Journal of Applied Horticulture, 24(2): 135-139, 2022

DOI: https://doi.org/10.37855/jah.2022.v24i02.26

Journal of Applied Horticulture

ISSN: 0972-1045

Partial root zone drying irrigation for higher water use efficiency in papaya (*Carica papaya* L.)

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Abstract

Field experiment to standardize the partial root-zone drying irrigation in papaya (*Carica papaya* L.) cultivar 'Red Lady' indicated that replenishing 70 % of the evaporative demand and changing the irrigation sides once in 12 days found to store higher soil moisture (14.6 %) in the root zone. Irrigation meeting 60 % ER was found to enhance the photosynthetic rate (13.9μ mol/m^2/s) significantly while shifting the irrigation at 16 days found to reduce the rate (9.9 μ mol/m^2/s). ABA production increased with an increase in the interval between the changing irrigation sides. Vertical growth of roots was significantly higher (67.3 cm) when irrigation was scheduled, meeting 60 % pan evaporation with irrigation side changing once in 16 days. Replenishing 60 % of evaporation recorded a significantly higher number of fruits (46.1/plant) and further changing the irrigation sides once in 12 days found to yield significantly more papaya fruits (53 /plant) and total yield (32.4 kg/plant) accounting to 100 t/ha. This treatment also recorded significantly higher water use efficiency (100.4 kg/ha.mm), saving 14.3 % water. Further, scheduling irrigation at 60 % ER and changing the irrigation sides at 12 days intervals was found to be more economical with higher gross returns (Rs. 10,00,000), net returns (Rs. 6,09,340) and benefit-cost ratio (2.60).

Key words: Benefit-cost ratio, irrigation, papaya, *Carica papaya* L., partial root zone drying, scheduling irrigation, water use efficiency

Introduction

Availability of adequate, timely and assured irrigation is critical for obtaining optimum growth, yield and quality papaya fruits (*Carica papaya* L.). The soil moisture content significantly impacts nutrient availability and other metabolic processes. A deficiency of soil moisture at any stage of papaya growth and development can adversely affect overall production and quality. Partial Root Zone Drying (PRD) is a technique where half of the root zone is irrigated while the other half remains dry, and this wet-dry alternation is repeated in successive irrigations (Dry *et al.*, 2000; Jovanovic and Stikic, 2018).

PRD irrigation helps maintain a reduced soil moisture level by compensating water from the dry part of the root zone to the wetter part, which is alternately rewetted. This approach allows us to cut the amount of irrigation water applied to half (Kirda *et al.*, 2004; Tang *et al.*, 2005; Zegbe *et al.*, 2004). By irrigating only a portion of the root system, the leaves stay hydrated, while the drying of the other part of the root system triggers the production of abscisic acid (ABA), a chemical signal that moves from roots to shoots via the xylem, inducing a physiological response (Dodd *et al.*, 2015).

This ABA-based chemical signaling system helps control water absorption, movement, and utilization by plants, increasing water use efficiency by allowing plants to use irrigation water conservatively and effectively (Davies *et al.*, 2002). Moreover, the PRD irrigation method limits vegetative vigor and has the potential to significantly reduce crop water usage while maintaining yields, thereby improving water use efficiency (Kriedmann and Goodwin, 2003).

Wetting and drying each side of roots depend on crops, growing stage, evaporative demands, soil texture and soil water balance (Saeed *et al.*, 2008) and there is little understanding of the mechanism of PRD effects on crop growth. In PRD, roots sense the drying of soil and sufficient water is absorbed in wet soil to maintain a high water status in the shoot (Liu *et al.*, 2006). However, the level of meeting the crop evapotranspiration demand based on the PRD irrigation in a given agro-climatic situation needs to be standardized for a given crop.

Papaya is a common fruit crop grown in the Southern region of India. The crop is normally grown under protective irrigated conditions as repeated stress cycles imposed from the vegetative phase prevent fruit formation by constantly causing flower abscission. The stressed plants also will be stunted in size. The mid-vegetative, flowering and fruit enlargement phases are moisture-sensitive (Aiyelaagbe *et al.*, 1986). However, in the recent past, owing to water scarcity for irrigation, following the alternate approaches to save the scarce water and bring more area under cultivation assumes significance.

With this perspective in mind, a field trial was initiated at ICAR-Indian Institute of Horticultural Research to establish the standardization of partial root zone drying irrigation in papaya.

Materials and methods

Field experiments were conducted from 2018 to 2019 at ICAR-Indian Institute of Horticultural Research, Hessaraghatta, Bengaluru, located at latitude13°8'12"N and a longitude of 77°29'45"E. The experimental soil was sandy loam in texture with a pH of 6.27 and an EC of 0.16 dS m^{-1}. The soil had an initial nutrient content of 283 kg available N/ha, 42.0 kg available phosphorus/ha and 246.4 kg available potassium/ ha. The experimental soil had 11.66 % moisture in 0-30cm depth and 12.81 % in 30-60 cm depth, at field capacity level.

Uniform and well-developed 45 days old seedlings of papaya cultivar 'Red Lady' were planted at a spacing of 1.8 m x 1.8 m (as per the standard package) on raised beds during June 2018 and the treatments were imposed with the crop establishment. Papaya cultivar 'Red Lady' is a dwarf self-pollinating variety with medium sized fruits of both oblong and round shape and excellent flavour, aroma, and texture and is a popular variety of the region.

The crop was managed with the recommended package of practices except for irrigation. FYM was applied @ 10 kg plant^{-1} at planting. A fertilizer dosage of 250 g N + 250 g P_2O_5 + 500 g K_2O per plant/year was given in six equal splits at bimonthly intervals as crop growth and flowering are noticed throughout the year. Need-based foliar application of micronutrients, especially zinc and boron, were taken up. Plant protection measures were followed to control powdery mildew, anthracnose and papaya ring spot virus.

The field experiment was conducted in a Split plot design with four replications. The main plot treatments included three levels of irrigation *viz.,* I_1: 0.5 ER (50 % of evaporation replenishment), I_2: 0.6 ER (60 % of evaporation replenishment) and I_3 : 0.7 ER (70 % of evaporation replenishment) while the subplot treatments included four frequencies of alternating the irrigation sides *viz.*, F_1: PRD irrigation through shifting sides at eight days interval, F_2: PRD irrigation through shifting sides at 12 days interval and F_3: PRD irrigation through shifting sides at 16 days interval with F_4: Normal drip irrigation as control. In all, there were 12 treatment combinations replicated four times.

The irrigations were scheduled as per the treatments and alternate partial irrigation was provided by laying out double laterals for each papaya line (wherever required) and controlling the water through the control valves at intervals as per the treatments. The evaporation data was collected from USWB Class A open pan evaporimeter of a meteorological observatory situated in the experimental farm of ICAR-IIHR. The crop coefficient for papaya is 80 % of reference evapotranspiration (ETo). The actual evapotranspiration was estimated by multiplying reference evapotranspiration with crop coefficient values for different periods. For computing water use efficiency (kg fruits ha^{-1} mm of water applied^{-1}), the total water applied through drip irrigation and effective rainfall were considered. Irrigation scheduling was done based on the treatment combinations' pan evaporation data (Epan).

The observations on all the growth, yield and quality parameters, soil moisture, and physiological parameters were recorded at periodic intervals. The horizontal and vertical root growth was measured for the longest spread and the root volume was calculated based on the displacement of water technique. The dry weight of the roots was calculated by carefully uprooting the roots with soil, washing with water and drying in a hot air oven. The number of fruits was recorded in all plants in each treatment at every harvest. Fruit yield and quality parameters included number of fruits/plant, fruit weight and TSS. The abscisic acid (ABA) production was analyzed following the HPLC procedure of Kelen *et al.* (2004) with modifications.

Soil samples were collected from 0-30 at 30-40 cm away from the base of the plant. Soil chemical and fertility parameters such as pH, organic carbon, available phosphorus (P) and potassium (K) were analyzed as per standard procedures.

The total water applied through drip irrigation and effective rainfall were considered to estimate water use efficiency. The water use efficiency of critical inputs was estimated using the following formula.

$$\text{Water Use Efficiency} = \frac{\text{Yield (kg of papaya ha}^{-1})}{\text{Water used (mm)}}$$

All the experimental data were statistically analyzed per the standard procedures and the differences in means were compared at a 5 % significance level.

Results and discussion

Soil moisture characteristics*:* The area of wetted perimeter of soil was found to be significantly higher with irrigation meeting 70 % evaporation replenishment (1611.8 cm^2), while the shorter interval (8 days) of shifting of irrigation side, especially at 0.50 ER irrigation level also recorded least difference (1.79 %) between wet and dry soil moisture regimes. The least differences between dry and wet soil zones with frequent intervals of changing the irrigation side also indicate that sufficient moisture levels were maintained in the root zone even at a lower rate of irrigation level. Further, replenishing 70 % of the evaporative demand and changing the irrigation sides once in 12 days also recorded higher soil moisture (14.63 %) in the root zone, which was 19.5 % higher than field capacity level. The increased soil moisture observed with higher irrigation levels can be attributed to the larger wetted soil volume resulting from the increased irrigation water. This is because a higher water application rate allows for more horizontal water distribution, while a lower rate encourages more vertical water distribution for a given volume of water applied. Furthermore, the availability of higher soil water with a moderate interval of changing the irrigation sides (12 days) suggests that this 12-day interval is optimal for balancing the moisture in the dry and wet zones. However, this optimal balance was reduced when widening the interval to 16 days (Table 1).

Physiological parameters: The irrigation treatment meeting 60 % ER was found to enhance the photosynthetic rate (13.9 µ mol/ m^2/s). Among the shifting intervals, alternating the irrigation at 16 days interval found to cause a reduction in the photosynthesis rate (9.9 µ mol/m^2/s) (Table 1). A significantly lower transpiration rate (1.32 m mol/m^2/s) was recorded in irrigation treatment meeting 50 % ER with shifting interval once in eight days, which also recorded lower stomatal conductance (0.10 mol H_2O/m^2/s). The production of ABA increased with a longer interval between changing irrigation sides, reaching the highest value at a 16-day interval (378.2 ng/g fresh weight). This response is a result of irrigating one part of the root zone, which keeps the leaves hydrated, while the unirrigated portion of the roots remains dry. This allows for synthesizing and transporting chemical signals, particularly ABA, from roots to shoots through the xylem (Jovanovic and Stikic, 2018; Loveys *et al.*, 2000). This leads to partial stomatal closure, preventing excessive water loss and promoting a better water balance (Chaves *et al.*, 2002). Simeneh and Llorens (2020) also found that in partial root-zone drying irrigation, ABA-mediated aquaporin activity increases, leading

Table 1. Difference in the root zone soil moisture and physiological parameters in papaya as influenced by PRD irrigation treatments

Treatment	Difference in the root zone soil moisture (%)	Photosynthesis (µ mol m-2 s-1)	Stomatal conductance (mol m-2 s-1)	Transpiration (m mol m-2s-1)	ABA (ng/g)
I_1F_1	1.79	12.42	0.07	1.15	273.8
I_1F_2	5.68	14.24	0.11	1.82	281.6
I_1F_3	5.74	14.82	0.13	2.12	348.9
I_1F_4	4.39	15.7	0.15	2.12	390.9
Mean	4.4	14.3	0.11	1.9	323.8
I_2F_1	4.57	12.48	0.14	2.54	324.8
I_2F_2	4.96	15.11	0.16	2.93	329.7
I_2F_3	5.7	14.8	0.13	2.42	340.7
I_2F_4	3.69	12.89	0.11	2.16	395.3
Mean	4.73	13.82	0.14	2.51	347.6
I_3F_1	5.39	14.29	0.12	2.57	449.9
I_3F_2	7.14	13.65	0.09	2.16	285.6
I_3F_3	4.37	11.7	0.07	1.68	444.9
I_3F_4	3.97	14.4	0.13	2.73	342.4
Mean	5.22	13.51	0.1	2.29	380.7
S Em±					
Main	0.46	0.136	0.004	0.06	3.9
Sub	0.82	0.257	0.007	0.1	3.95
Main x Sub	1.31	0.409	0.011	0.16	7.1
C.D (P=0.05)					
Main	NS	0.48	0.013	0.2	15.71
Sub	NS	0.75	NS	0.3	11.84
Main x Sub	NS	1.22	0.033	0.48	23.47

Main Plot treatments : Irrigation levels
I_1 : 0.50 ER (50 % of evaporation replenishment)
I_2: 0.60 ER (60 % of evaporation replenishment)
I_3 : 0.70 ER (70 % of evaporation replenishment)
Sub Plot treatments : Irrigation methods
F_1: PRD through shifting irrigation at 8 days interval
F_2: PRD through shifting irrigation at 12 days interval
F_3: PRD through shifting irrigation at 16 days interval
F_4: Normal drip Irrigation

to enhanced water movement upward into the stem and leaves in both the wet and dry zones.

Root growth: The impact of PRD irrigation treatments on root growth parameters indicated that the interval of PRD significantly influenced both the lateral and vertical root growth in papaya, although the level of irrigation showed nonsignificant differences. In general, most of the root growth parameters were higher up to 60 % ER and decreased after that, except that the vertical growth and the oven-dry weight of roots increased with the irrigation levels. A significantly higher lateral root spread of 133.8 cm was noticed in 8 days of changing the irrigation sides. A significantly higher lateral root spread of 133.8 cm was detected in 8 days of changing the irrigation sides. Further, the interaction between the irrigation level and the interval of changing the irrigation sides was significant. Significantly higher vertical root growth of 50.3cm was noticed when the irrigation side was changed at 12 days intervals. Vertical growth of roots was considerably higher (67.3 cm) when irrigation was scheduled, meeting 60 % pan evaporation with changing the side once in 16 days. The drier environments at lower irrigation levels and longer intervals of changing the sides might have stimulated additional root growth in papaya, which was evident from the results. Kang *et al.* (2000) and Kang (2004) and Mingo *et al.* (2004) also noticed that PRD induces new roots as a result of alternate drying and rewetting cycle, which increases hydraulic conductance.

The dry weight of papaya roots, although did not differ significantly both due to irrigation levels and the interval of changing the sides (Table 2), meeting 50 % of the evaporative demand and changing the irrigation sides at 16 days intervals in general recorded higher dry weight of roots (586.4 g/plant). This may be attributed to the higher volume of the roots (3.25 cm^3x 10^3) produced with longer intervals of changing the irrigation sides. In a field trial conducted earlier, similar results of significantly higher dry weight of roots in papaya were observed when the irrigation was scheduled on one side of the plant, meeting 50 % of evaporative demand (Manjunath *et al.*, 2017).

Biological activity: Management factors that increase the colonization of effective microorganisms can be expected to improve nutrient and water-use efficiencies (Campostrini and Glenn, 2007). Irrigation strategies may cause significant differences in soil water distribution in the root profile and thus may affect soil bio-physicochemical processes differently (Shahnazari *et al.*, 2007). These processes influence soil microbial community and, consequently, nutrient availability. In the experiment, scheduling irrigation at 60 % ER recorded a significantly higher population of bacteria (6.4 x 10^6 cfu /g of soil), fungi (10.5 x 10^3cfu /g of soil) and zinc solubilizers (14.4 x 10^3cfu /g of soil) (Table 2). Whereas irrigation at 70 % recorded a significantly higher population of actinomycetes (9.3x 10^4cfu /g of soil) and P solubilizers (4.6 x 10^4cfu /g of soil) (Table 2). Changing the irrigation sides at 16 days affected the bacterial population, especially Azotobacter, while fungal and actinomycetes populations were higher when irrigation was shifted at 12 days. Further, phosphorus and zinc solubilizers were higher when the irrigation side was changed once in eight days. These differences may be attributed to the fact that moisture levels influence microbial growth greatly. Further, colonization rates and spore density were positively correlated with soil organic matter and the P solubilizers in improving the acquisition of nutrients and water in papaya production (Campostrini and Glenn, 2007).

Soil fertility: All the major soil fertility parameters were significantly influenced by PRD irrigation treatments (Table 3). Organic carbon was considerably higher (1.57 %) at 60 % ER as compared to either 50 % ER (1.14 %) or 70 % ER (1.22 %). Among the intervals of irrigation, changing the irrigation sides once in 16 days recorded higher organic carbon (1.57 %) and available nitrogen (568.8 %). Among the interactions, 60 % ER with normal drip irrigation and 70 % ER with changing the irrigation sides once in 16 days recorded higher (both 1.98 %) organic carbon. Available N (544.9 kg/ha) and K (1372.7 kg/ha) were significantly higher with 60 % ER. Changing the irrigation sides once in eight days recorded higher available P (29.5 kg/ha), while once in 12 days recorded higher available K (1430.8 kg/

Table 2. Root characteristics and soil microbial population in papaya as influenced by the irrigation levels and the intervals of changing the irrigations sides

Treatment	Root volume (cm3x 103)	Dry.weight of root (g)	Bacteria (cfu x 106)	Fungi (cfu x103)	Actinomycetes (cfu x 104)	P solublizers (cfu x 104)
I_1F_1	2.30	334.4	3.0	10.0	8.0	3.0
I_1F_2	2.85	427.6	3.0	6.5	8.0	3.5
I_1F_3	3.18	586.4	4.5	14.5	5.0	5.5
I_1F_4	2.23	231.6	1.5	10.0	6.5	6.0
Mean	2.64	395.0	3.0	10.3	6.9	4.5
I_2F_1	3.78	440.9	5.0	7.5	3.5	6.0
I_2F_2	3.55	358.3	6.0	14.0	2.5	1.0
I_2F_3	3.95	411.0	11.5	12.5	3.0	5.0
I_2F_4	3.58	433.3	3.0	8.0	7.5	2.0
Mean	3.71	410.9	6.4	10.5	4.1	3.5
I_3F_1	2.90	375.1	2.0	3.5	5.5	11.5
I_3F_2	2.13	494.2	2.0	23.5	12.5	1.5
I_3F_3	2.63	572.7	5.0	3.0	9.0	2.5
I_3F_4	3.13	413.7	3.0	5.5	10.0	3.0
Mean	2.69	463.9	3.0	8.9	9.3	4.6
S Em ±						
Main	0.17	52.0	0.2	0.1	0.3	0.1
Sub	0.26	62.0	0.3	0.3	0.3	0.2
Main x Sub	0.43	106.5	0.4	0.3	0.7	0.2
C.D (P=0.05)						
Main	0.58	NS	0.7	0.5	1.3	0.4
Sub	NS	NS	0.8	0.9	0.9	0.5
Main x Sub	NS	NS	1.5	1.6	1.8	1.0

ha). It may be attributed to better availability of nutrients under higher soil moisture conditions. The form of nitrogen not only appeared to influence seedling growth but may have also affected the uptake of other plant nutrients (*e.g.*, P and Ca). Further, in a study conducted by Dodd *et al.* (2015), it was inferred that fertility showed higher availability of major nutrients under PRD irrigation and crop nutrition improved, which was attributed to the fact that rewetting the dry soil provokes both physical and biological changes which affect soil nutrient availability.

Fruit yield: The fruit number per plant in papaya was significantly influenced by the irrigation levels and the interval of changing the irrigation sides. A significantly higher number of fruits was observed with 0.60 ER (46.1 fruits/plant) and further changing irrigation sides once in 12 days recorded more number of fruits (53/plant) (Table 3). Further, normal drip irrigation recorded significantly more fruits (45.6/ plant). Among the interactions, 60 % ER with changing the irrigation sides at 12 days recorded 53 fruits/plant considerably differing from the rest of the treatments. Scheduling the irrigation meeting 60 % of evaporative demand and alternating the irrigating sides at 12 days intervals yielded significantly higher papaya fruit yield (32.4 kg/plant), accounting for 100 t/ha. The higher yield in this treatment combination may

Table 3. Soil fertility characteristics and fruit yield and water use efficiency in papaya as influenced by PRD irrigation

Treatment	pH	O.C (%)	No. of fruits /plant	Mean yield(kg/plant)	Mean fruit weight (g/ fruit)	Fruit yield (t/ha)	WUE (kg/ ha.mm)
I_1F_1	5.34	0.99	26.00	13.20	512.00	40.70	48.90
I_1F_2	5.73	1.16	18.00	10.00	562.20	30.70	37.00
I_1F_3	5.83	1.16	41.50	26.70	631.30	82.30	99.10
I_1F_4	6.02	1.24	42.80	26.80	629.20	82.00	98.80
Mean	5.73	1.14	32.08	19.18	583.70	58.90	70.95
I_2F_1	5.49	1.72	40.80	26.50	659.20	81.90	82.20
I_2F_2	5.48	0.99	53.00	32.40	607.70	100.00	100.40
I_2F_3	5.91	1.57	39.80	30.90	777.00	95.40	95.80
I_2F_4	5.40	1.98	50.80	32.00	622.80	98.60	99.00
Mean	5.58	1.57	46.10	30.50	666.70	93.98	94.35
I_3F_1	5.92	0.63	36.80	23.00	675.90	70.90	61.00
I_3F_2	5.86	1.65	15.00	8.03	603.10	24.80	21.30
I_3F_3	6.33	1.98	27.00	13.00	599.00	40.00	34.50
I_3F_4	6.13	0.63	43.30	28.90	680.50	89.20	76.80
Mean	6.06	1.22	30.53	18.23	639.60	56.20	48.40
S. Em							
Main	0.02	0.03	3.73	2.48	29.70	7.64	7.25
Sub	0.01	0.06	3.07	2.03	44.70	6.26	6.64
Main x Sub	0.03	0.10	5.94	3.92	73.30	12.12	12.32
C.D (P=0.05)							
Main	0.06	0.12	13.17	8.73	NS	26.95	25.59
Sub	0.04	0.17	8.98	5.92	NS	18.27	19.37
Main x Sub	0.08	0.28	18.76	12.40	NS	38.26	38.55

be attributed to the fact that the physiological and morphological alteration of plants under partial root-zone irrigation may bring more benefits to crops where carbon redistribution among organs is crucial to the determination of the quantity and quality of the products (Shaozhongkang and Jianhua Zhang, 2004). Further, PRD irrigation improves crop nutrition and rewetting dry soil provokes physical and biological changes affecting soil nutrient availability (Dodd *et al.,*2015).

Water use efficiency: Enhancing WUE at the canopy level can be achieved by adopting practices that reduce the soil water evaporation component and divert more water into transpiration which can be through crop residue management, mulching, row spacing, and irrigation (Hatfield and Dold, 2019). The instantaneous WUE was found to be higher at 0.50 ER (8.0 μ mol/m mol) and further changing the irrigation side once in eight days recorded higher instantaneous water use efficiency (716 μ mol/m mol) (Table 3). The higher efficiency at lower irrigation levels may be attributed to better water utilization at deficit levels. This may also be due to regulating the growth of leaf area and size and increasing canopy water use efficiency because of its ability to facilitate movement of water into the canopy (Jovanovic and Stikic, 2018).

Total water used varied with the irrigation levels, with 70 % of ER recording the highest water usage (5954m^3/ha). Scheduling the irrigation to meet 60 % of evaporative demand and alternating the irrigating sides at 12 days intervals was better, saving 14.3 % water. This may be attributed to the increased root growth and development under PRD irrigation, which in turn enhances plant hydraulic conductivity and water movement and its use efficiency (Ahmadi *et al.*, 2011; Mingo *et al.,* 2004; Pérez-Pérez *et al.*, 2012). Further, the increase in the interval of alternating the irrigated sides reduces the simultaneous root water uptake time on both sides of the plant rows.

Scheduling the drip irrigation on an alternate day meeting 60 % of evaporative demand (an average of 26 liters/plant during summer, 19 liters/plant during rainy season and 15 liters/plant during winter with drip system) under experimental site conditions and alternating the irrigating sides at 12 days interval through single dripper found to yield a significantly higher number of fruits (53/plant), fruit yield (100 t/ha), water use efficiency (100.4 kg/ha.mm) and better benefit-cost ratio (3.10) in papaya.

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Received: October, 2021; Revised: December, 2021; Accepted: January, 2022