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ORIGINAL ARTICLE

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Effects of partial root zone drying irrigation on physiological parameters, yield attributes and water use efficiency of Pomegranate (*Punica granatum* L.)

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ABSTRACT

A field experiment was conducted from 2015-2020 during the *hasta bahar* in Solapur (17°10' N, 74°42' E, 483.5 m asl) to evaluate the impact of partial root zone drying irrigation (PRZDI) on physiological growth, yield, and water use efficiency (WUE) in light-textured soils under the semi-arid conditions of Maharashtra, India. The study tested four irrigation treatments [40, 60, 80, and 100% of pomegranate evapo-transpiration (ET_p)] and three sub-treatments for scheduling irrigation at 20, 40, and 60% available soil moisture deficit (ASMD) on the drying side. Results indicated that PRZDI produced optimal vegetative growth, reduced water shoots, and minimized deep percolation. The highest plant height, branches, flowers, and yield were observed at 40, 60, and 80 * % ET_p with irrigation shifted at 20 % ASMD. Moisture content ranged from 17.29-36.12%, while relative leaf water content varied from 60.24-83.15%. Root geometry analysis revealed the greatest root length, weight, and density (69.44 cm, 89.91 g, and 1.48 kg/m³) in the 40% ET_p with 20% ASMD treatment. The highest yield and WUE under PRZDI were recorded as 23.16 kg/tree and 3.93 kg/m³, respectively, in older pomegranate trees (Bhagawa *cv.*) at 60% ET_p. The study concluded that PRZDI, particularly at 40, 60 and 80 *% ET_p with 20%*ASMD, is an effective water-saving strategy, maintaining growth and yield while increasing WUE. This technique offers a viable alternative to other water management methods when resources are limited, optimizing water use without compromising physiological growth and other critical parameters.

HIGHLIGHTS

- A field experiment (2015-2020) in late *hasta bahar* studied partial root zone drying irrigation (PRZDI) impact on growth, yield, and WUE.
- Optimal growth was seen with 40%, 60%, and 80% ET_p irrigation, no water shoots, and lush vegetation.
- Soil moisture and leaf water content ranged from 17.29-36.12% and 60.24-83.15%, respectively.
- The highest yield and WUE under PRZDI were recorded as 23.16 kg/tree and 3.93 kg/m³, respectively, in older pomegranate trees (Bhagawa *cv.*) at 60% ET_p.
- PRZDI proved to be a highly efficient water-saving strategy for older pomegranate trees.

1 | INTRODUCTION

Pomegranate (*Punica granatum* L.) is a hardy, deciduous shrub or small tree that is native to regions spanning from Iran to the Himalayas in Northern India. It has been cultivated for centuries across the Mediterranean and other parts of the world due to its resilience and adaptability (Meshram *et al.,* 2020). Pomegranate is highly drought-tolerant, capable of tolerating heat and thriving in semi-arid, making it well-suited for regions with limited water availability (Aseri *et al.,* 2008). In India, pomegranate is commonly grown on marginal lands using a fertigation system along with *bahar* treatments, which help regulate flowering and fruiting cycles. Three primary flowering *bahars* are employed in Indian pomegranate cultivation: *Ambia bahar* (Jan-Feb flowering), *Mrig bahar* (June-July flowering), and *Hasta bahar* (Sept-Oct flowering) (Meshram *et al.,* 2019). These treatments play a crucial role in optimizing fruit production across different regions and climatic conditions. However, due to its sensitivity to water stress, efficient water management practices are essential for sustaining pomegranate cultivation, especially in water-scarce regions.

Soil water uptake is determined by root distribution and activity. Understanding the interaction between soil and water uptake is vital for devising sustainable irrigation schedules and developing efficient water management systems. Key factors such as soil texture, structure, and water distribution significantly impact root growth and function (Wang *et al.,* 2012). One promising irrigation technique for improving water use efficiency in crops like pomegranate is Partial Root-Zone Drying Irrigation (PRZDI). This method involves alternately irrigating one side of the root zone while leaving the other side dry, shifting irrigation based on soil water depletion and crop water consumption (Manjunath *et al.,* 2017). The dry side of the root system sends signals that cause physiological responses, such as reduced stomatal opening and leaf expansion, thus conserving water (Hutton and Loveys, 2011). PRZDI has been applied successfully in various fruit crops, including pear, peach, citrus, and pomegranate, and it shows potential for improving water productivity without significantly reducing yield (Sepaskhah and Ahmadi, 2010).

With increasing pressure on freshwater resources in pomegranate-growing regions of India, there is a need to adopt irrigation strategies like PRZDI (Gorantiwar *et al.,* 2011). This study evaluates the effects of PRZDI on physiological parameters, yield, and water use efficiency.

2 | MATERIALS AND METHODS

2.1 | Study Area

A field experiment was conducted at the ICAR-Research Farm of the National Research Centre on Pomegranate, Solapur (17°10' N, 74°42' E, 483.5 m asl) during the *Hasta Bahar* from 2015-2016 to 2019-2020. Pomegranate plants were spaced at 4.5 × 2.0 m. The experiment followed a split-plot design with four replications, including main-plot irrigation regimes (I_1-40%, I_2-60%, I_3-80%, I_4-100% ET_p) and sub-plot treatments of irrigation shifting (T_1-20%, T_2-40%, T_3-60% ASWD) for 3th to 7th year-old Bhagwa *cv.* pomegranate.

2.2 | Climatic Parameters During the Crop Growth Period

Daily weather data were recorded from a meteorological station on the same farm. The avg. monthly max. and min. temperatures, relative humidity, sunshine hours, wind speed, evaporation, and rainfall during *Hasta Bahar* were 33.6°C, 24.7°C, 75.7%, 45.5%, 8.8 hours, 7.9 km h^{-1}, 7.7 mm, and 441.8 mm, respectively, based on a five-year avg. (2015-2020) from July to June (Table 1). These daily weather data were used to estimate crop evapotranspiration (ET_p) by using the Penman-Monteith model.

2.3 | Physical Condition of Drip Irrigation System and Plant Growth Parameters for the Experiment

In the PRZDI experiment, a 16 mm online lateral was used with pressure-compensating drippers having a discharge capacity of 4 liters per hour (lph). The main (90 mm) and sub-main (63 mm) lines were installed at a depth of 60 cm. As the plants matured and their canopy expanded, the lateral lines were adjusted up to 60 cm from the tree trunks. The irrigation system was operated based on atmospheric and

TABLE 1 Average monthly air temperature, relative humidity, wind speed, sunshine hours, evaporation and rainfall during five years crop-growing *bahars*

Phenophase	Months / Climatic parameters	T_{mean} (^{0}C)	RH_{mean} (%)	WS (km hr^{-1})	Ssh (hr)	E_{pan} (mm)	Rainfall (mm)	Ave. ET_r (mm)
Stress	July	28.7	83.5	12.41	9.2	8.6	11.8	4.50
	August	29.1	84.0	6.43	9.2	8.8	186.7	3.98
Initial	September	27.8	75.0	8.2	6.7	5.5	146.1	3.88
Development	October	28.1	73.4	6.8	8.1	6.0	69.1	3.85
	November	27.1	69.1	7.3	8.9	6.8	8.6	4.80
	December	25.3	69.2	6.6	8.8	6.5	0.0	5.85
Maturity	January	24.7	69.3	6.7	8.5	7.1	0.0	6.55
	February	28.2	64.7	7.6	9.7	7.7	2.9	6.85
Harvesting	March	32.7	64.2	10.7	10.0	9.9	6.8	9.00
	April	33.6	46.2	9.4	9.5	12.3	9.8	10.00
Rest	May	34.4	81.5	7.42	10.0	12.2	0.0	12.23
	June	34.9	79.0	11.12	10.0	13.6	0.0	8.25

plant water demands. The drip system's operating time was calculated by considering the dripper discharge rate and the required water volume. Double laterals with 4 drippers per tree were placed 80 cm apart. The system was replicated four times, with water application tailored to the plants' needs. System specifications are detailed in Table 2, while plant height, canopy area, water application, and irrigation duration for 3rd to 7th year pomegranate orchards are summarized in Table 3.

2.4 | Soil and Water Analysis

The chemical, physical, and hydraulic properties of the soil and water at the experimental site were analyzed. The soils are stony and classified as marginal land, generally unsuitable for cultivation. Soil texture, comprising sand, silt, and clay, ranged from 44.18-61.14%, 25.87-34.90%, and 12.73-29.86%, respectively. The soil's pH and electrical conductivity (EC) were within permissible limits, at 8.69 and 0.31 dS m^{-1}, respectively. Organic carbon levels were medium to high, while $CaCO_3$ content was slight to medium-low at depths of 0-30 cm, 30-60 cm, and 60-90 cm (Table 4). Based on FAO guidelines (Ayers and Westcot, 1985), the irrigation water, classified as Class 2, was suitable for agriculture, with an EC of 0.93 dS m^{-1} and a residual sodium carbonate level of 2.2 meq L^{-1}.

2.5 | Pomegranate Evapotranspiration (ET_p)

Pomegranate farmers need information on the amount of irrigation to be applied in liters day^{-1} $tree^{-1}$ and the time required in hours for each pomegranate tree. Irrigation volume and time were estimated daily for pomegranate trees at 40%, 60%, 80%, and 100% irrigation levels using equation (1) (Meshram *et al.,* 2012):

TABLE 2 Physical condition of drip-irrigation and plants for the experiment in the field

Drip-irrigation parameters	Treatments			
	I_1	I_2	I_3	I_4
Number of laterals per row	Double	Double	Double	Double
Number of drippers per tree	4	4	4	4
Two drippers spacing (cm)	80	80	80	80
Dripper Discharge (LPH)	4	4	4	4
Distance between lateral from tree trunk (cm)	60	60	60	60

$$ET_p = \frac{(ET_r \times K_c \times WA \times A)}{IE} \quad ...(1)$$

Where, ET_p - Pomegranate evapotranspiration, $Ld^{-1}t^{-1}$; ET_r - Reference crop evapotranspiration, mm; K_c - Crop coefficient, fraction; WA - Wetted area, fraction; A - Area occupied by each tree, m^2; IE - Irrigation efficiency of the drip irrigation system (fraction).

Daily irrigation requirement were estimated for each phenological growth stage of crop.

2.5.1 | Estimation of reference crop evapotranspiration (ET_r)

The Penman-Monteith method is highly accurate to predict ET_r across various locations and climates (Allen *et al.,* 1998), monthly ET_r values calculated using eq. 2.

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)u_{2(e_s - e_a)}}{\Delta + \gamma(1 + 0.34u_2)} \quad ...(2)$$

TABLE 4 Chemical, physical and hydraulic properties of the soil profile of the experimental site

Chemical properties	Depths (cm)		
	0-30	30-60	60-90
pH	8.65	8.98	8.45
EC(dS m^{-1})	0.35	0.32	0.28
OC (%)	0.98	0.49	0.43
CaCo3 (%)	5.54	4.68	11.34
Available major nutrients (kg ha^{-1})			
N	297	224	144
P	112	74	53
K	786	722	432
Available micro-nutrients (ppm)			
Fe	3.13	3.59	4.44
Mn	9.16	6.45	6.96
Zn	4.57	1.39	1.17
Cu	15.6	4.59	5.66
Physical and Hydraulic properties			
Sand (%)	61.14	52.37	44.18
Silt (%)	25.87	34.90	25.96
Clay (%)	12.99	12.73	29.86
BD (Mg m^{-3})	1.68	1.78	1.52
HC(mm h^{-1})	9.8	5.8	14.9

Note: BD - Bulk density, HC - Hydraulic conductivity, EC - Electrical conductivity, OC - Organic carbon

TABLE 3 Plants growth parameters during study period

Ave. plant parameters	Age of the Orchards				
	3rd	4th	5th	6th	7th
Plant height (m)	1.20	1.80	2.30	2.50	2.70
Plant canopy area (m^2)	1.38	2.40	3.40	4.50	5.20
Amount of water ($Lday^{-1}tree^{-1}$)	1.1-8.8	2.5-10.6	2.6-23.9	4.0-32.2	5.7-50.7
Operating time (hrs)	0.13-1.1	0.31-1.33	0.16-1.49	0.25-2.01	0.35-3.16

Where, ET_r = Reference crop evapotranspiration, (mm day^{-1}); G = Soil heat flux density, (MJm^{-2} day^{-1}); R_n = Net radiation, ($MJm^{-2}day^{-1}$); T = Mean daily air temperature, (^0C); γ = Psychometric constant, (kPa^0C^{-1}); Δ = Slope of saturation vapour pressure curve, (kPa $^0C^{-1}$); e_s = Saturation vapour pressure at air temperature T, (kPa); e_a = Actual vapour pressure at dew point température, (kPa); u_2 = Average daily wind speed at 2 m height, (m sec^{-1}).

2.5.2 | Crop coefficient (K_c)

The K_c for various phonological stages of crop were estimated using the shaded area approach, calculated with eq. 3, designed for deciduous fruit crops (Gorantiwar *et al.,* 2011).

$$K_c = 0.014x + 0.08 \quad ...(3)$$

Where, K_c = Crop coefficient; x = Percentage of shaded area, (%).

2.5.3 | Shaded area approach

Pomegranate, a widely spaced fruit crop, typically takes 2-3 years to stabilize, necessitating cultivation in large lysimeters during this period. While accurate, this setup is both costly and time-consuming. To simplify the process, two representative pomegranate trees were selected for shaded area observations. Weekly measurements of the shaded area were taken at solar noon using specially prepared plywood boards (3.5 × 3.5 m) marked with a 20 × 20 cm grid, recording the total number of grids occupied.

2.5.4 | Irrigation time (hrs)

Irrigation time was calculated (4) (Gorantiwar *et al.,* 2011).

$$IT = \frac{WR}{DC} \quad ...(4)$$

Where, IT - Irrigation time (hr); WR - Water requirement ($Ld^{-1}t^{-1}$); DC - Dripper discharge capacity (Lhr^{-1}).

2.5.5 | Wetted area (WA)

The wetted area represents the proportion of the effective root zone relative to the total area. Canopy area, measured weekly at solar noon for all experimental trees, was used to computed the wetted area using eq. 5 (Gorantiwar *et al.,* 2011).

$$WA = SA/A \quad ...(5)$$

Where, SA - Shaded area of tree, m^2 and A - Area occupied each tree, m^2.

2.5.6 | Soil water content (SWC)

Soil moisture measurements were taken before and after irrigation for each treatment using the gravimetric method. SWC was assessed at three depths: 0-30 , 30-60, and 60-90 cm, converting gravimetric values to volumetric moisture based on bulk density. Only the SWC within the 0-90 cm depth range was considered for this study.

2.5.7 | Relative leaf water content (RLWC,%)

To determine relative leaf water content as a percentage, harvested leaflets were weighed, floated on deionized water for 4 to 6 hours, reweighed, and then oven-dried at 80°C for 12 hours, the relative to the amount of water in a saturated leaf is calculated by using method given in eq. 6.

$$RLWC\ (\%) = \frac{FM - DM}{SM - DM} \times 100 \quad ...(6)$$

Where, FM - Leaf fresh mass at the time of collection; SM - Leaf mass at saturated condition; DW - Sample dry mass.

2.5.8 | Water use efficiency (WUE)

From the observed data, *bahars* wise fruit yield per hectare and daily water requirement were calculated and WUE determined by using equation 7, (Hutton and Loveys, 2011).

$$WUE = \frac{\text{Yield (kg ha}^{-1})}{\text{Season wise WR (litres)}} \quad ...(7)$$

2.5.9 | Plant spread

Observations on vegetative growth and flowering parameters of pomegranate were recorded every 30 days for three randomly selected plants from each treatment.

2.5.10 | Leaf area index (LAI)

The LAI is a key measure of canopy structure, influenced by tree morphology, leaf orientation, and distribution. LAI was first defined in 1997 as the total one-sided area of photosynthetic tissue per unit of ground surface area. It is now understood as the ratio of the leaf area of a plant to the ground area occupied, as represented in eq. 8.

$$LAI = \frac{TLAP}{GAP} \quad ...(8)$$

Where, LAI - Leaf area index, (Dimensionless); TLAP - Total leaf area of the plant, (m^2); GAP - Ground area occupied by the plant (m^2).

2.5.11 | Fruit quality, sunburn fruit cracking and root distribution parameters

Fruit quality was evaluated based on sunburn percentage, peel color, aril color, aril weight, and juice content. Sunburn percentage was calculated as the ratio of sunburned fruits to the total fruits on each plant. Peel and aril color were measured with a Hunter Color Lab (Model No. LX16244, Hunter Associates Laboratory, Virginia), assessing

CIE values for lightness ('L'), redness ('a'), and yellowness ('b'), with five replications. Aril weight (g) and juice content (ml) were measured from the samples.

2.6 | Statistical Analysis

The data were statistically analyzed according to Gomez and Gomez (1984), with significant differences between treatment means determined at a 5% confidence level using the WASP (version 2.0).

3 | RESULTS AND DISCUSSION

3.1 | Climate During Crop Growth Period and Effect of Climate on Growth Period of Pomegranate

Daily climatic data of 1,200 days at the ICAR-NRCP experimental site at Solapur, covering September 2015 to April 2020, were analyzed to calculate the reference ET_r using the Penman-Monteith method. The average monthly ET_r, in millimeters, is presented in Table 1. Variations in climatic parameters over time led to fluctuations in the estimated ET_r and atmospheric water demand. Table 1 shows that rainfall was higher and temperatures lower in June (harvesting), benefiting fruit and aril color development. From Nov to Feb (new leaf initiation, development, and maturity), rainfall was lower. The average *Hasta Bahar* rainfall was 243.30 mm. ET_r peaked between February and June and was lowest from November to January. During the study, average ET_r values for pomegranate stages were 213.5 mm (new leaf initiation), 410.2 mm (development), 1,019.2 mm (maturity), and 828.1 mm (harvesting). The annual average ET_r was 2,469.6 mm, with daily values ranging from 3.85 mm (Nov) to 12.00 mm (May).

3.2 | Phenological Stages, Crop Coefficient and Wetted Area

According to irrigation scheduling for horticultural crops, six key irrigation stages were identified: stress, new leaf initiation, crop development, maturity, harvesting, and rest period, lasting 62, 25, 92, 64, 61, and 61 days, respectively (Fig. 1). A total of 240 days were required for the complete phenological cycle in the *Hasta bahar*. Bhagawa *cv.,* took over 200 days to reach harvesting. Age-wise variation in K_c and WA values for different growth stages of pomegranate trees are depicted in Fig. 1 and 2. On average, K_c and WA values ranged from 0.20-0.99 and 0.30-0.60, respectively, for 3rd to 7th year-old pomegranate trees during new leaf initiation, development, maturity, and harvesting stages. K_c and WA were low during the initial growth stage, increased during development, remained constant during crop maturity, and decreased drastically during the crop harvesting stage. The trends observed in K_c and WA values aligned with previous studies by Gorantiwar *et al.* (2011).

3.4 | Pomegranate Evapotranspiration (ET_p)

The actual water applied to pomegranate trees during the five-year study is shown in Table 3, illustrating significant variation in water requirements due to changing weather conditions and different growth stages. As indicated in Fig. 4, water demand fluctuates across irrigation levels during phenological stages in the *Hasta bahar*. Drip irrigation at 40%, 60%, and 80% under partial root-zone drying (with 20% shifting of irrigation to the drying side) ranged from 2.8 to 26.5, 4.0 to 42.8, and 8.5 to 48.0 liters day^{-1}tree^{-1} for 3rd to 7th year pomegranate trees. This variation is influenced by

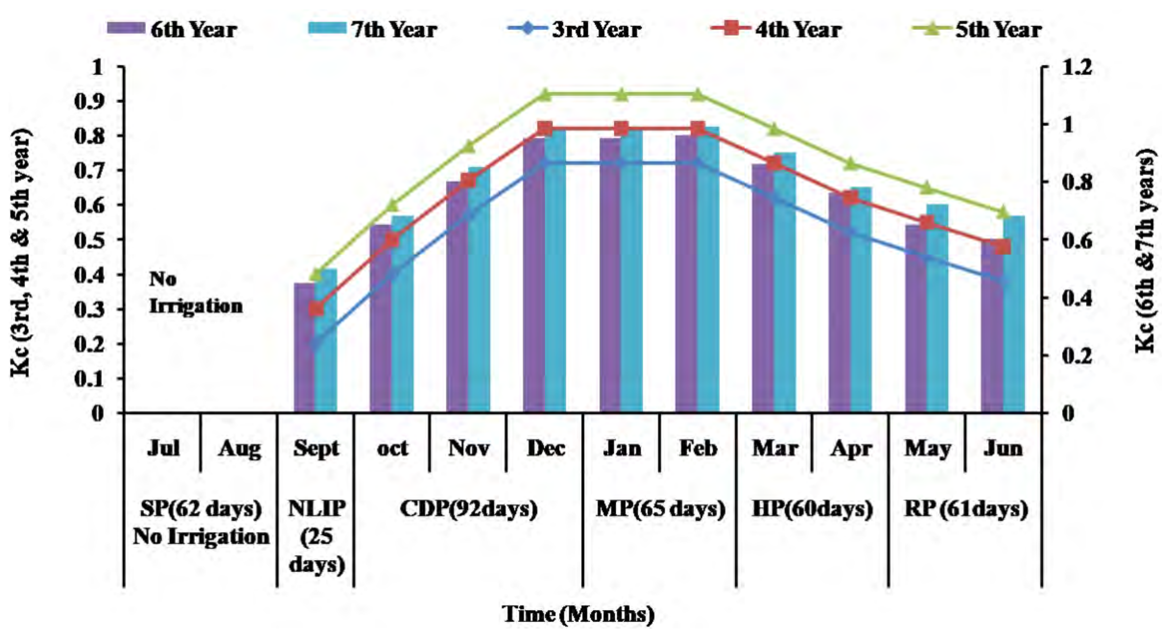

FIGURE 1 Average crop coefficient (K_c) for 3rd to 7th old age pomegranate orchards during 2015-2016 to 2019-2020

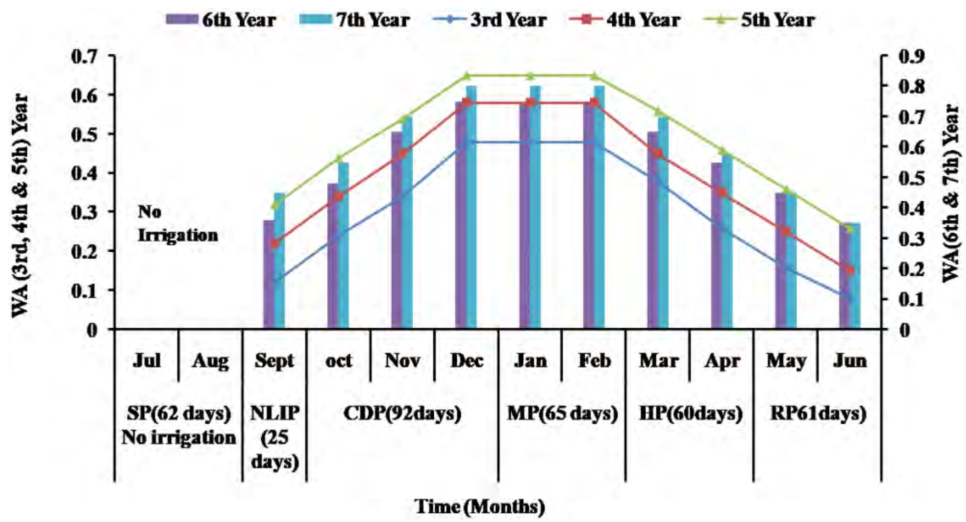

FIGURE 2 SMC values in % age for 3rd to 7th old age pomegranate trees during 2015-2016 to 2019-2020

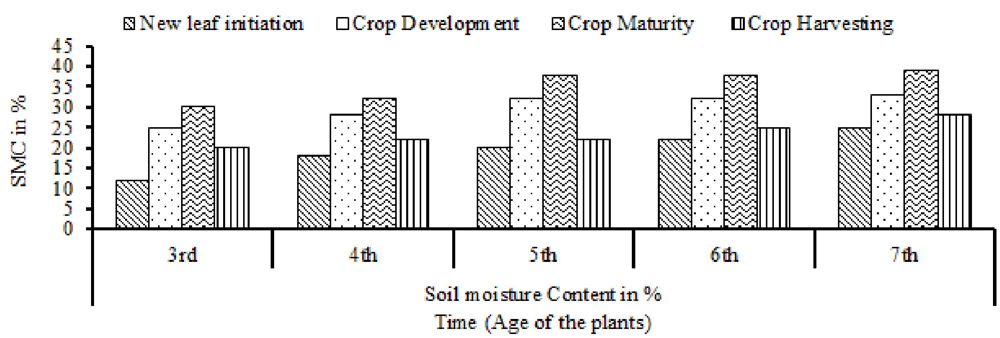

FIGURE 3 Average wetted area (WA) for 3rd to 7th old age pomegranate trees during 2015-2016 to 2019-2020

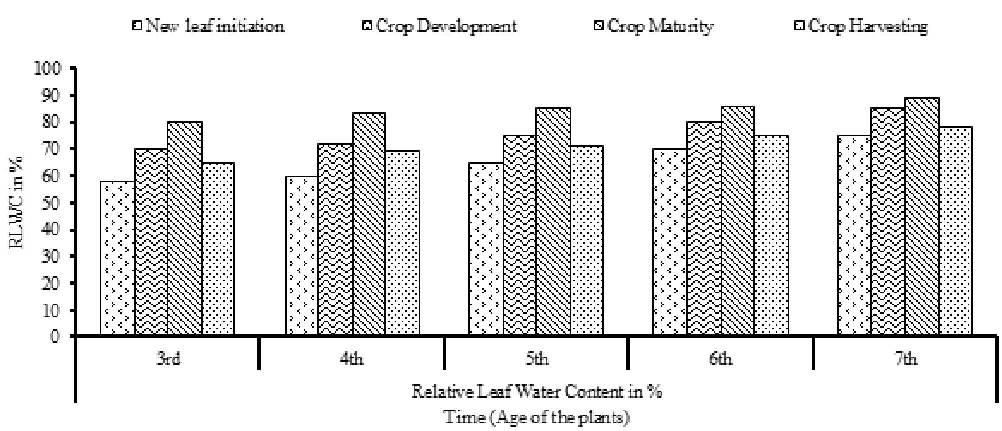

FIGURE 4 RLWC values in % age for best irrigation level of PRZDI for 3rd to 7th year old age pomegranate

ET_r, K_c, and WA values (Meshram *et al.,* 2012). Well-distributed rainfall in June typically reduced irrigation needs. Total water applied per treebahar^{-1} at 40%, 60%, and 80% ET_p was 3,328.0, 8,128.8, and 13,364.3 liters, respectively, for 3rd to 7th year trees, with a 20% irrigation shift to the drying side. These results support optimizing partial root-zone drying in pomegranate orchards.

3.4.1 | Vegetative growth

The data on vegetative growth, as shown in Table 5, reveal that varying irrigation levels significantly influence plant growth parameters compared to the control group. Treatments I_1*T_4, I_2*T_1, and I_3*T_1, corresponding to irrigation levels of 40%, 60%, and 80% with a 20%*ASMD, resulted in increased plant height, spread, and leaf area

TABLE 5 Effect of partial root zone drying irrigation system on growths characteristics for 3rd to 7th year pomegranate tree

Treatments	Plant height (m)					LAI (%)					Plant spread (m)									
	3rd	4th	5th	6th	7th	3rd	4th	5th	6th	7th	3rd		4th		5th		6th		7th	
											E-W	N-S	E-W	N-S	E-W	N-S	E-W	N-S	E-W	N-S
Irrigation levels																				
I_1*40%	1.59	1.61	1.62	1.65	1.69	2.57	2.45	2.68	2.8	3.3	1.33	1.34	1.55	1.63	1.73	1.66	1.61	1.72	1.58	1.66
I_2*60%	1.61	1.63	1.64	1.66	1.71	2.69	2.57	3.02	3.0	3.4	1.34	1.39	1.58	1.65	1.77	1.69	1.56	1.76	1.65	1.75
I_3*80%	1.62	1.64	1.65	1.67	1.70	2.87	3.23	3.00	3.1	3.5	1.35	1.52	1.58	1.68	1.76	1.70	1.61	1.77	1.65	1.75
I_4*100%	1.66	1.67	1.69	1.72	1.77	2.88	3.34	3.19	3.2	3.7	1.37	1.56	1.66	1.69	1.87	1.72	1.65	1.76	1.63	1.69
Shifting of irrigation at drying side (ASMD)																				
T_1- 20%	1.66	2.23	2.25	2.28	2.33	3.58	3.50	3.77	3.7	4.1	1.84	1.99	1.93	2.26	2.42	2.14	2.22	2.23	2.27	2.39
T_2-40%	1.63	2.18	2.19	2.23	2.28	3.65	3.88	3.94	4.0	4.2	1.78	1.96	2.21	2.22	2.41	2.27	2.12	2.36	2.23	2.24
T_3-60%	1.56	2.10	2.14	2.19	2.21	3.78	4.22	4.17	4.4	4.9	1.72	1.87	2.22	2.17	2.30	2.30	2.04	2.42	2.01	2.22
Main (CD 5%)	4.83	4.30	3.98	3.44	3.70	0.03	0.07	0.06	0.08	0.07	0.021	0.01	0.017	0.04	0.14	0.02	0.080	0.03	0.046	0.03
Sub-main (CD 5%)	10.8	10.8	10.88	10.62	12.08	0.07	0.15	0.13	0.14	0.19	0.037	0.05	0.096	0.07	0.188	0.09	0.088	0.08	0.095	0.08
Main*Sub-main	21.6	21.6	21.76	21.25	24.16	0.13	0.32	0.25	0.27	0.42	0.074	0.11	0.193	0.14	0.377	0.19	0.166	0.14	0.191	0.16
CV(a)	3.3	2.89	2.62	2.22	2.33	1.16	2.57	2.19	2.9	2.3	1.71	1.12	1.02	3.14	9.01	2.72	5.65	1.78	3.03	1.41
CV(b)	9.2	9.10	9.06	8.68	9.63	3.03	7.34	5.70	5.9	8.1	3.7	4.75	8.33	0.58	14.61	8.14	6.88	5.59	8.39	5.93

Note: I_1- 40% Irrigation, I_2- 60% Irrigation, I_3- 80% Irrigation, I_4- 100% Irrigation, T_1- 20% ASMD, T_2- 40% ASMD and T_3- 60% ASMD (Plant Spacing - 4.5×2.0 m)

index. Adequate irrigation during critical phenological stages enhances the nutritional status in the root zone, promoting overall plant growth. The greatest improvements in plant height, spread, and leaf area index occurred at the 100% irrigation level with a 20% shift to the drying side for 3rd to 7th year pomegranate trees. It is indicates that pomegranates can better tolerate drought stress when applied selectively to specific parts of the plant. PRZDI has emerged as an effective water-saving strategy that does not compromise tree growth. Furthermore, reduced vegetative growth and canopy area can enhance fruit exposure to sunlight, facilitating the remobilization of assimilates from vegetative tissues to fruits, ultimately improving yield and quality (Dos Santos *et al.,* 2007).

3.4.2 | Fruit quality parameters, fruit cracking and root distribution pattern

Table 6 shows that PRZDI significantly influenced juice content, with treatment I_4 recording 39%, which was on par with T_3. However, the highest TSS: acid ratio (16.50) was observed in T_4, along with the maximum fruit cracking (13.25%) and sunburn (9.9%). This level of irrigation minimized plant growth and reduced carbohydrate accumulation in the fruit during subsequent development. The maximum rooting depth reached 1.4 m, with most roots concentrated in the first 30 to 50 cm. In asymmetric cases, root densities were highest under 100%*ET_p, followed by 80%, 60%, and 40%*ET_p with 20%* ASMD irrigation shifting. Roots were distributed throughout the soil profile, and high root intensities often coincided with localized organic matter. It can be concluded that 100% *ET_p has a significant effect on root development.

3.4.3 | Soil water content

PRZDI resulted in decreased moisture content, while the highest plant height, branch count, and flower numbers were recorded in the treatment irrigated at 100%*ET_p with a 20% *ASMD. Fig. 3 illustrates the soil moisture content under PRZDI. The avg. soil water at phenological stages ranged from 17.29% to 36.12%. During new leaf initiation, maximum soil moisture across treatments varied from 17.29% to 19.24%. This increased to 22.36% to 26.17% during crop development, peaking at 32.34% to 36.12% at maturity, before decreasing to 20.78% to 24.22% during harvesting for 3rd to 7th year-old plants. SWC, % rose from the new leaf initiation to fruit maturity due to increased irrigation but decreased from maturity to harvesting as fruits were picked and irrigation reduced.

3.4.4 | Relative leaf water content

The ratios of fresh mass to dry mass and dry mass to saturated mass indicate how these components contribute to overall changes. RLWC under PRZDI is shown in Fig. 4.

TABLE 6 Effect of partial root zone drying irrigation system on fruit quality parameters and fruit cracking for 3rd to 7th year pomegranate tree

Treatments	Juice Content (%)					TSS: Acid ratio					Fruit cracking (%)					Sun burn (%)				
	3rd	4th	5th	6th	7th	3rd	4th	5th	6th	7th	3rd	4th	5th	6th	7th	3rd	4th	5th	6th	7th
Irrigation levels																				
I_1*40%	30.08	33.0	35.4	32.8	32.8	16.0	15.5	16.2	16.9	16.4	7.3	7.7	7.8	10.0	8.3	8.7	8.3	8.0	8.9	9.5
I_2*60%	30.50	33.5	34.4	33.4	34.7	15.7	15.3	16.6	15.8	16.3	8.3	7.1	8.5	7.3	9.3	7.1	7.5	9.4	9.6	10
I_3*80%	30.83	34.5	33.7	34.1	34.0	15.5	16.2	16.5	16.4	16.1	8.1	6.6	6.9	8.8	8.9	8.0	8.0	8.1	9.6	10
I_4*100%	30.08	34.8	34.1	32.2	34.0	15.3	15.4	16.6	16.6	15.8	8.0	8.1	7.5	8.2	8.4	8.8	7.4	11	9.5	13
Shifting of irrigation at drying side (ASMD)																				
T_1-20%	39.75	43.7	45.3	43.0	44.2	20.4	20.9	22.2	22.1	22.0	8.5	8.4	7.8	9.0	11.8	13.4	12.5	14	13	16
T_2-40%	40.58	45.4	46.3	44.3	45.8	20.7	20.5	22.1	22.1	21.4	10.8	9.2	8.8	10.2	8.7	9.4	10.2	11	12	14
T_3-60%	41.17	46.7	45.9	45.2	45.5	21.5	20.9	21.6	21.5	21.2	12.4	11.9	13.9	15.1	14.3	9.8	8.5	10	11	13
Main (CD5%)	0.54	0.28	0.82	0.91	1.13	0.41	0.22	0.60	0.32	0.71	0.33	0.69	1.28	1.21	1.03	1.40	1.59	1.46	1.39	1.99
Sub-main (CD5%)	1.19	1.31	2.17	2.71	3.03	0.68	0.69	0.67	0.67	1.01	0.53	1.35	1.49	1.51	1.94	1.45	1.65	2.18	2.01	1.95
Main*Sub-main	2.38	2.63	4.34	5.42	6.06	1.36	1.39	1.35	1.34	2.03	1.06	2.70	2.98	3.02	3.88	2.91	3.30	4.37	4.02	3.9
CV(a)	1.81	0.97	2.59	3.01	3.62	2.89	1.55	3.99	2.12	4.84	4.60	10.15	18.21	15.33	12.8	18.66	22.18	17.3	16.7	19.3
CV(b)	5.37	5.30	8.66	11.22	12.27	5.97	6.12	5.63	5.60	8.63	9.22	25.15	26.75	24.19	30.5	24.49	29.10	32.6	29.3	23.9

Note: I_1 - 40% Irrigation, I_2 - 60% Irrigation, I_3 - 80% Irrigation, I_4 - 100% Irrigation, T_1 - 20% ASMD, T_2 - 40% ASMD and T_3 - 60% ASMD (Plant Spacing - 4.5×2.0 m)

RLWC percentages ranged from 60.3% to 80.5%. In the best treatments, RLWC during the new leaf initiation period varied from 60.24% to 64.24%, while during crop development, it ranged from 70.25% to 74.25%. At maturity, RLWC increased to between 80.24% and 83.15%, before decreasing to 65.36% to 68.95% at harvesting due to reduced irrigation and leaf drop.

3.4.5 | Water use efficiency (WUE)

WUE of pomegranate was calculated and presented in Table 7. The influence of PRDZI is significant; yield increments were recorded while saving irrigation water by up to 60%, 40%, and 20% for 3rd to 7th year pomegranate trees. Furthermore, the PRZDI significantly impacted mean yield, which showed considerable reductions in absolute quantities compared to other irrigation levels. Specifically, irrigation level I_1 and shifting level T_1 achieved a mean yield of 14.5 kg tree^{-1}, comparable to I_2*T_2.

Drip irrigation at the 60% and 80% levels (T_2) demonstrated improved yield attributes, as consistent moisture levels in the soil enabled active root growth throughout the growth phase. This ensured optimum moisture availability and effective translocation of nutrients, enhancing fruit growth and quality. Table 7 further illustrates that varying irrigation levels, along with shifts in ASMD, significantly influenced the WUE of pomegranate. The maximum WUE values were recorded at 2.91, 2.68, and 2.55 kg/m³ for 40%, 60%, and 80% ASMD, respectively, for 3rd to 7th year pomegranate trees in *Hasta bahar*. Earlier research by Abd El-Samad (2005) noted that increased WUE and fruit yield result from reductions in crop evapotranspiration and deep percolation. Similar, findings by Consoli *et al.* (2017) indicated that improved peel color in apple fruits under PRZDI correlated with canopy structure changes, which also enhanced yield and WUE.

4 | CONCLUSIONS

This study highlights the significant effects of PRZDI on the growth and yield of pomegranate (Bhagawa *cv.*), particularly in water-limited environments. The findings indicate that PRZDI effectively reduces fruit cracking by ensuring that irrigation replenishes evapotranspiration losses. The reference crop evapotranspiration, crop coefficient, wetted area, and water requirement varied from 4.58 to 9.95 mm, 0.24 to 0.90, 0.40 to 0.50, and 10.5 to 37.5 Lday^{-1}tree^{-1}, respectively, during the growth stage. Pomegranate trees consumed an average of 5,890 to 9,360 liters bahar^{-1} at 40%, 60%, and 80% of evapotranspiration (ET_p) irrigation levels, with a 20% soil moisture deficit. The variation in ET_p, crop coefficient, and water requirements underscores the precise irrigation needs of pomegranates. Overall, the WUE ranged from 2.52 to 3.93 kg m^{-3} across different years and irrigation levels. Thus, applying 40-80% ET_p with a 20% moisture

TABLE 7 Effect of partial root zone drying and best shifting of irrigation on yield attributes and water use efficiency for 3rd to 7th year pomegranate tree

1	2					3					(4 = 3*2)					5					6 = (4/2)				
Treatments	Nos. of fruit per tr. (Nos.)					Av. fruit weight (gms)					Yield (kg tree^{-1})					WU (m^3)					WUE (kg m^{-3})				
	3rd	4th	5th	6th	7th	3rd	4th	5th	6th	7th	3rd	4th	5th	6th	7th	3rd	4th	5th	6th	7th	3rd	4th	5th	6th	7th
Irrigation levels																									
I_1*40%	34.83	44.83	62.42	71.92	78.33	299.33	291.58	337.17	313.58	308.75	12.94	13.02	21.14	22.58	24.19	5.89	7.02	9.53	9.13	9.36	2.58	2.17	1.53	1.13	1.83
I_2*60%	38.50	47.42	64.17	69.08	73.75	283.33	281.58	293.00	337.17	297.58	10.95	13.42	18.83	23.16	21.96	5.89	7.02	9.53	9.13	9.36	2.18	3.25	2.52	2.12	2.69
I_3*80%	44.42	44.50	69.25	71.33	70.75	289.17	299.42	312.42	311.05	302.33	10.88	13.50	21.69	22.20	21.35	5.89	7.02	9.53	9.13	9.36	1.99	2.01	2.15	3.93	3.69
I_4*100%	41.58	45.25	60.75	71.92	72.25	274.58	275.83	295.42	303.83	306.50	11.48	12.58	18.01	21.84	22.13	5.89	7.02	9.53	9.13	9.36	2.32	1.88	2.20	2.73	2.22
Shifting of irrigation at drying side (ASMD)																									
T_1- 20%	60.58	72.50	91.33	93.00	95.00	397.00	386.00	411.33	438.63	399.33	17.96	17.96	28.28	30.53	28.41	5.05	6.01	8.16	7.83	8.02	4.92	4.80	4.67	5.39	4.90
T_2-40%	48.67	58.67	86.17	94.00	99.17	378.92	380.25	415.25	415.92	409.67	13.81	13.81	26.82	29.24	30.50	7.85	9.35	12.7	12.1	12.4	2.39	2.43	2.90	3.28	3.31
T_3-60%	50.08	50.83	79.08	97.25	100.92	370.50	382.17	411.42	411.08	406.17	14.04	14.04	24.58	30.01	30.73	10.6	12.6	17.2	16.5	16.9	1.76	1.56	1.93	2.46	2.43
Main (CD 5%)	5.54	4.91	7.65	4.12	5.77	14.02	21.36	12.25	34.15	11.14	2.01	2.25	2.32	2.01	1.23	0.01	1.0	0.02	7.19	8.25	0.40	0.410	0.301	0.29	0.181
Sub-main (CD 5%)	3.62	4.62	6.92	5.49	5.40	15.21	29.35	17.35	15.31	12.22	2.03	2.26	2.45	2.06	1.32	0.45	0.5	0.55	0.70	0.85	0.38	0.336	0.391	0.451	0.412
Main*Sub-main	7.23	9.31	13.84	10.99	10.81	31.45	38.15	35.5	31.25	25.65	4.25	4.05	5.22	4.01	3.02	0.91	1.24	1.35	1.41	1.52	0.76	0.673	0.78	0.912	0.831
CV(a)	15.07	11.80	12.92	6.28	8.74	5.30	7.91	4.25	11.65	3.58	20.12	20.12	12.35	11.25	8.12	0.16	1.0	0.18	8.5	9.15	19.21	20.15	14.22	11.32	7.51
CV(b)	12.43	14.15	14.78	10.59	10.04	7.44	9.25	7.55	6.45	5.35	21.65	21.25	19.65	12.45	10.25	10.6	10.2	11.3	10.6	11.2	23.15	21.14	22.14	22.15	21.25

Note: I_1- 40% Irrigation, I_2- 60% Irrigation, I_3- 80% Irrigation, I_4- 100% Irrigation, T_1- 20% ASMD, T_2- 40% ASMD and T_3- 60% ASMD (Plant Spacing - 4.5×2.0 m)

deficit is a viable water-saving strategy, optimizing water consumption while maintaining crop yield and quality.

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DATA AVAILABILITY STATEMENT

Data will be made available on request.

CONFLICT OF INTEREST

The authors declare that there are no known competing financial interests or personal relationships that could have influenced the research reported in this paper.

AUTHOR'S CONTRIBUTION

The research conceptualization was carried out by DTM and ADU. The experimental design was developed by DTM and SDG. DTM, AKN, and PP contributed the experimental materials. The execution of field and laboratory experiments, along with data collection, was conducted by DTM, AKN, and PP. Data analysis and interpretation were performed by DTM, PP, and ADU. The manuscript was prepared by DTM and ADU. All authors reviewed and contributed to earlier versions and approved the final version.

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