practice in citrus (Singh and Srivastava 2004). Low water use efficiency (WUE) and FUE are the two major drawbacks of surface irrigation methods (Phene 1995). Moreover, the substantial loss of nutrients from plant root zone through deep percolation and surface runoff under traditional methods of irrigation and fertilization causes the pollution of water in surface and ground water sources of the region, which is a threat to human life (Hanson *et al.* 2006). The use of water and nutrients through DI in concurrence with plant demand therefore, could be one of the potential options for sustainable citrus production. However, due to higher investment for cost of DI and fertigation system, the financial analysis of crop production under drip-fertigation is utmost essential.

In recent past, the impact of drip-fertigation had been studied in different citrus cultivars under various agro-climates of the world. Holzapfel *et al.* (2001) investigated the effects of water and fertilizer application through DI in Thompson Navel orange in a sandy soil and concluded that drip-fertigation increased yield and quality of fruits compared to conventional irrigation and fertilizer application in the crop. Duenhas *et al.* (2005) reported that the fertigation with reduced fertilizer rates did not result in loss of productivity and fruit quality compared with that in conventional fertilization in sandy soil in Valencia orange. Moreover, they observed that fertilizer application methods had no effect on the nutritional status of the citrus tree. Quiñones *et al.* (2005) studied the Navelina orange plants' responses to N application (two and five times equally split applications) under flood irrigation and drip-fertigation (66 times equally to number of irrigation) when they grafted on Carrizo citrange in sandy soil. They did not observe any significant differences in fruit yield and fruit quality (except colour index) under the treatments; however both WUE and nitrogen use efficiency (NUE) were higher under drip-fertigation. Wassel *et al.* (2007) reported that among the irrigation (16, 20, 24, and 30 m^3 $tree^{-1}$ yr^{-1}) and N fertigation (400, 600, 800 and 1 000 g N $tree^{-1}$ yr^{-1}), irrigation at 24 m^3 $tree^{-1}$ with 800 g N $tree^{-1}$ yr^{-1} was recommended for optimum yield in Balady mandarin trees in sandy soil in Egypt. Martínez-Alcántara *et al.* (2012) compared the effects of split N application with DI (DI-F) with a single broadcast application with flood irrigation (FI-B) and concluded that irrigation-fertilizer management practices had no effect on either total tree biomass or in fruit yield; however, NUE was higher with lower nitrate leaching under DI-F compared to FI-B in citrus trees. Kumar *et al.* (2013) evaluated the response of sweet orange *cv*. Mosambi to different volumes of water applied under surface irrigation (V) *viz*., 60, 80 and 100% V along with different quantities of fertilizer *viz.,* 75, 100 and 125% of recommended dose of fertilizer (RDF, N:P_2O_5:K_2O=600 g :200 g:100 g) in an arid environment in sandy soil and concluded that irrigation at 80 with 100% RDF produced the highest fruit yield with better quality of fruits. Barua and Hazarika (2014) reported that DI at 100% of crop water requirement with 120% RDF under black plastic mulch resulted 22% higher fruit yield compared with that under soil application of fertilizers with RDF in Assam lemon in sandy loam soil under a humid climate. Qin *et al.* (2016a) reported that deficit irrigation (80% of water demand) and N input (low N demand, 200 kg ha^{-1}) through simulation-modelling significantly reduced N losses without yield reduction in drip-irrigated Clementine mandarin in loamy soil under Mediterranean climate. Moreover, Qin *et al.* (2016b) estimated that reducing over-optimal irrigation to optimal irrigation may increase citrus yield by 20%, WUE by 30% and NUE by 15%. Similarly, reducing over-optimal N fertilization to optimal N fertilization might increase yield by 10%, WUE by 15% and NUE by 40%. Overall, the response of any crop to irrigation and fertilizer application differs with locations, soil types, and agricultural practices (Yavuz *et al.* 2016).

Nagpur mandarin (*Citrus reticulate* Blanco) is commercially grown in around 0.2 million ha of Central India (Singh and Srivastava 2004). The soil of the citrus orchards of central India is mostly dominated by vertisol with 45–60% clay content. The productivity of the crop (9.2 t ha^{-1}) is too low as compared to productivity of mandarin varieties (25–30 t ha^{-1}) in other countries like USA, Spain, Brazil and China (NHB 2014). One of the major causes of low productivity of Nagpur mandarin is shortage of irrigation water in critical growth stages of the crop (Huchche *et al.* 1999). Ground water is the sole source of irrigation for the crop. Basin irrigation (BI) and furrow irrigation along with traditional broadcasting or band placement of fertilizer (BPF) in tree basins are widely practiced in Nagpur mandarin cultivation in the region. For the last few years, the water level in bore wells and dug wells is declined alarmingly creating water shortage in summer for sustaining the crop. So every year thousands ha of citrus orchard is permanently wilted due to shortage of water, which is a great economical loss for the orchard growers of this region. On the other hand, the loss of fertilizers through surface runoff and leaching causes the sub-optimum availability of nutrients to citrus plants under traditional fertilizer application with surface irrigation (Huchche *et al.* 1999; Panigrahi *et al.* 2009). Hence, optimum water application under efficient irrigation method with precise application of fertilizer is quite necessary for profitable and sustainable citriculture in central India.

In recent years, DI is gradually gaining popularity among the citrus growers (Singh and Srivastava 2004). The growers are more interested in application of fertilizers through drip system, as it saves a bulk number of manpower over traditional fertilization methods. However, the information regarding optimal irrigation and fertilizer application through drip, and the performance of drip-fertigation compared to conventional irrigation and fertilizer application in citrus cultivation in clay soil (Vertisol) is limited world-wide. Keeping this in view, a study was undertaken to compare the performance of water and fertilizer application through DI with that under BI with BPF in Nagpur mandarin in a Vertisol.

2. Materials and methods

2.1. Experimental site

The field experiment was conducted at experimental farm of National Research Centre for Citrus, Nagpur, India (21° 08´45´´N, 79°2´15´´E and 340 m above mean sea level) during 2007–2009 with 12-year-old Nagpur mandarin (*Citrus reticulata* Blanco) plants budded on rough lemon (*Citrus Jambhiri* Lush) root stock with spacing of 6 m×6 m. The citrus orchard (1.73 ha) having 480 trees was taken for the study. The orchard was divided into 30 treatment plots (576 m^2 area) with each having 16 trees in four rows (24 m×24 m). Four trees located centrally in each plot were considered as experimental trees. All the observations of the study were recorded with these experimental trees. Each treatment was replicated thrice in the experiment. The effective soil depth of experimental site is 62 cm, underlain by stony and gravel layer. The details of the physico-chemical parameters of experimental soil are presented in Table 1. The mean available N, P, K, Fe, Mn, Cu, and Zn in the upper 30 cm of soil were of 115, 10.0, 144, 18.2, 9.4, 1.1 and 0.72 mg kg^{-1}, respectively. The average daily Class-A E_p rate varied from 2 mm in December to as high as 12 mm in May at the experimental site. Out of 810 mm annual average rainfall, 10–15 mm rain was recorded in irrigation season (November–June) at the study site. The water level in the well near to the experimental site was around 15 m deep from ground surface.

2.2. Experimental treatment

The treatments imposed to irrigate the plants were DI at 50% of daily E_p (I_1), 75% E_p (I_2) and 100% E_p (I_3), and BI at 50% depletion of available soil water content at 0-0.30 m soil profile. Under DI, water was applied using 4 pressure compensated on-line emitters (each 8 L h^{-1} capacity) per plant, whereas in BI, water was applied to each plant through a circular basin of radius 1.2 m. Irrigation was applied during flowering (mid-November) to fruit enlargement stage (June) along with the monthly fertilizer doses. As the soil of tree basins was almost at field capacity/saturation, water supply was withheld during rainy seasons (July–October). Irrigation quantity for different DI treatments was calculated using the formula (Germanà *et al.* 1992):

$$V=S'\times K_p'\times K_c'\times(E-ER)/r$$

Where, V is the irrigation volume (L $tree^{-1}$ d^{-1}), S is the tree canopy area (m^2), K_p is the pan factor (0.7) as suggested by Shirgure *et al.* (2004) , K_c is the crop factor (0.6) as suggested by Allen *et al.* (1998), E is the daily class-A E_p rate (mm), ER is the effective rainfall (mm), and r is the water application efficiency of irrigation system (~90%). Under basin irrigation, water was supplied through flexible hosepipe, when the soil water at 30 cm depth attains 50% of available soil water (23.9%, v/v). Water quantity applied in BI method was computed using the equation:

$$V=(F.C-R.S.M)\times d\times A$$

Where, V, volume of irrigation water (m^3); $F.C$, field capacity (v/v, %); $R.S.M$, required soil water level »23.9% (v/v); d, depth of effective root zone (0.30 m); A, mean canopy area of the plants. No runoff during irrigation periods was observed in the orchard, assuming effective rainfall »rainfall.

The fertilizers applied under each DI treatment were at 50% of RDF (F_1), 75% RDF (F_2), and 100% RDF (F_3), where RDF was taken as N:P_2O_5:K_2O=600 g:200 g:100 g annually, as suggested by Srivastava and Singh (1997). Water soluble form of urea phosphate (N:P:K=18:44:0) and murate of potash (N:P:K=0:0:60) were used for supplying

Table 1 Physico-chemical properties of soil at the experimental site

Soil depth (cm)	Particle size distribution				Soil moisture characteristics[1]		BD (g cm^{-3})[2]	pH	EC (dS m^{-1})[3]
	Sand (%)	Silt (%)	Clay (%)	Texture class	FC (%)	PWP (%)			
0–15	32.3±0.6 a	24.7±0.4 b	43.0±0.7 b	Clay	36.8±1.2 b	23.8±1.2 a	1.28±0.2 a	7.8±0.3 b	0.84±0.08 c
15–30	31.0±0.4 a	22.5±0.4 a	46.5±0.8 c	Clay	38.7±1.4 c	25.9±1.1 b	1.27±0.3 b	7.5±0.2 a	0.72±0.04 b
30–45	34.7±0.3 b	23.4±0.3 a	41.9±0.6 a	Clay	35.7±1.5 a	23.2±0.8 a	1.29±0.3 c	7.3±0.1 a	0.64±0.04 a
45–60	32.0±0.2 a	25.4±0.2 c	42.6±0.4 a	Clay	36.7±1.3 b	23.6±0.7 a	1.28±0.4 a	7.4±0.3 a	0.66±0.02 a

[1] FC, field capacity; PWP, permanent wilting point.
[2] BD, bulk density.
[3] EC, electrical conductivity.
Data are means±standard deviation. Data within a column followed by same letters do not differ significantly at $P<0.05$.

required quantity of P and K, respectively. Some quantity of N was also supplied through urea phosphate and the rest amount was supplied through urea (N:P:K=46:0:0). Monthly fertigation was done using fertilizer injection pump during November to June, with equal splits of annually required fertilizers as estimated in various treatments. The circular band placement of granular fertilizers (urea, single super phosphate and murate of potash) at 1 m radius from plant stem under BI (control) was performed three times in a year. As a whole, ten treatments (I_1F_1, I_1F_2, I_1F_3, I_2F_1, I_2F_2, I_2F_3, I_3F_1, I_3F_2, I_3F_3 and control) were imposed in split plot design (SPD), with four replications and three adjacent plants in a row per replication. The orchard floor was kept cleaned and all the experimental trees were grown under uniform cultural and management practices.

2.3. Measurement and analysis

The soil water content was monitored twice a week at 0.30 and 0.60 m depths by neutron moisture meter (Troxler model-4300, Troxler, USA). The water use by the crop was estimated from water balance equation (Ahmed and Mishra 1987) as: Water use=P+I+C_p–D_p–R_f–DS; where, P is rainfall, I is depth of irrigation water, C_p is contribution through capillary rise from ground water table, D_p is deep percolation loss, R_f is surface water runoff and DS is change in moisture storage in the soil profile to a depth of 60 cm. All units are in mm. Tensiometers were placed at 30, 60 and 75 cm soil depths in three tree basins per treatment (at 5 cm away from drip emitter) for determining the water potential gradient. Since no enhancement of water potential was observed at 75 cm depth during irrigation season, D_p from top 60 cm soil profile was assumed negligible. C_p was ignored as the water table was below 15 m throughout the growing season. As C_p, D_p, and R_f were negligible, water use was calculated as the difference between precipitation plus irrigation and changes in total moisture content in the soil profile. The indexed leaf samples (2nd–4th leaf from tip of branches) surrounding the trees at a height of 1.5 to 1.8 m from the ground were collected at the end of irrigation seasons and nutrient (N, P, K, Fe, Mn, Cu, and Zn) analysis was done as per the standard procedure followed by Srivastava and Singh (2008). The leaf samples were thoroughly washed and ground with Willey grinding machine. The homogeneous samples were digested in tri-acidic mixture of 2:5:1 of $HClO_4$:HNO_3:H_2SO_4. N was analysed by an auto-nitrogen analyser (Model Perkin Elmer-2410, USA), P by vanadomolybdophosphoric acid method and K by flame photometry. Micro-nutrients (Fe, Mn, Cu, and Zn) were analysed by atomic absorption spectrophotometry.

The net photosynthesis rate (P_n), stomatal conductance (G_s), and transpiration rate (T_r) of leaves were measured fortnightly, in 1 h interval from 9 a.m. to 3 p.m. on a clear-sky day using a portable infrared gas-analyser (LI-COR-6400, Lincoln, Nebraska, USA). Four mature leaves per plant (3rd or 4th leaf from tip of shoot) from exterior canopy position (one leaf in each North, South, East and West direction), and two plants per treatment were taken for these measurements. Leaf water use efficiency (LWUE) was calculated as the ratio of P_n to T_r of leaves (Ribeiro *et al.* 2009).

The vegetative growth parameters such as tree height, stem height, canopy width, and stem (stock and scion) girth were measured for all trees and their polled annual incremental magnitudes were compared. The canopy volume was calculated based on the formula, Canopy volume=$0.5233H\times W^2$, where H=Tree height–Stem height, and W is the canopy width (Obreza 1991). The weight of total fruits from each tree under various treatments was recorded and five fruits per tree were taken randomly for determination of fruit quality parameters (juice percent, acidity and total soluble solids). Juice was extracted manually by juice extractor and its percent was estimated on weight basis with respect to fruit weight. The total soluble solid (TSS) was determined by digital refractometer (Atago model-PAL 1, Atago, Japan) and acidity was measured by volumetric titration with standardized sodium hydroxide, using phenolphthalein as an internal indicator (Ranganna 2001). The WUE and FUE were calculated as fruit yield per unit quantity of irrigation water and fruit yield per unit quantity of fertilizer applied per year under different treatments in Nagpur mandarin orchard, respectively.

All the data generated were subjected to analysis of variance (ANOVA) and the least significant difference (LSD) at 5% probability was obtained according to the method described by Gomez and Gomez (1984).

3. Results

3.1. Irrigation requirement

Irrigation was applied during flowering (November) to fruit enlargement stages (June) of citrus plants. The water applied under various irrigation treatments is presented in Table 2. The lowest quantity of water was applied in December (12.5–41 L d^{-1} $plant^{-1}$), whereas the highest quantity was applied in May (75.6–165.5 L d^{-1} $plant^{-1}$). The volume of water applied increased from January to June under each irrigation treatment. The water used in BI (41–165.5 L day^{-1} $plant^{-1}$) was higher than that in DI (12.5–151.2 L day^{-1} $plant^{-1}$) during both the years of experiment. Irrigation was withheld during rainy season (July–October) due to lower cumulative evaporation than rainfall. Overall, the quantities of water applied through DI were 2 798, 4 196 and 5 595 m^3 ha^{-1} yr^{-1} under 50, 75 and 100% E_p irrigation regimes, respectively, whereas water applied under BI was 6 340 m^3 ha^{-1} yr^{-1}.

3.2. Soil water variation and water use

The mean monthly soil water variation observed at 0.30 and 0.60 m depths during irrigation periods indicated that all the DI regimes (except 50% E_p) with fertigation showed a significantly higher soil water content (25.8–28.0%, v/v) compared to BI with BPF (24.2–26.7%, v/v) at 0.30 m depth (Fig. 1-A and B). The soil water content at 0.30 m depth increased invariably in all the treatments during January–February. The fluctuation of soil water content between two measurements in a week under BI was observed to be wider than that under any of the DI treatment. Among different DI regimes, the range of soil water depletion at 0.30 m depth was progressively increased with increasing irrigation level. However, the soil water fluctuation under DI treatments was almost zero at 0.60 m depth. The fluctuation of soil water content at 0.60 m depth in BI was relatively higher during April to June than November to March. The higher soil water depletion was observed in higher levels of fertilizer with any irrigation regime.

Table 3 shows the variation of water balance components in mandarin orchard under various irrigation treatments. The maximum soil water use was observed under BI (625.5 mm) followed by DI at 100% E_p (570.5 mm). The mean seasonal soil water content in 0–60 cm soil profile was enhanced under both BI and DI at 100% E_p. Conversely, some decrease in soil water content was observed under DI at 50 and 75% E_p. Percolation losses from top 60 cm soil were found to be negligible during the irrigation periods.

3.3. Leaf nutrients composition

The leaf nutrient contents responded differentially to various irrigation and fertigation treatments (Table 4). Increase in irrigation regime from 50% E_p (I_1) to 75% E_p (I_2) under DI enhanced the leaf N content in corresponding fertilizer levels. The further increase in irrigation to 100% E_p (I_3) reduced leaf-N content. However, the leaf-N content increased with increase in fertilizer levels under each irrigation regime. Overall, the highest leaf-N (2.15%) was registered under I_2F_3 and the lowest under I_1F_1 (1.65% N) versus 1.98% leaf-N in BI with BPF. Leaf-K content followed the similar pattern of response

Table 2 Mean daily irrigation water applied (L d^{-1} $plant^{-1}$) under different irrigation treatments in various months[1)]

Treatment[2)]	Months								TWA
	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	(m^3 ha^{-1} yr^{-1})[3)]
I_1	21.8±1.2 a	12.5±0.7 a	19.6±0.9 a	31.7±1.4 a	47.6±1.6 a	61.8±1.8 a	75.6±2.1 a	59.3±2.2 a	2 798±91.5 a
I_2	32.8±1.4 b	19.0±0.9 b	29.4±1.1 b	47.6±1.6 b	71.4±1.9 b	92.6±2.2 b	113.4±2.4 b	88.9±2.5 b	4 196±101.2 b
I_3	43.7±1.7 c	25.0±1.1 c	39.2±1.2 c	63.4±1.9 c	95.2±2.2 c	123.5±2.4 c	151.2±2.6 c	118.6±2.8 c	5 595±131.4 c
BI+BPF (Control)	50.5±2.4 d	41.0±1.6 d	45.2±2.2 d	82.3±2.6 d	107.8±2.9 d	134.6±3.2 d	165.5±3.5 d	132.4±3.9 d	6 340±162.7 d

1) Mean data are measured during 2007–2009.
2) I_1, drip irrigation (DI) at 50% Class-A pan evaporation (E_p); I_2, DI at 75% E_p; I_3, DI at 100% E_p; BI+BPF, basin irrigation+band placement of fertilizers.
3) TWA, total water applied.
Data are means±standard deviation. Data within a column followed by same letters do not differ significantly at P<0.05.

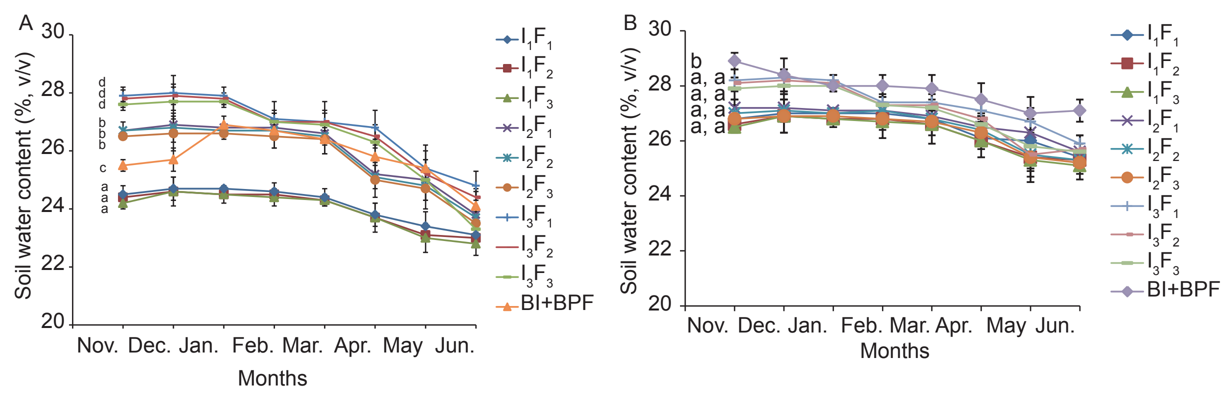

Fig. 1 Soil water content at 0–0.30 m (A) and 0.30–0.60 m (B) depths under various irrigation treatments in different months in Nagpur mandarin. I_1, drip irrigation (DI) at 50% Class-A pan evaporation (E_p); I_2, DI at 75% E_p; I_3, DI at 100% E_p; F_1, 50% recommended dose of fertilizer (RDF, N:P_2O_5:K_2O=600 g:200 g:100 g); F_2, 75% RDF; F_3, 100% RDF; BI, basin irrigation; BPF, band placement of fertilizers. Vertical bars represent the standard deviation (n=72). Values with different letters for each variable are significantly different among the treatments at P<0.05.

as leaf-N. Leaf-P content increased with increasing both irrigation and fertilizer levels applied through DI, with the highest magnitude under I_3F_3. Among micro-nutrients (Fe, Mn, Cu, Zn), only Fe concentration was observed to be significantly higher in I_3F_3 (113.99 mg kg^{-1}) over other treatments.

3.4. Leaf physiological parameters

The leaf physiological parameters (P_n, T_r and G_s) were significantly influenced by different irrigation and fertilizer application strategies (Table 5). The highest value of P_n was recorded in I_2F_3, followed by I_2F_2. The plants under BI+BPF exhibited the minimum P_n value, reflecting the negative effect of soil water deficit on P_n of citrus trees in this treatment. The T_r and G_s values were higher in I_3F_3, followed by I_3F_2. However, the magnitude of LWUE was the highest in I_2F_2, followed by I_2F_3.

3.5. Plant growth

The annual incremental vegetative growth parameters (plant height, stock girth, scion girth, canopy volume) of the plants under different treatments were recorded for two years and the mean values were presented in Table 6. The trend of increase in all the growth parameters in relation to irrigation and fertigation was similar in both the years of observation. The mean annual increase in plant height, stock girth, scion girth, and canopy volume varied in the range 0.25–0.55 m, 3.1–5.6 cm, 2.9–5.4 cm and 6.23–9.98 m^3, respectively, under drip-fertigation treatments (except I_1F_1) over 0.22 m

Table 3 Water use of Nagpur mandarin under different irrigation treatments[1)]

Treatment[2)]	Irrigation applied (mm)	Effective rainfall (mm)	Soil water contribution (mm)[3)]	Water used (mm)
I_1				
F_1	290±8.4 a	12.5±9.4 a	–47±7.2 a	349.5±6.6 a
F_2	295±9.2 a	12.5±9.4 a	–47±8.5 a	354.5±7.4 a
F_3	300±10.1 a	12.5±9.4 a	–47±9.1 a	359.5±8.9 a
I_2				
F_1	431±9.1 b	12.5±9.4 a	–28±8.2 b	471.5±8.8 b
F_2	440±11.4 b	12.5±9.4 a	–28±8.7 b	480.5±9.1 b
F_3	449±15.6 b	12.5±9.4 a	–28±10.2 b	489.5±10.4 b
I_3				
F_1	583±11.1 c	12.5±9.4 a	+32±9.2 c	563.5±9.8 c
F_2	590±14.2 c	12.5±9.4 a	+32±11.7 c	570.5±11.6 c
F_3	597±18.4 c	12.5±9.4 a	+32±14.5 c	577.5±15.4 c
BI+BPF	665±19.8 d	12.5±9.4 a	+52±19.2 d	625.5±16.5 d

1) Mean data are measured during 2007–2009.
2) I_1, drip irrigation (DI) at 50% Class-A pan evaporation (E_p); I_2, DI at 75% E_p; I_3, DI at 100% E_p; F_1, 50% recommended dose of fertilizer (RDF, N:P_2O_5:K_2O=600 g:200 g:100 g); F_2, 75% RDF; F_3, 100% RDF; BI+BPF, basin irrigation+band placement of fertilizers.
3) –, indicates loss in soil water content; +, indicates gain in soil water content during irrigation seasons.
Data are means±standard deviation. Data within a column followed by same letters do not differ significantly at P<0.05.

Table 4 Leaf nutrients composition under different irrigation and fertigation treatments in Nagpur mandarin[1)]

Treatment[2)]	Macro-nutrients (%)			Micro-nutrients (mg kg^{-1})			
	N	P	K	Fe	Mn	Cu	Zn
I_1							
F_1	1.65±0.1 a	0.071±0.002 a	1.16±0.2 a	79.52±1.2 a	28.87±1.2 a	13.00±0.6 a	15.03±0.2 a
F_2	1.88±0.1 a	0.081±0.002 b	1.34±0.4 b	86.52±1.4 b	31.90±0.9 a	13.76±0.8 a	15.27±0.5 a
F_3	1.93±0.3 a	0.081±0.004 b	1.55±0.4 c	92.69±1.5 b	32.70±0.9 a	13.23±0.5 a	15.28±0.5 a
I_2							
F_1	1.99±0.2 a	0.080±0.003 b	1.76±0.4 d	98.06±1.1 b	29.90±1.0 a	14.47±0.7 a	15.43±0.4 a
F_2	2.14±0.3 a	0.082±0.004 b	1.85±0.4 d	100.93±1.3 b	32.97±1.0 a	15.17±0.4 a	16.14±0.7 a
F_3	2.15±0.4 a	0.084±0.005 c	1.87±0.4 d	101.17±1.4 b	33.10±1.5 a	15.10±0.6 a	16.63±0.6 a
I_3							
F_1	1.97±0.2 a	0.084±0.006 c	1.67±0.4 d	100.46±1.2 b	29.93±1.3 a	16.00±0.9 a	15.50±0.5 a
F_2	2.08±0.2 a	0.108±0.007 d	1.71±0.4 d	100.68±1.4 b	30.77±1.4 a	15.80±0.2 a	15.89±0.3 a
F_3	2.09±0.4 a	0.110±0.009 d	1.78±0.4 d	100.99±1.5 b	29.77±1.1 a	16.37±0.4 a	15.50±0.2 a
BI+BPF	1.98±0.6 a	0.081±0.01 ab	1.64±0.4 d	93.52±1.9 b	31.90±1.0 a	13.76±0.2 a	15.27±0.1 a

1) Mean data are measured during 2007–2009.
2) I_1, drip irrigation (DI) at 50% Class-A pan evaporation (E_p); I_2, DI at 75% E_p; I_3, DI at 100% Ep; F_1, 50% recommended dose of fertilizer (RDF, N:P_2O_5:K_2O=600 g:200 g:100 g); F_2, 75% RDF; F_3, 100% RDF; BI+BPF, basin irrigation+band placement of fertilizers.
Data are means±standard deviation. Data within a column followed by same letters do not differ significantly at P<0.05.

(plant height), 3.0 m (stock girth), 2.8 cm (scion girth), and 5.96 m^3 (canopy volume) under BI with BPF. However, among different growth parameters, only plant height and canopy volume showed a significant response to irrigation and fertigation individually as well as in combination. All the growth parameters were increased with increasing irrigation level from 50 to 100% E_p under DI with corresponding fertilizer dose (except I_3F_3). The similar response of plant growth parameters to fertigation levels was also observed within any irrigation treatment. However, the highest magnitude of all incremental growth parameters was recorded under DI at 75% E_p with 75% RDF.

3.6. Fruit yield, WUE, FUE and fruit quality

Fruit yield changed significantly in response to irrigation and fertigation levels (Table 7). The highest fruit number (523) was recorded in I_2F_3, followed by I_2F_2 (520); whereas the heaviest fruits were harvested in I_2F_2 (113.4 g) followed by I_2F_3 (110.3 g). The average annual fruit yield increased with increase in fertilizer level under each DI regime, except I_2F_2. The fruit yield was observed to increase from 8.5 t ha^{-1} in I_1F_1 to as high as 16.39 t ha^{-1} in I_2F_2 compared with fruit yield of 10.0 t ha^{-1} in BI+BPF. The WUE and FUE under different treatments are presented in Table 7. The highest WUE (3.90 kg m^{-3}) was observed in I_2F_2 followed by I_2F_3 (3.82 kg m^{-3}). Likewise, the highest FUE was observed under I_2F_2 (87.36 kg kg^{-1}) followed by I_2F_1 (86.08 kg kg^{-1}). However, the lowest WUE (1.57 kg m^{-3}) and FUE (39.96 kg kg^{-1}) were observed in BI+BPF.

All the fruit quality parameters (juice content, TSS and acidity) varied significantly with irrigation and fertigation

Table 5 Leaf photosynthesis, transpiration (T_r), stomatal conductance (G_s) and leaf water use efficiency (LWUE) of Nagpur mandarin under different irrigation and fertigation treatments1)

Treatment2)	P_n (mmol m^{-2} s^{-1})	T_r (mmol m^{-2} s^{-1})	G_s (mmol m^{-2} s^{-1})	LWUE
I_1				
F_1	1.72±0.2 a	1.65±0.06 a	43.22±0.8 a	1.04±0.01 b
F_2	2.69±0.1 b	2.21±0.05 b	50.45±0.5 b	1.21±0.02 c
F_3	2.83±0.1 c	2.29±0.02 b	58.67±0.9 b	1.23±0.04 c
I_2				
F_1	2.45±0.3 b	2.11±0.04 b	48.19±1.1 b	1.16±0.03 c
F_2	3.13±0.4 a	2.36±0.03 a	51.95±1.2 a	1.32±0.05 ab
F_3	3.35±0.3 d	2.58±0.02 d	59.25±1.5 d	1.29±0.07 d
I_3				
F_1	2.38±0.1 b	2.37±0.07 b	52.14±0.9 b	1.00±0.01 b
F_2	3.01±0.2 c	2.89±0.05 c	54.61±1.2 c	1.04±0.07 b
F_3	3.11±0.3 c	2.99±0.02 c	56.24±1.4 c	1.04±0.06 b
BI+BPF	1.68±0.6 a	1.79±0.08 a	44.37±1.9 a	0.93±0.12 a

1) Mean data are measured during 2007–2009.
2) I_1, drip irrigation (DI) at 50% Class-A pan evaporation (Ep); I_2, DI at 75% Ep; I_3, DI at 100% Ep; F_1, 50% recommended dose of fertilizer (RDF, N:P_2O_5:K_2O=600 g:200 g:100 g); F_2, 75% RDF; F_3, 100% RDF; BI+BPF, basin irrigation+band placement of fertilizers.
Data are means±standard deviation. Data within a column followed by same letters do not differ significantly at P<0.05.

Table 6 Annual incremental vegetative growth of the Nagpur mandarin plants under different irrigation and fertigation treatments1)

Treatment2)	Plant height (m)	Stock girth (cm)	Scion girth (cm)	Canopy volume (m^3)
I_1				
F_1	0.20±0.05 a	2.8±0.08 a	2.6±0.03 a	5.68±0.04 a
F_2	0.26±0.03 b	3.1±0.05 b	2.9±0.05 b	6.23±0.01 b
F_3	0.30±0.01 b	3.1±0.03 b	3.0±0.01 b	7.44±0.01 b
I_2				
F_1	0.25±0.02 b	3.4±0.02 b	2.9±0.04 b	6.91±0.03 b
F_2	0.37±0.04 c	3.8±0.04 b	3.7±0.02 b	9.67±0.07 b
F_3	0.55±0.05 ab	5.6±0.04 ab	5.4±0.01 ab	9.98±0.06 ab
I_3				
F_1	0.37±0.02 c	3.9±0.03 c	3.4±0.05 c	9.32±0.05 c
F_2	0.46±0.01 d	4.0±0.02 d	3.7±0.07 d	9.73±0.02 d
F_3	0.48±0.04 d	4.4±0.02 d	4.2±0.03 d	9.79±0.03 d
BI+BPF	0.22±0.07 a	3.0±0.06 a	2.8±0.09 a	5.96±0.08 a

1) Mean data are measured during 2007–2009.
2) I_1, drip irrigation (DI) at 50% Class-A pan evaporation (Ep); I_2, DI at 75% Ep; I_3, DI at 100% Ep; F_1, 50% recommended dose of fertilizer (RDF, N:P_2O_5:K_2O=600 g:200 g:100 g); F_2, 75% RDF; F_3, 100% RDF; BI+BPF, basin irrigation+band placement of fertilizers..
Data are means±standard deviation. Data within a column followed by same letters do not differ significantly at P<0.05.

Table 7 Yield, fruit quality, water use efficiency (WUE) and fertilizer use efficiency (FUE) as affected by irrigation and fertigation in Nagpur mandarin[1)]

Treatment[2)]	Yield parameters			WUE (kg m^{-3})	FUE (kg kg^{-3})	Quality parameters[3)]		
	No. of fruits per plant	Average fruit weight (g)	Total yield (t ha^{-1})			Juice (%)	Acidity (%)	TSS (^{0}Brix)
I_1								
F_1	364±8.4 a	84.0±2.2 a	8.50±0.3 a	3.03±0.1 b	67.94±1.3 c	37.4±1.4 a	0.85±0.04 d	8.5±0.3 a
F_2	410±5.2 c	89.2±1.4 b	10.16±0.6 b	3.63±0.3 c	54.13±1.5 b	38.6±1.5 b	0.83±0.02 b	9.1±0.5 b
F_3	421±6.7 c	89.6±3.1 b	10.48±0.4 b	3.74±0.2 c	41.88±1.7 a	38.7±1.7 b	0.83±0.06 b	9.3±0.6 c
I_2								
F_1	429±4.4 c	100.8±2.2 c	12.02±0.8 c	2.86±0.1 a	86.08±1.4 ab	38.4±0.8 b	0.83±0.08 b	9.0±0.2 b
F_2	520±5.1 ab	113.4±1.7 ab	16.39±0.3 bc	3.90±0.4 d	87.36±1.6 ab	39.3±0.5 c	0.82±0.01 a	10.3±0.1 bc
F_3	523±6.6 ab	110.3±1.7 d	16.03±0.5 a	3.82±0.6 c	64.06±1.5 c	40.1±0.3 ab	0.84±0.03 c	10.1±0.3 ab
I_3								
F_1	431±7.0 c	96.2±2.7 b	11.52±0.6 c	1.92±0.4 a	86.01±1.7 ab	39.9±1.1 d	0.84±0.05 c	10.1±0.4 ab
F_2	468±8.4 d	102.6±3.2 c	13.35±0.7 d	2.38±0.5 b	71.16±1.9 d	40.2±1.3 ab	0.85±0.07 d	10.0±0.7 ab
F_3	518±7.8 a	109.5±1.8 d	15.77±0.6 ab	2.81±0.6 a	63.02±1.0 c	40.4±0.8 a	0.86±0.06 ab	9.7±0.5 d
BI+ BPF	380±14.7 b	94.6±7.2 b	10.00±1.01 b	1.57±0.8 a	39.96±1.9 a	38.4±1.8 b	0.84±0.04 c	9.4±0.6 c

[1)] Mean data are measured during 2007–2009.
[2)] I_1, drip irrigation (DI) at 50% Class-A pan evaporation (Ep); I_2, DI at 75% Ep; I_3, DI at 100% Ep; F_1, 50% recommended dose of fertilizer (RDF, N:P_2O_5:K_2O=600 g:200 g:100 g); F_2, 75% RDF; F_3, 100% RDF; BI+BPF, basin irrigation+band placement of fertilizers.
[3)] TSS, total soluble solid.
Data are means±standard deviation. Data within a column followed by same letters do not differ significantly at P<0.05.

levels (Table 7). The fruits with the highest juice content (40.1%) were harvested in I_3F_3, whereas I_2F_2 produced the fruits with the highest TSS (10.3 °Brix) and the lowest acidity (0.82%). The BI with BPF produced the fruits with 38.4% juice content, 0.84% acidity and 9.4 °Brix TSS.

4. Discussion

4.1. Irrigation requirement

Quantity of irrigation under different treatments during November to June in Table 2 indicted that the lowest quantity of water was applied in December and the highest in May. It was due to increased atmospheric evaporative demanded from December to May, which was evident from E_p data at the study site. Moreover, the water used in BI was 51% higher than that in DI. The higher water consumption was caused by water loss due to percolation and seepage under crop root zone in conjunction with increased evaporation in BI compared to DI. Earlier studies also demonstrated the reduction of water consumption of 40% in Verna lemon in Spain (Sáchez-Blanco *et al.* 1989), 30% in Thompson Navel orange in Spain (Holzapfel *et al.* 2001) and 35% in Kinnow in north India (Singh *et al.* 2001) under DI compared with conventional BI. These variations are due to the nature of citrus cultivars used under varied soil-climate, and methods adopted in scheduling irrigation.

4.2. Soil water variation and water use

The soil water content under different DI treatments and BI showed differential responses with higher magnitudes in DI. The higher soil water content under DI was due to frequent water application in precise quantities under the method. The increase in soil water content at 0.3 m soil during January–February was due to some un-seasonal rains (10–15 mm) in these months. The higher fluctuation of soil water between two measurements in a week under DI compared to BI was due to higher rate of evaporation from larger wetted surface area under BI, as reported by Cohen (2001). Moreover, the progressively increase in range of soil water depletion at 0.30 m depth with increasing irrigation level indicated the higher rate of evapo-transpiration (ET) of the plants under higher level of irrigation, even under low volume irrigation system. However, the least soil water fluctuation under DI at 0.60 m depth reflected the confinement of effective root zone of DI plants within top 0.30 m soil profile. The increased soil water content at 0.60 m depth under BI indicated the percolation of irrigation water from 0–0.30 m soil profile under this irrigation method. The higher fluctuation of soil water content at 0.60 m depth during April to June than November to March was probably due to higher percolation caused by higher quantum of irrigation water supply during summer months (April–June) under BI. The higher soil water depletion with higher levels of fertilizer might be caused by increased ET due to higher vegetative growth of the plants under these treatments. The water balancing under different treatments shown in Table 3 indicated that the soil water use in BI (625.5 mm) was higher than that in DI. This was due to increased loss of water through deep percolation under BI compared with under DI. Conversely, some decrease in soil water content under DI at 50 and 75% E_p indicated that the trees under DI at 50 and 75% E_p used some quantity of residual soil water in irrigation seasons.

4.3. Leaf nutrients composition

The leaf nutrient contents under different treatments presented in Table 4 shows that both N and K increased with increase in irrigation regime from 50 to 75% E_p and then decreased in 100% E_p under DI. This indicated that this might be caused due to optimum availability of N and K in soil with 75% E_p irrigation regime. The higher leaf-N and K under optimal irrigation and fertilizer level was also observed earlier in Thompson Navel orange (Holzapfel *et al.* 2001) and Valencia orange (Duenhas *et al.* 2005). However, the leaf-P content increased with increasing irrigation. The response of irrigation and fertigation in relation to leaf-P corroborates the findings of Obreza and Schumann (2010) in citrus in Florida. The leaf-Fe concentration flowed the similar trend of P. The higher leaf nutrient contents might be due to the increased availability of such nutrients in soil with optimum soil water regime created under irrigation at 75% E_p. Overall, the leaf-N, P, K and Fe contents registered under all the irrigation and fertilizer regimes (except I_1F_1) was higher than the optimum leaf nutrients content (1.70–2.81% N, 0.08–0.15% P, 1.62–2.59% K, 88.9–112.4 mg kg^{-1} Fe) required for sustainable production of Nagpur mandarin in central India, as suggested by Srivastava and Singh (2008).

4.4. Leaf physiological parameters

The plants under BI+BPF exhibited the minimum P_n value, reflecting the negative effect of soil water deficit on P_n of citrus trees in this treatment. The highest P_n value was recorded in I_2. However, T_r and G_s values were higher in I_3F_3, followed by I_3F_2. The higher P_n, G_s and T_r values were caused by higher soil water content in root zone of the plants under higher irrigation regimes. Earlier studies also reported higher P_n, G_s and T_r values under higher soil water availability in root zone of citrus plants (Vu and Yelenosky 1988; Ribeiro *et al.* 2009).

4.5. Plant growth

Table 6 showed that the growth parameters increased with increasing irrigation level from 50 to 100% E_p under DI with corresponding fertilizer dose (except I_3F_3). The highest magnitude of the growth parameters was recorded under DI at 75% E_p with 75% RDF. The higher plant growth was due to increased P_n and higher partitioning of the photosynthates towards vegetative development of the plants under I_2F_2. The higher plant growth under drip-fertigation over BI with BPF was also observed earlier in Valencia orange by Koo and Smjstrala (1984) and in Thompson Navel orange by Holzapfel *et al.* (2001).

4.6. Fruit yield, WUE, FUE and fruit quality

The maximum fruit yield observed under I_2F_2 was due to better photosynthesis of leaves caused by optimum available soil water and nutrients in root zone of citrus plants under this treatment (Table 7). The higher fruit yield under optimal drip-fertigation over surface irrigation with conventional fertilization was also observed earlier in various citrus cultivars (Holzapfel *et al.* 2001; Duenhas *et al.* 2005). The highest WUE and FUE were also observed in I_2F_2, due to higher increase in yield per unit increase in water and fertilizer use under this treatment compared to other treatments.

In relation to fruit qualities presented in Table 7, the highest juice content (40.1%) was recorded in I_3F_3. The I_2F_2 treatment produced the fruits with the highest TSS (10.3 °Brix) and lowest acidity (0.82%). The higher soil water availability might be a reason of higher juice content which resulted in lower TSS and higher acidity of fruits in I_3F_3. The BI with BPF produced the fruits with inferior fruit qualities compared to DI (except I_1F_1). The higher TSS and lower acidity in fruits under optimal water supply and fertilization through drip system over surface irrigation with traditional fertilizer application was also observed earlier in Valencia orange (Koo and Smajstrla 1984) and Thompson Navel orange (Holzapfel *et al.* 2001).

5. Conclusion

The application of irrigation and fertilizers through drip system is found to be a potential water and fertilizer saving technique in Nagpur mandarin. The optimal DI regime (75% of class-A) in combination with 75% of RDF saved around 40% water and 25% fertilizers over basin irrigation with band placement of fertilizer. Drip-fertigation also enhanced the fruit yield to the tune of 65% and improved the fruit qualities (Juice percent, TSS, acidity) over basin irrigation with band fertilization method in Nagpur mandarin. The higher productivity using less water and fertilizer resulted 148 and 118% improvement in WUE and FUE, respectively under optimal irrigation and fertilizer regime (I_2F_2) compared with band placement fertilizer under basin irrigation. Improved fruit yield with superior quality fruits using less water and fertilizers under drip-fertigation warrants its adoption in citrus cultivation of central India and elsewhere in the world having similar agro-climate of the study region. This could help in bringing more area under irrigation, resulting in large increase in production of citrus with prolonged orchard longevity.

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(Managing editor SHI Hong-liang)