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Comparative effects of alternate partial root-zone drying and conventional deficit irrigation on growth and yield of field grown maize (*Zea mays* L.) hybrid

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Abstract: A field experiment was conducted to study the effects of partial root-zone drying on growth and yield of maize (*Zea mays* L.), grown under drip irrigation system. Experimental treatments included alternate partial root-zone drying (APRD), fixed partial root-zone drying (FPRD), deficit irrigation (DI) and full irrigation (FI). Soil moisture in root-zone of plants under FI treatment was kept close to the field capacity while plants under other treatments were irrigated with 50% of the water applied to FI throughout the growing season. Water deficit under APRD, FPRD and DI treatments caused significant inhibition of plant growth by affecting plant height, leaf area, and produced biomass. Number of leaves per plant remained at par with each other for plants under FI and APRD treatment, however, significant reduction in plant leaves was observed in FPRD and DI treatments. Water deficit in APRD, FPRD and DI treatment decreased grain yield per plant by 14.44%, 27.52% and 29.29% respectively. The difference between FPRD and DI was not significant either in the vegetative growth or grain yield. Data indicated maximum water use efficiency, higher grain yield, and better vegetative growth in plants under APRD irrigation scheme when compared to FPRD and DI.

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1. Introduction

Water scarcity and the growing competition for better portion of the fresh water among different sectors of the society like agriculture, industries and environmental habitats has forced irrigation experts to device strategies for enhanced water use efficiency (Baber et al., 2015). Several suggestions have been made by water and irrigation experts to achieve maximum production under irrigated agriculture through utilizing available water efficiently, among those the most common is deficit irrigation scheduling (Makau et al., 2014).

Water is crucial factor for crop production especially under arid and semi-arid agro-climatic regions. Changing climate and ever increasing population seriously threatening availability of water. Water stress is one of the most yield limiting factor for maize crop (Paudyal et al., 2001), as it has negative influence on growth, development and physiological processes of maize plant (Cakir, 2004), including reduction in leaf area (Pandey et al., 2000), plant height, impaired cell division and expansion of leaves (Raymond et al., 2003) and finally lead to reduction in biomass and grain yield (Payero et al., 2009). Lower water use efficiencies of agricultural production system further aggravates water crisis (Yin et al., 2014).

It is believed that, identification of relatively drought resistance crop growth stages and reduction of evapotranspiration during those stages of plant growth through deficit irrigation results into enhanced crop productivity under limited water conditions (Jalota et al., 2006). Under deficit irrigation, not only evapotranspiration is reduced but plants are also encouraged to enhance root growth to extract soil moisture beyond readily available water. Increased crop water use efficiency (WUE) through deficit irrigation is achieved either by reducing the amount of water during each irrigation or by reducing the number of irrigation events (Kirda, 2002). However, growers find difficulty in using deficit irrigation scheduling effectively due to lake of prior knowledge about sensitive crop growth stages. Further, deliberate water deficit sustained by plants under deficit irrigation scheduling can consequently lead to yield reduction up to some extent (Zhang et al., 2004).

Another irrigation technique used to enhance WUE is partial root-zone irrigation (PRI) or partial root-zone drying (PRD). PRD have been developed as an agronomic practice for more efficient use of the limited water resources (Kirda et al., 2004; Mingo et al., 2004; Zegbe et al., 2004). PRD technique involves exposure of one half of plant root system to drying soil conditions while the other half is supplied with water quantity enough for plant requirements (Sepaskhah and Ahmadi, 2010; Stikic et al., 2003). Theoretical backgrounds involved in the development of PRD technique of irrigation include. (1) Widely opened stomata of fully irrigated plants contribute to water loss through leaf transpiration and small narrowing of these stomatal openings can reduce transpiration substantially without affecting photosynthesis. (2) Root sourced signals from drying part of soil in response to water stress can inhabit stomatal function thus reduce water loss (Kang and Zhang, 2004). As during exposure of plant roots to drying cycles, stomatal regulation is controlled by root oriented chemical signals targeting the leaves (Tardieu and Davies, 1992).Earlier studies indicated that PRD reduced transpiration and helped to maintain higher level of photosynthesis (Zegbe et al., 2004).

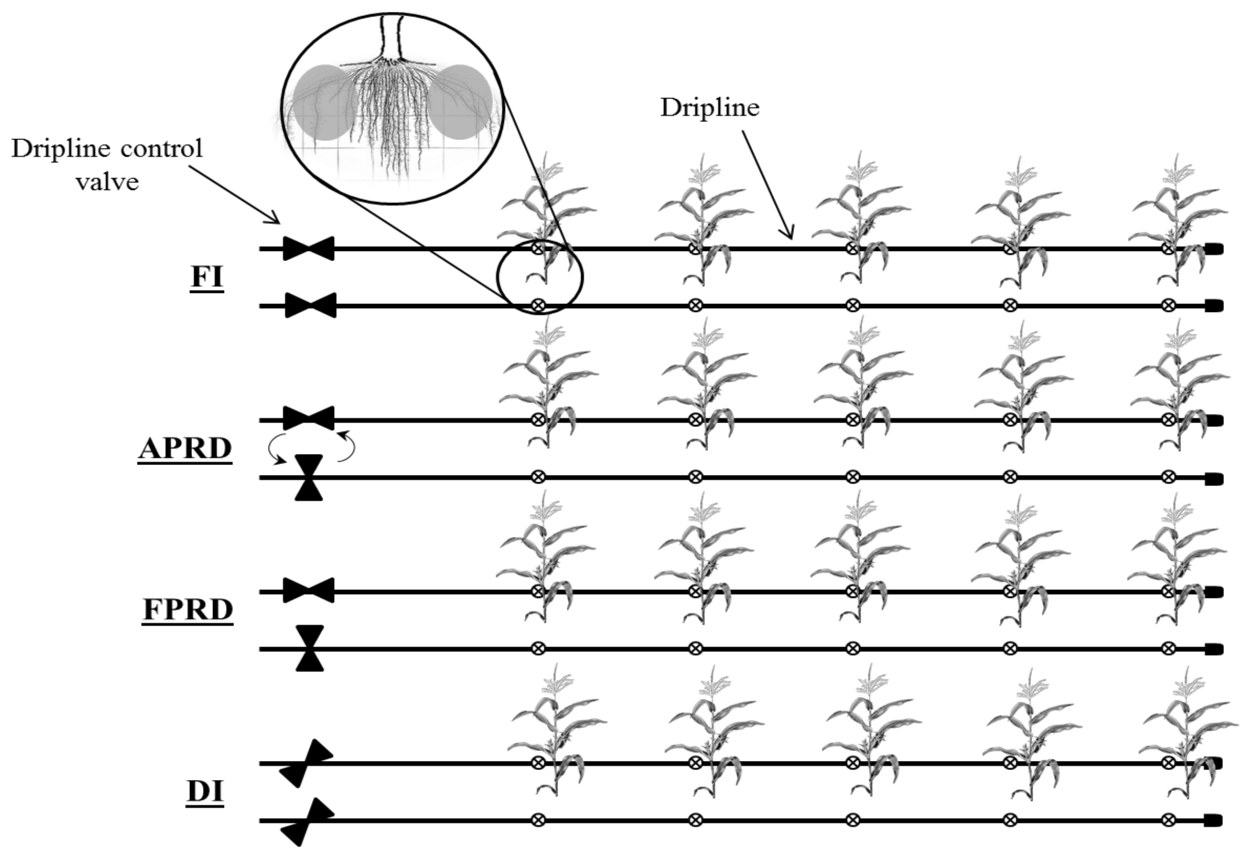

Fig. 1. Description of experimental design. Note: For different deficit irrigation strategies two driplines, each on one side of plant row, were placed. For FI treatment; both sides of the plant roots were fully irrigated, APRD; irrigated and non irrigated sides were switched, FPRD; only one fixed side of the plants was irrigated and for DI; both sides of the plant roots were irriagted by dividing equally the amount of water to be applied.

PRD technique can be applied in two different ways, i.e. alternate partial root-zone drying (APRD) and fixed partial root-zone drying (FPRD). In APRD, irrigation is swapped between two different halves of root-zone and the frequency of rotation depends on crop water requirement and soil drying rate. On the other hand a fixed half of root-zone is irrigated and other half is kept dry throughout the grown season in FPRD. It is expected that PRD may increase irrigation water use efficiency (IWUE) and thereby reduce irrigation water requirement, especially in regions facing water scarcity. Early field tests of the new evolving irrigation practice were done on grapevines in Australia where IWUE was doubled with better quality grapes without significant yield reduction (Dry and Loveys, 1998).

Recent results in field grown maize (Kang et al., 2000a), pot grown pepper (Kang et al., 2001) and pear orchard (Kang et al., 2002) confirmed earlier findings of increase in IWUE without compromising crop yield. However PRD has so far been tested only in a few crop species and growing conditions. The objective of this study was therefore to assess comparative yield responses of field grown maize under both techniques of PRD i.e. APRD and FPRD as well as under conventional deficit irrigation in maize.

2. Materials and Methods

2.1 Experimental Materials and Design

Maize (Zea *mays* L.) hybrid Hycorn-984 was used for the field experiment conducted during maize growing season. Soil type of experimental plot was clay with 8.48 pH, 2.45 dSm^{-1} ECw and 0.4% sodium absorption ratio. The irrigation water used had 7.82 pH, 1.12 dSm^{-1} ECw and 0.4% sodium absorption ratio.

At field capacity and permanent wilting point the soil could hold respectively 4.8 and 2.6 inches per foot water, so the available water to plant in soil amounted 2.2 inches per foot. Maize plants were grown in rows 80 cm apart and 10 m long and plant to plant distance was maintained 30 cm as illustrated in Fig. 1.

Experimental treatments were based on different irrigation techniques including full irrigation (FI) which was used as control, alternate partial root-zone drying (APRD), fixed partial root-zone drying (FPRD) and deficit irrigation (DI). Each experimental treatment was replicated five times, each in a separate row. For irrigation, two drip lines were set, one on each side of plant row providing each plant have two dippers, each with flow rate of 4 liters per hour.

Moisture in root-zone of FI treatment was kept close to the field capacity while for all other treatments 50% of the water quantity applied to FI treatment was used throughout the growing season, while the irrigation frequency was kept same in all experimental treatments. In APRD treatment irrigation was applied to one side of the plant row while soil moisture level in the other side decreased fast, generally two consecutive irrigations were applied to one side before shifting to another.

On the other hand in FPRD a fixed side of plant row was irrigated throughout the growing season. Further, for DI treatment irrigation was supplied to both sides of the plant rows; however during 12 leaves stage to blister kernel stage, DI treatment received irrigation water quantity equivalent to 60% of the water supplied to FI treatment and it was amounted 40% during the rest of the plant growth. The experimental plot was covered with rain shelter to protect plants from occasional rain. From sowing up to 12 leaf stage soil depth of 2 feet was kept at field capacity for good root development and from 12 leaf stage onward soil depth of 3 feet was maintained at field capacity.

As it is reported that corn, throughout its growing season obtains 90% water from upper three feet of its root-zone (Rhoads and Yonts, 2000). To monitor soil water tension in the root-zone, tensiometers were installed mid-way between the dripper and plant roots at 30 cm and 60 cm soil depth. The readings of the shallower tensiometers were used to observe the time for the start of irrigation while the readings of the deeper tensiometer were used to avoid over irrigation. Soil water tension in the root-zone of FI treatment was managed between 50centibars and 70centibars (Ratliff et al., 1983).

Water use efficiency was used to evaluate comparative benefits of the irrigation treatments. Grain yield water use efficiency (WUEy) and total dry biomass (shoot+roots) water use efficiency (WUEb) were calculated by using the following equation (Viets, 1962):

$$WUEy = \frac{\text{Economic yield}}{\text{water used to produce the yield}} \quad [1]$$

and

$$WUEb = \frac{\text{Dry biomass}}{\text{water used to produce the biomass}} \quad [2]$$

Table 1 Number of irrigations and irrigation water quantity applied to maize plants subjected to different irrigation strategies during their growth.

No.	Growth Stages	Days to reach the stage	No. of irrigations	FI (inches)	APRD (inches)	FPRD (inches)	DI (inches)
1	4th leaf	15	2	1.76	0.88	0.88	0.704
2	8thleaf	15	3	2.64	1.32	1.32	1.056
3	12th leaf	10	3	2.64	1.32	1.32	1.056
4	Early tasseling	10	3	3.96	1.98	1.98	2.376
5	Silking	10	4	5.28	2.64	2.64	3.168
6	Blister kernel	10	3	3.96	1.98	1.98	2.376
7	Beginning dent	10	2	2.64	1.32	1.32	1.056
8	Full dent	22	3	3.96	1.98	1.98	1.584
9	Maturity	28	2	2.64	1.32	1.32	1.056
	Total	**130**	**25**	**29.48**	**14.74**	**14.74**	**14.432**

Notes: Treatments include: full irrigation (FI); alternate partial root-zone drying (APRD); fixed partial root-zone drying (FPRD) and deficit irrigation (DI).

If crop produce is expressed in $g.m^{-2}$ and the water use is expressed in mm, then WUE has units of $kg.m^{-3}$ on a unit water volume basis. Further at physiological maturity, morphological and yield characteristics of all four treatments were recorded for plant growth assessment.

2.2 Statistical analysis

SPSS 16.0 software (SPSS Inc., Chicago, USA) was used for one-way analysis of variance to identify significant differences among the treatments. The treatment means were compared using Student-Newman-Keuls test at a significance level of $p<0.05$.

3. Results and Discussion

3.1 Quantity of irrigation applied different growth stages

The total quantity of water applied throughout the season was 29.48 inches for FI, 14.74 inches for DI and 14.43 inches for both APRD and FPRD treatments. Quantity of irrigation water for both APRD and FPRD treatments was always half of the water applied to FI treatment (Table 1).

Water applied in DI treatment from sowing to 12th leaf stage and from beginning of the dent till maturity was 40% of the water applied to FI and during 12 leaf stage to the blister kernel stage it was 60% of the water applied to FI treatment. As reproductive stage is the single most important stage to avoid water stress (Benham, 1998). Irrigation water applied to FI, APRD, FPRD and DI treatments from 12 leaf stage to blister kernel stage was13.2, 6.6, 6.6 and 7.92 inches, so during this period DI treatment received 18.18% more water than APRD and FPRD. Whereas during the rest of plant growth, plants of DI treatment received 22.22% less water when compared to the plants of APRD and FPRD treatments.

3.2 Water use efficiency:

Highest WUEy was achieved under APRD (2.03) and it was recorded minimum under FI treatment (1.17), as shown in Fig. 2. WUEy between FPRD and DI treatments was statistically comparable and significantly lower than APRD treatment. Similar results were reported in maize under furrow, hot pepper in pot experiment and in greenhouse grown hot pepper (Kang et al., 2001, 2000a; Shao et al., 2008). Similar trend was observed for WUEb, which was significantly higher in APRD, FPRD and DI when compared to FI. APRD treatment; with 50% less water than required by the plants, increased WUEy by 53.65% and WUEb by 57.31%when compared to FI. Further, under FPRD an increase of 41.27% and 44.81% was recorded respectively in WUEy and WUEb and under DI increase in WUEy and WUEb was recorded respectively 41.43% and by 46.95% when compared to FI. Tafteh and Sepaskhah, (2012) reported that alternate furrow irrigation in maize under conditions of Shiraz, Iran reduced evapotranspiration by 20%, which mainly contributed by reduction in surface evaporation, which ultimately increased water use efficiency of maize crop. Khaliq et al., (2016), found that irrigation treatments significant impact of dry matter based water use efficiency of maize hybrids.

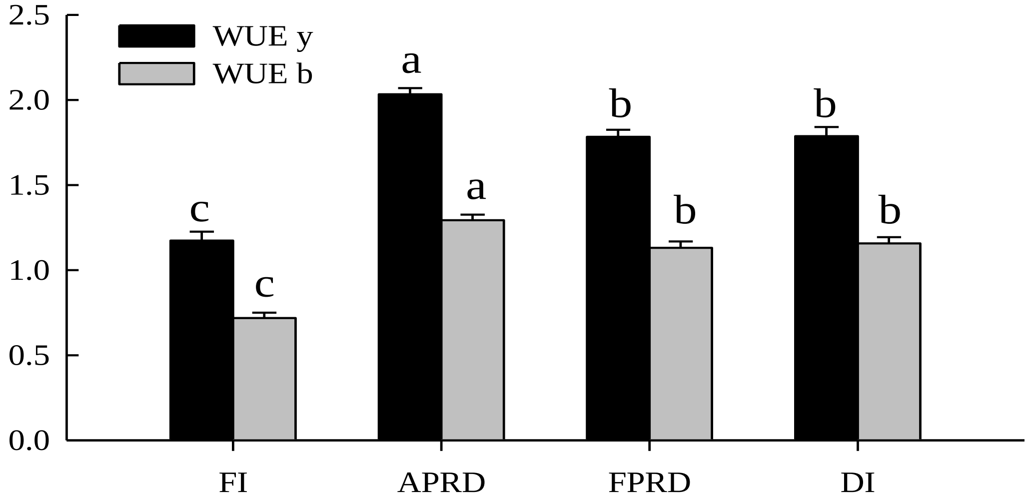

Fig. 2. Effects of different deficit irrigation strategies on grain yield based water use efficiency (WUEy) biomass production based water use efficiency (WUEb) of maize plants.

3.3 Effects on plant growth and yield

Though plant height under APRD decreased compared to the FI (Table 2), plant height as a result of APRD increased significantly compared to the plants under FPRD and DI, which indicate a successful control of vegetative growth as a result of APRD irrigation scheme. When compared to FI, plant height under APRD decrease by 2.97% while under FPRD and DI the decrease in plant height was respectively 7.81% and 7.92%, suggesting that vegetative growth was stunted under both DI and PRD. These results were in agreement with the findings of Shao et al. (2008) in hot peppers, where highest plant height was obtained for the full irrigation and lowest under conventional deficit irrigation. Decreasing irrigation water quantity significantly inhibited root growth in all deficit irrigation treatments. APRD showed higher root biomass build-up in the soil than either FPRD or DI, and there was no significant difference in root biomass between FPRD and DI as shown in Fig. 2. Khaliq et al., 2016 also showed significant effect of irrigation treatments on yield of maize hybrids in agro-climatic conditions of Faisalabad, Pakistan.

Table 2 Effects of different deficit irrigation strategies on maize plant morphology and produced biomass.

Treatments	Plant height (cm)	Number of leaves plant^{-1}	Root biomass plant^{-1} (g)	Shoot biomass plant^{-1} (g)	Leaf biomass plant^{-1} (g)	Root to shoot ratio
FI	252.53±2.44a	13.62±0.66a	19.84±1.79a	110.48±0.28a	57.76±0.92a	0.176±0.005a
APRD	245.13±2.66b	13.38±0.80a	16.76±1.03b	100.61±0.34b	55.11±0.83b	0.166±0.003ab
FPRD	233.53±2.23c	12.86±0.65b	14.26±1.03c	88.39±0.55c	50.62±0.72c	0.161±0.003b
DI	233.27±1.98c	12.62±0.49b	14.36±1.25c	88.46±0.27c	50.51±0.72c	0.162±0.004b

Notes: Treatments include: full irrigation (FI); alternate partial root-zone drying (APRD); fixed partial root-zone drying (FPRD) and deficit irrigation (DI). The values represent means ± standard error. Different small letters within the same column indicate significant difference at 0.05 level by the Duncan's test (n=5).

Table 3 Effects of different deficit irrigation strategies on leaf morphology of maize plants.

Treatments	Leaf area plant^{-1} (m^2)	Mean leaf area (cm^2)	Specific leaf area	Leaf area ratio	Leaf area index
FI	6.01±0.02a	437.22±8.09a	104.02±0.83a	15.83±0.07a	2.47±0.01a
APRD	5.36±0.02b	403.85±8.08b	97.376±0.35b	15.73±0.09a	2.21±0.01b
FPRD	4.66±0.03c	376.17±8.78c	92.16±0.68c	14.98±0.11b	1.92±0.01c
DI	4.67±0.02c	372.71±4.27c	92.53±0.52c	14.87±0.08b	1.93±0.01c

Notes: Treatments include: full irrigation (FI); alternate partial root-zone drying (APRD); fixed partial root-zone drying (FPRD) and deficit irrigation (DI). The values represent means ± standard error. Different small letters within the same column indicate significant difference at 0.05 level by the Duncan's test (n=5).

Interestingly, significantly lesser inhibition of root and shoot growth and higher root-shoot ratio under APRD when compared to other deficit irrigation schemes points out that the alternate soil drying and rewetting helped the plants to maintain normal growth up to some extent. Ahmad et al., 2011 in potato crop, by indicating non-significant influence of deficit irrigation and partial root-zone drying on dry root mass, root length density when compared with control.

On the other hand, when only a fixed side of root system was watered, both root development and root-shoot ratio were severely inhibited. Compared to the FI, total biomass per plant was reduced by 10.49%, 23.74% and 23.58% under APRD, FPRD and DI respectively and similar results were reported in field grown grapevines (Dry and Loveys, 1998).

There was no significant difference in the number of leaves per plant between FI and APRD but leaves decreased significantly in FPRD and DI. Photosynthetic area of the maize plants was significantly reduced as a result of deficit irrigation as shown in Table 3. Plants under FI treatment produced significantly larger leaves than the plants under APRD, FPRD and DI treatments. Leaf area per plant was lower under APRD, FPRD and DI treatments respectively by 11.43%, 25.30% and 25.09% compared to FI treatment. Similar results have been previously reported in lysimeter grown strawberry (Liu et al., 2007).

Highest grain yield per plant was obtained under FI and it decreased significantly as a result of deficit irrigation (Table 4). Grain yield per plant reduction under APRD was 14.44% and under FPRD and DI grain yield per plant was reduced by 27.52% and 29.29% respectively, showing no significant difference between FPRD and DI treatments. Similar results were concluded in maize, table grapes and in tomato grown under APRD and DI (Du et al., 2008; Kang et al., 2000b; Kirda et al., 2004). Data for harvest index was also consistent with the envisaged treatment effects, with the lowest value under FPRD but not significantly different from DI and the highest under FI treatment (Fig. 3).

Table 4 Effects of different deficit irrigation strategies on grain yield of maize plants.

Treatments	Cobs plant^{-1}	Grains cob^{-1}	100-Grains weight (gm)	Grain yield plant^{-1} (gm)	Grain yield hec^{-1} (kg)
FI	1.66±0.11a	662.76±20.90a	32.10±0.95a	213.34±8.36a	8800.41±81.29a
APRD	1.42±0.11a	608.43±22.42b	30.59±0.90b	184.59±6.25b	7614.34±24.57b
FPRD	1.14±0.07b	566.38±16.18c	28.70±0.95c	161.73±4.39c	6671.43±68.94c
DI	1.09±0.06b	558.10±25.03c	28.62±0.73c	158.82±5.89c	6551.36±50.25c

Treatments include: full irrigation (FI); alternate partial root-zone drying (APRD); fixed partial root-zone drying (FPRD) and deficit irrigation (DI). The values represent means ± standard error. Different small letters within the same column indicate significant difference at 0.05 level by the Duncan's test (n=5).

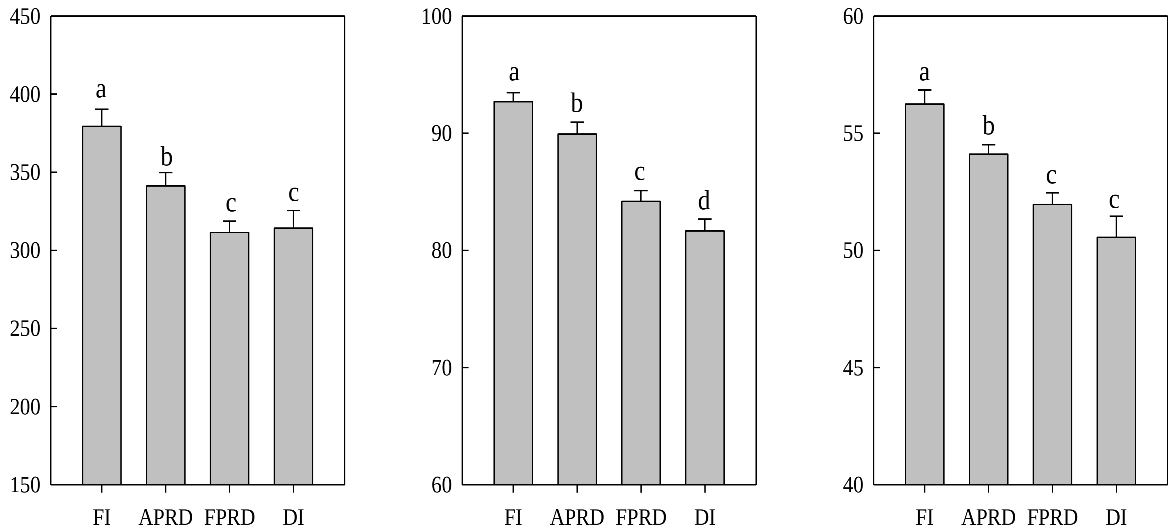

Fig. 3. Effects of different deficit irrigation strategies on total biological yield, shelling percentage and harvest index of maize plants. Treatments include: full irrigation (FI); alternate partial root-zone drying (APRD); fixed partial root-zone drying (FPRD) and deficit irrigation (DI). Different small letters above the data bars indicate significant difference among the treatments at 0.05 level by the Duncan's test (n=5).

Number of grains per cob and shelling percentage of the cobs under APRD was statistically higher compared to the cobs from FPRD and DI but was significantly lower than FI. This reduction of grains per cob and grain weight can be attributed to the reduction in vegetative growth because of water deficit. The grain yield per hectare was decrease in APRD by only 14.45%, but the yield reduction per hectare was almost 27.52% and 29.30% respectively under FPRD and DI treatments when compared to FI.

4. Conclusion

When root-zone of maize plants was kept close to the field capacity, plants produced maximum grain yield, higher vegetative growth and root biomass. APRD irrigation scheme resulted into better plant growth and higher grain yield as compared to FPRD and DI irrigation schemes. Water use efficiency based on grain yield of maize hybrid under APRD was almost double than the water use efficiency obtained under FI and it was also greater than both FPRD and DI. From the data it was concluded that through alternate watering of half root-zone of maize plants, 50% of the water can be saved with just around 15% reduction in yield, and APRD proved better than FPRD and DI water saving strategies.

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Competing Interests: The authors declare that there is no potential conflict of interest.

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