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Effect of alternate irrigation on root-divided Foxtail Millet (*Setaria italica*)

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Abstract

Improper irrigation management is a major factor contributing to water shortage problem. A pot experiment was conducted in order to evaluate water use efficiency of partial root zone drying in root-divided foxtail millet. The study was conducted as a factorial experiment based on randomized complete block design (RCBD) with three replications. We tested three irrigation methods (conventional, fixed and alternate irrigation) which applied at three intervals (2, 3 and 4 days). In conventional irrigation, the whole root system was evenly dried. In fixed irrigation, water was always applied to one part of root system, and in alternate irrigation watering was alternated between two halves of root system. Results showed that forage fresh yield were reduced by increasing irrigation interval. Under conventional irrigation, irrigation interval of 3 and 4 days had a dry biomass reduction of 5% and 34% compared with irrigation interval of 2 days, respectively. Under irrigation interval of 3 and 4 days, less water was used by the alternate and fixed irrigation, compared to conventional irrigation, but plant growth in terms of dry biomass, plant height, leaf to stem ratio, specific leaf weight, leaf area, root dry weight, root volume, root surface area and root length, was not affected. Under irrigation interval of 3 days, fixed and alternate irrigation used 29% and 20% less water compared with conventional irrigation, respectively. However, water stress increased specific leaf weight, but reduced leaf area, leaf dry weight and leaf relative water content. Root growth was less sensitive than shoot to water stress. Under mild water stress, alternate irrigation performed better than fixed irrigation compared to all irrigation methods under non-water stress, so to achieve acceptable yield along with efficient use of water, alternate irrigation under mild water stress is recommended.

Keywords: chlorophyll, irrigation methods, relative water content, water use efficiency.
Abbreviations: RCBD-randomized complete block design, ABA-abscisic acid, AW-alternate watering, WUE- water use efficiency, RWC-relative water content, I1-irrigated every 2 days, I2- irrigated every 3 days, I3-irrigated every 4 days, M1-conventional irrigation, M2-fixed irrigation, M3-alternate irrigation, LA-leaf area, LDW-leaf dry weight, SLW-specific leaf weight, ANOVA- analysis of variance, R/S-root to shoot ratio.

Introduction

Forage crops have important role in protein production and food security. Foxtail millet is one of these crops. This plant is a C_4 plant and well-adapted to arid and semiarid areas of Iran. Millet has high WUE (Hatfield et al., 2001) and produces high quantity and quality of grains (Heidari Zooleh et al., 2006). Irrigation is an increasingly important practice for sustainable agriculture in semi-arid environment of Iran. Karaj region in Iran is particularly relies on the dwindling ground water resources, so traditional irrigation methods in this region have experienced significant improvements with introduction of new technologies over the years. A new method of irrigation proposed by Kang et al. (1998) is the alternate irrigation system, by which, water is supplied to alternate sides of the plants root system. This method induces some root signals, such as production of Abscisic Acid (ABA) in the xylem to trigger drought responses, reduced stomatal conductence that reduces transpiration rate and photosynthesis to a lesser extent (Sepaskhah and Ahmadi, 2010). Kang et al. (2002) investigated alternate watering in soil vertical profile with pot-grown maize plants and found water consumption fell by between 20% (moderate soil drying) and 40% (severe soil drying) depends on the length of the watering intervals. The response also differed whether the application was based on alternate watering (AW) or drying, on either part of soil column which largely keeps its biomass production under moderate soil drying.

Table1. Effect of irrigation treatments on fresh forage weight, dry forage yield, WUE, plant height and water consumption of foxtail millet.

Irrigation treatment [a]	Fresh forage weight (g/plant) [b]	Dry forage yield (g/plant)	WUE (g/L)	Plant height (cm)	Water consumption (L/plant)
M1I1	3.653 a	1.08 ab	1.185 b	29.89 ab	0.8773 a
M2I1	3.557 a	1.02 abc	1.406 ab	28.06 ab	0.7267 b
M3I1	3.557 a	1.147 a	1.405 ab	31.85 a	0.816 ab
M1I2	3.463 a	1.025 abc	1.346 ab	29.34 ab	0.759 b
M2I2	2.537 abc	0.7833 bcd	1.414 ab	27.21 abc	0.5393 cd
M3I2	2.763 ab	0.8567 abcd	1.408 ab	27.12 abc	0.6067 c
M1I3	2.187 bc	0.7167 cd	1.280 ab	22.08 cd	0.564 c
M2I3	2.074 bc	0.6593 d	1.661 a	24.53 bc	0.3947 e
M3I3	1.543 c	0.6033 d	1.355 ab	18.42 d	0.4397 ed

[a] M1, M2 and M3 are irrigation methods of evenly on whole roots, fixed on ½ roots and alternate on ½ roots, respectively. I1, I2 and I3 are irrigation interval of 2, 3 and 4 days, respectively.

[b] Means followed by the same letter within a column are not significantly different at $P < 0.05$ as determined by Duncan's Multiple Range Test.

Table 2. Pearson's correlation coefficients among studied traits in foxtail millet under different irrigation treatments.

FW	1																					
WC	.939**	1																				
DW	.979**	.962**	1																			
PH	.922**	.811**	.912**	1																		
LTOS	-.701*	-.829**	-.723*	-.431	1																	
WUE	-.340	-.603	-.374	-.105	.745*	1																
LNO	.368	.482	.392	.288	-.589	-.431	1															
SLW	-.783*	-.732*	-.722*	-.763*	.340	.336	-.037	1														
LDW	.879**	.839**	.932**	.888**	-.596	-.178	.411	-.499	1													
LA	.948**	.910**	.921**	.874**	-.593	-.392	.188	-.927**	.750*	1												
RWC1	.907**	.922**	.920**	.797*	-.789*	-.540	.367	-.680*	.798**	.853**	1											
RWC2	.909**	.838**	.905**	.859**	-.534	-.248	.035	-.832**	.765*	.940**	.880**	1										
RWC3	.785*	.664	.706*	.762*	-.445	-.148	.579	-.637	.635	.692*	.669*	.600	1									
CHL1	-.055	-.052	-.067	-.250	-.307	-.089	.345	.364	-.063	-.231	.144	-.119	.222	1								
CHL2	-.196	-.292	-.187	-.053	.243	.228	-.247	.328	-.013	-.307	.026	-.124	-.092	.300	1							
CHL3	-.081	-.145	-.071	-.014	.222	.322	-.101	-.045	-.163	-.040	.002	.160	.047	.246	-.092	1						
RDW	.913**	.931**	.955**	.809**	-.721*	-.377	.469	-.648	.888**	.854**	.869**	.848**	.702*	.085	-.284	.058	1					
RV	.938**	.909**	.964**	.829**	-.702*	-.304	.336	-.652	.907**	.872**	.884**	.895**	.689*	.093	-.176	-.003	.977**	1				
RTOS	-.697*	-.653	-.699*	-.661	.660	.315	-.245	.308	-.716*	-.544	-.748*	-.581	-.381	.012	-.292	.336	-.509	-.589	1			
RNO	.518	.212	.404	.669*	.147	.481	-.112	-.540	.398	.490	.321	.538	.671*	-.085	.176	.224	.305	.397	-.260	1		
RA	.914**	.826**	.913**	.824**	-.606	-.182	.253	-.658	.850**	.845**	.872**	.906**	.748*	.195	-.049	.106	.924**	.971**	-.556	.549	1	
RL	.843**	.723*	.825**	.767*	-.507	-.112	.158	-.639	.749*	.784*	.841**	.883**	.745*	.285	.080	.211	.837**	.900**	-.500	.622	.976**	1
	FW	**WC**	**DW**	**PH**	**LTOS**	**WUE**	**LNO**	**SLW**	**LDW**	**LA**	**RWC1**	**RWC2**	**RWC3**	**CHL1**	**CHL2**	**CHL3**	**RDW**	**RV**	**RTOS**	**RNO**	**RA**	**RL**

FW, WC, DW, PH, LTOS, WUE, LNO, SLW, LDW, LA, RWC1, RWC2, RWC3,CHL1, CHL2, CHL3, RDW, RV, RTOS, RNO,RA and RL are fresh forage yield, water consumption, forage dry weight, plant height, leaf to stem ratio, water use efficiency, leaf number, specific leaf weight, leaf dry weight, leaf area, relative water content at sampling stage 1, relative water content at sampling stage 2, relative water content at sampling stage 3, chlorophyll content at sampling stage 1, chlorophyll content at sampling stage 2, chlorophyll content at sampling stage 3, root dry weight, root volume, root to shoot ratio, root number, root surface area and root length, respectively.

**.Correlation is significant at the 0.01 level

*.Correlation is significant at the 0.05 level

Alternate watering results in higher water use efficiency (WUE), root to shoot ratio, photosynthesis rate, total nutrient uptake (N, K) and crop quality (Kang et al., 1998; Kang et al., 2000; Tang and Zhang, 2005). Water-stressed plants usually have higher water use efficiencies than well-watered plant. The increase in efficiency is due to a larger decrease in plant transpiration, because of decreased green leaf area which probably reduces evaporation from soil (Karam et al., 2003). There is a negatively partial correlation between water stress and plant pigments such as chlorophyll (Abdalla and El-khoshiban, 2007; Zaidi et al., 2008). The water stress can decrease relative water content (RWC) of plant (Siddique et al., 2000; Moussa and Abdel-Aziz, 2008). Webber et al. (2006) found that common bean (*Phaseolus vulgaris*) is not well suited to water scarce conditions and alternate furrow irrigation as green gram (*Mung bean*). So, it should be necessary to test every plant for water stress and alternate irrigation method in different conditions. There are only a few studies about agronomic traits of foxtail millet and its response to partial root zone drying. The main objectives of this study were to (i) evaluate morphological and physiological traits of foxtail millet under partial root zone drying and deficit irrigation (ii) determine the WUE and forage yield of foxtail millet under partial root zone drying and deficit irrigation.

Materials and methods

Plant materials and root division method

The pot experiment was conducted in 2009 at Research Greenhouse, Faculty of Agricultural Science and Engineering, University of Tehran, Karaj, Iran. Foxtail millet seeds (*Setaria italica*, cv. KFM9) were planted in 27 pots (20 cm in diameter, 20 cm in depth) on May 7th, 2009. The pots were filled with light loam soil. Seeds were densely sown 1 cm deep but after emergence seedling were thinned to 12 plants per pot. The inside of the pots was divided into two vertical halves separated with a sandy soil layer (3 cm in diameter) covered by thin layer (2-3 mm in diameter) of wax, such that water exchange between the two halves of root system was prevented. This layer can break the capillarity movement of water between two layers of the soil. Seeds were planted at the sandy soil layer. In order to supply nutrients for the seedling at the sandy soil layer, it was nourished with Hogland solution. Plants were initially well-watered and irrigation treatments were only imposed 44 days after sowing.

Experimental design and treatments

The study was involved a factorial experiment in a randomized complete block design (RCBD) with three replications. The treatments were different irrigation methods and intervals. There were three irrigation intervals: I1: Control, irrigated every 2 days. I2: Mild water stress, Irrigated every 3 days. I3: Sever water stress, irrigated every 4 days. There were three methods of water application, viz: Conventional irrigation (M1): the whole root system was relatively evenly dried. Fixed irrigation (M2): fixed irrigation group, by which, water was always applied to one part of root system during the whole experimental period. Alternate irrigation (M3): watering was alternated between two halves of root system of the same pot. The watered and dried halves of root system were alternately replaced each irrigation interval. Irrigation intervals were determined according to factors such as greenhouse temperature and humidity. At each irrigation event, enough water was allowed to be absorbed by the soil in each pot, and any excess water was allowed to drain. The pots were weighed before and after each irrigation event to determine the water consumption by the plant in each pot (Sivapalan, 2006).

Plant sampling and measurements

Relative water content (RWC) of leaf was estimated according to the method proposed by Turner and Kramer (1980): RWC (%) = (fresh weight - dry weight) / (turgid weight - dry weight). Chlorophyll content was measured using chlorophyll meter (SPAD-502, Minolta, Japan) (Bail et al., 2005). The upmost leaf per plant was selected for measuring RWC and chlorophyll content. Leaf relative water content was measured at 55, 67 and 87 days after sowing. Chlorophyll content was measured at 57, 63 and 86 days after sowing. Water use efficiency was computed as following equation (Viets, 1962):

WUE=forage yield (kg) / water used to produce the yield (lit). Root volume was measured by water volume changes in a graduated cylinder. To estimate root length (R), the roots were spread out on a flat surface (of area A), on which, there were sample lines (total length H), and the number of intersections (N) between roots and lines were counted. Then root length was estimated as following formula (Newman, 1966):

$R = \pi NA/2H$, Root surface area was estimated as (Darra and Raghuvanshi, 1999): Root surface area (cm^2) = $2\{[\text{root volume, cc}] \times \pi \times [\text{root length, cm}]\}^{0.5}$, Leaf Area (LA) was measured using leaf area meter. LA and Leaf Dry Weight (LDW) were used to calculate Specific Leaf Weight (SLW) as: SLW = LDW/LA, Measurement of fresh forage yield, dry forage yield, leaf area, leaf to stem ratio, specific leaf weight, leaf dry weight, root dry weight and root volume was carried out by 12 plants while plant height, leaf number per plant, RWC, chlorophyll content, root number and root length were measured by random selection of three plants per each pot. Harvest time for total dry weight was 89 days after sowing and plant samples were dried in a forced-air oven at 65 °C for 2 days.

Statistical analysis

Analysis of variance (ANOVA) was used to determine significant differences. The Multiple Range Test of Duncan (α=5%) performed the separation of means. Correlation coefficients were calculated for the relationship between crop yield and several crop parameters. All statistics were performed with the program MSTATC (version 2.10) and SPSS (version 10.0).

Results

Fresh forage yield

Irrigation interval of 2 days produced the highest fresh forage yield. Irrigation interval of 3 days did not have significant difference compared with irrigation of 2 days in terms of fresh forage yield, but irrigation interval of 4 days significantly redu-

Table 3. Effect of irrigation treatments on leaf to stem ratio, specific leaf weight (SLW), leaf dry weight (LDW) per plant and leaf area (LA) per plant of foxtail millet.

Irrigation treatment [a]	Leaf to stem ratio [b]	SLW (g/m^2)	LDW (g)	LA (cm^2)
M1I1	0.71233 bc	98.77 c	0.4273 ab	42.141 a
M2I1	0.72500 bc	119.3 bc	0.4286 bc	36.583 ab
M3I1	0.7555 bc	126.9 abc	0.5631 a	35.275 abc
M1I2	0.68800 c	137.2 ab	0.4992 bc	31.392 bc
M2I2	0.89000 ab	124.4 abc	0.3631 cd	28.666 bcd
M3I2	0.77667 abc	134.8 abc	0.3692 cd	27.750 cd
M1I3	0.77267 bc	144.4 ab	0.3132 cd	22.092 de
M2I3	0.9535 a	139.4 ab	0.3191 cd	22.792 de
M3I3	0.81800 abc	158.6 a	0.2808 d	18.025 e

[a] M1, M2 and M3 are irrigation methods of evenly on whole roots, fixed on ½ roots and alternate on ½ roots, respectively. I1, I2 and I3 are irrigation interval of 2, 3 and 4 days, respectively. [b] Means followed by the same letter within a column are not significantly different at $P < 0.05$ as determined by Duncan's Multiple Range Test.

Table 4. Effect of irrigation treatments on leaf relative water content and chlorophyll content of foxtail millet.

Irrigation treatment [a]	RWC1	RWC2	RWC3	Chlorophyll3 (SPAD)
M1I1	0.8793 ab [b]	0.9087 a	0.924 a	23.67 ab
M2I1	0.9090 a	0.9403 a	0.936 a	24.97 a
M3I1	0.9300 a	0.9193 a	0.9235 a	25.00 a
M1I2	0.8067 abc	0.7055 b	0.9325 a	21.27 b
M2I2	0.7010 bc	0.7160 b	0.902 ab	23.00 ab
M3I2	0.7800 abc	0.7560 b	0.8975 ab	26.20 a
M1I3	0.6547 cd	0.5307 c	0.923 a	24.70 a
M2I3	0.3757 e	0.5707 c	0.8975 ab	25.10 a
M3I3	0.4770 de	0.5127 c	0.8185 b	23.27 ab

[a] M1, M2 and M3 are irrigation methods of evenly on whole roots, fixed on ½ roots and alternate on ½ roots, respectively. I1, I2 and I3 are irrigation interval of 2, 3 and 4 days, respectively. [b] Means followed by the same letter within a column are not significantly different at $P < 0.05$ as determined by Duncan's Multiple Range Test. RWC1, RWC2 and RWC3 are leaf relative water content at 55, 67 and 87 days after sowing, respectively. Chlorophyll3 is chlorophyll content at third stage of sampling (86 days after sowing) as measured by SPAD index.

uced fresh forage yield (Table 1). Less water was used by M2I3 and M3I3 compared with M1I3 but fresh forage yields were not affected. In addition to that, less water was used by M2I2 and M3I2 compared with M1I2 but fresh forage yields were not affected. There was positive and significant correlation between fresh forage yield and dry weight of forage, water consumption, plant height, leaf area, LDW, RWC at three stage samplings (RWC1, RWC2, RWC3), dry weight of root, root volume, root surface area and root length, but there was negative and significant correlation between fresh forage yield and leaf to stem ratio, SLW and R/S (Table 2).

Dry forage yield

The I1 had the highest dry forage yield, while I2 did not have significant difference compared with I1, but I3 had a significant reduction of dry forage yield compared with I1 (Table 1). For example under conventional irrigation, I2 and I3 had a dry biomass reduction of 5% and 34% compared with I1, respectively. Less water was used by M2I3 and M3I3 compared with M1I3 but dry forage yields were not affected. Under conventional irrigation, irrigation interval of 3 and 4 days had a dry biomass reduction of 5% and 34% compared with irrigation interval of 2 days, respectively. In addition to that, less water was used by M2I2 and M3I2 compared with M1I2 but dry forage yields were not affected. The most important point is that M2I2 significantly reduced dry forage yield compared with M3I1, while M3I2 did not have a significant reduction compared with M1I1, M2I1 and M3I1. These suggest that alternate irrigation of root is the best irrigation method among other irrigation methods. There was positive and significant correlation between dry forage yield

Table 5. Effect of irrigation treatments on root development of foxtail millet.

Irrigation treatment [a]	Root dry weight (g)	Root volume (cm^3)	Root number	Root surface area (cm^2)	Root length (cm)
M1I1	0.355 ab [b]	0.8473 abc	11.56 ab	120.8 abc	1386.37 abc
M2I1	0.347 ab	0.9031 ab	12.89 a	142.1 a	1785.00 a
M3I1	0.394 a	0.9444 a	12.00 ab	138.9 ab	1647.97 ab
M1I2	0.322 abc	0.8197 abc	11.89 ab	118.6 abc	1344.30 abc
M2I2	0.244 bc	0.6665 bc	12.56 a	104.8 abc	1316.50 abc
M3I2	0.275 abc	0.6948 abc	12.00 ab	106.2 abc	1297.14 abc
M1I3	0.278 abc	0.6667 bc	10.89 ab	101.4 bc	1236.45 abc
M2I3	0.240 bc	0.6247 c	12.66 a	96.29 c	1139.90 bc
M3I3	0.222 c	0.5973 c	9.667 b	84.84 c	964.54 c

[a] M1, M2 and M3 are irrigation methods of evenly on whole roots, fixed on ½ roots and alternate on ½ roots, respectively. I1, I2 and I3 irrigation interval of 2, 3 and 4 days, respectively. [b] Means followed by the same letter within a column are not significantly different at 0.05 as determined by Duncan's Multiple Range Test.

and fresh forage yield, water consumption, plant height, leaf area, LDW, RWC1, RWC2, RWC3, root dry weight, root volume, root surface area and root length, but there was negative and significant correlation between forage dry weight and leaf to stem ratio and SLW (Table 2).

Water use efficiency (WUE)

There was significant difference between M2I3 and M1I1 in terms of WUE and the difference among the other treatments were not significant (Table 1). M2I3 had a WUE increase of 40% compared with M1I1. There was positive and significant correlation between WUE and leaf to stem ratio (Table 2).

Plant height

I1 resulted in the highest plant height however there was no significant difference between I1 and I2, while plant height was significantly reduced in I3 (Table 1). For example under conventional irrigation, I2 and I3 had a plant height reduction of 2% and 26% compared with I1, respectively. Less water was used by M2I3 and M3I3 compared with M1I3 but plant height was not affected. In addition to that, less water was used by M2I2 and M3I2 compared with M1I2 but plant height was not affected. There was positive and significant correlation between plant height and dry forage yield, fresh forage yield, water consumption, leaf area, LDW, RWC (sampling stage 1, 2, 3), root dry weight, root volume, root number, root surface area and root length. There was negative and significant correlation between plant height and SLW (Table 2).

Water Consumption

By increasing irrigation intervals, water consumption was reduced evidently in the I2 in fixed and alternate irrigation (Table 1). Reductions in water consumption, but not in biomass, with fixed and alternate irrigation compared with conventional irrigation method suggests that these two irrigation methods can be used for saving soil water. This is especially achievable with alternate irrigation under mild water stress (M3I2) that did not reduce forage dry weight when compared with M3I1. Under irrigation interval of 3 days, fixed and alternate irrigation used 29% and 20% less water compared with conventional irrigation, respectively. There was positive and significant correlation between water consumption and fresh forage yield, dry forage yield, plant height, leaf area, leaf dry weight, leaf relative water content (sampling stage 1, 2), root dry weight, root volume, root surface area and root length, while there was negative and significant correlation between water consumption and leaf to stem ratio and SLW (Table 2).

Leaf to stem ratio

Under each irrigation interval of 3 and 4 days, fixed irrigation method had more leaf to stem ratio compared with conventional irrigation method (Table 3). M2I3 had the highest leaf to stem ratio, but there was no significant difference between M2I3 and M3I3, M3I2 and M2I2. These data show that by increasing water stress level, such as in the fixed irrigation, the leaf becomes smaller, but thicker (Table 3). There was positive and significant correlation between leaf to stem ratio and WUE, while there was negative and significant correlation between leaf to stem ratio and fresh forage yield, dry forge yield, water consumption, leaf relative water content (sampling stage 1), root dry weight and root volume (Table 2).

Specific leaf weight (SLW)

Decreasing water consumption by way of increasing irrigation interval under conventional irrigation method increased Specific Leaf Weight (SLW) or leaf weight (Table 3). M2I3, M1I3 and M1I2 had more SLW than M1I1 - and - M3I3 had more SLW than M2I1 and M1I1.

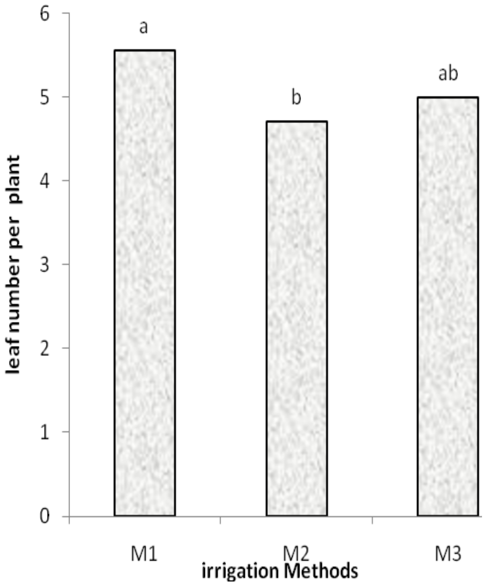

Fig 1. Effect of irrigation methods on leaf number per plant of foxtail. M1, M2 and M3 are irrigation methods of evenly on whole roots, fixed on ½ roots and alternate on ½ roots, respectively. Means followed by the same letter are not significantly different at $P < 0.05$ as determined by Duncan's Multiple Range Test.

Leaf dry weight (LDW)

Reducing water consumption by way of increasing irrigation interval reduced dry weight of leaf (Table 3). M3I1 had more LDW than M2I1 however there was no significant difference between them in terms of water consumption.

Leaf number per plant

The effect of irrigation interval on leaf number was not significant. Conventional irrigation and fixed irrigation had the highest and lowest leaf number per plant, respectively (Fig 1).

Leaf area

By increasing irrigation interval, leaf area was decreased. Less water was used by M2I3 and M3I3 compared with M1I3 but leaf area was not affected. In addition to that, less water was used by M2I2 and M3I2 compared with M1I2 but leaf area was not affected (Table 3). There was positive and significant correlation between leaf area and fresh forage yield, dry forage yield, water consumption, plant height, LDW, RWC1, RWC2, RWC3, root dry weight, root volume, root surface area and root length (Table 2).

Relative water content (RWC)

At first sampling stage for RWC (55 days after planting), I1 and I3 had the highest and lowest percent of RWC, respectively (Table 4). There was no significant difference between M2I2 and M3I2 regarding water consumption but M2I2 had significantly less RWC than M2I1 and M3I1 while M3I2 maintained its RWC under mild water stress. M3I3 and M2I3 statistically used similar water; M3I3 maintained its RWC compared with M1I3 while M2I3 had significantly less RWC than M1I3. These evidences imply that alternate irrigation is more suitable than conventional and fixed irrigation regarding RWC. At second sampling stage for RWC (67 days after planting), I1 and I3 had the highest and lowest RWC, respectively (Table 4). Less water was used by M2I3 and M3I3 compared with M1I3 but RWC was not affected. In addition to that, less water was used by M2I2 and M3I2 compared with M1I2 but RWC was not affected. At third sampling stage for RWC (87 days after sowing), M3I3 had the lowest RWC, however there was no significant difference among M3I3 and M2I2, M2I3 and M3I2 showing decreasing RWC under water stress (Table 4). There was positive and significant correlation between RWC (sampling stage 1) and fresh forage yield, dry forage yield, water consumption, plant height, leaf area, LDW, root dry weight, root volume, root surface area and root length, while there was negative and significant correlation between RWC (sampling stage 1) and leaf to stem ratio, SLW and R/S (Table 2).

Chlorophyll

Chlorophyll content (SPAD index) of foxtail millet at the first stage of sampling (57 days after sowing date) was not affected by any treatment but at second sampling stage (63 days after sowing date) I2 had the highest chlorophyll content, however there was no significant difference between I2 and I3 (Fig 2). At third sampling stage (86 days after sowing date), under conventional irrigation method, M1I3 has the highest chlorophyll content however there was no significant difference between M1I3 and M1I1 (Table 4). Under I2, M3I2 had significantly more chlorophyll content than M1I2.

Root dry weight

By increasing irrigation interval of all irrigation methods, except alternate irrigation, and by decreasing water consumption from conventional irrigation to fixed and alternate irrigation, dry weight production of root was not significantly affected by water amount. This shows that root growth continues under water stress compared to decrease in dry matter production of shoot (Table 5). Less water was used by M2I3 and M3I3 compared with M1I3 but root dry weight was not affected. In addition, less water was used by M2I2 and M3I2 compared to M1I2 but root dry weight was not affected. It is more important that M2I2 had significantly less root dry weight than M3I1 but root dry weight of M3I2 did not have significant reduction compared to all three irrigation methods under irriga-

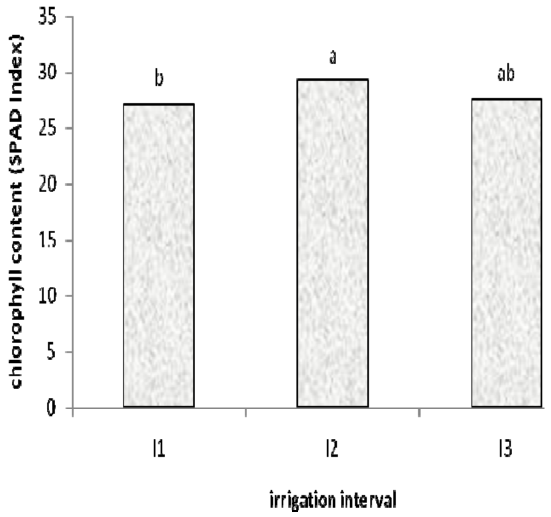

Fig 2. Effect of irrigation interval on chlorophyll content of foxtail millet at second stage of sampling (86 days after sowing) as measured by SPAD index. I1, I2 and I3 are Irrigation interval of 2, 3 and 4 days, respectively. Means followed by the same letter are not significantly different at $P < 0.05$ as determined by Duncan's Multiple Range Test.

tion interval of 2 days. There was positive and significant correlation between root dry weight and fresh forage yield, dry forage yield, water consumption, plant height, leaf area, LDW, RWC, root volume, root surface area and root length but there was negative and significant correlation between root dry weight and leaf to stem ratio (Table 2).

Root volume

By increasing irrigation interval under each irrigation method except conventional irrigation, root volume was reduced (Table 5). In conventional irrigation, even under severe water stress (I3), water consumption was high, so root volume was not reduced. However, this water stress (I3) had a significant effect on biomass production of shoot. Less water was used by M2I3 and M3I3 compared with M1I3 but root volume was not affected. In addition, less water was used by M2I2 and M3I2 compared with M1I2 but root volume was not affected. It is more important that M2I2 had significantly less root volume than M3I1 but root volume in M3I2 did not have significant reduction compared with all three irrigation methods under irrigation interval of 2 days. There was positive and significant correlation between root volume and fresh forage yield, dry forage yield, water consumption, plant height, leaf area, LDW, RWC, root dry weight, root surface area and root length. There was negative and significant correlation between root volume and leaf to stem ratio (Table 2).

Root to shoot ratio (R/S)

Analysis of variance showed that effect of irrigation method and interval on Root to Shoot ratio (R/S) of foxtail millet was not significant. There was negative and significant correlation between R/S and fresh forage yield, dry forge yield, LDW and RWC at sampling stage1 (Table 2).

Root number

Water stress had minor effect on root number (Table 5). Only M3I3 had significantly less root number than all three irrigation intervals under fixed irrigation. There was positive and significant correlation between root number and plant height and RWC (sampling stage 3). There was positively significant correlation between root number and plant height and RWC at sampling stage 3 (Table 2).

Root surface area

By increasing irrigation interval under each irrigation method except conventional irrigation method, root surface area was reduced (Table 5). Less water was used by M2I3 and M3I3 compared with M1I3 but root surface area was not affected. In addition to that, less water was used by M2I2 and M3I2 compared with M1I2 but root surface area was not affected. There was positive and significant correlation between root surface area and fresh forage yield, dry forage yield, water consumption, plant height, leaf area, LDW, RWC, root dry weight root, root volume and root length (Table 2).

Root length

By increasing irrigation interval under each irrigation method, except conventional irrigation method, root length was reduced (Table 5). Less water was used by M2I3 and M3I3 compared with M1I3 but root length was not affected. In addition to that, less water was used by M2I2 and M3I2 compared with M1I2 but root length was not affected. There was positive and significant correlation between root length and fresh forage yield, dry forage yield, water consumption, plant height, leaf area, LDW, RWC, root dry weight, root volume and root surface area (Table 2).

Discussion

This study investigated the effects of irrigation intervals and methods on eco-physiological traits of foxtail millet under controlled conditions. It was observed that dry biomass was reduced under sever water stress. Lack of reduction of dry forage yield in the mild water stress treatments may be attributed to maintaining the plant height, water use efficiency, leaf area, leaf relative water content at second stage of sampling (RWC2), root dry weight, root volume, root surface area and root length. Kang et al. (2002) and Webber et al. (2006) reported similar results. Lack of significant reduction of dry forage yield of foxtail millet with I2 and I3 compared with I1 is probably due to elastic (reversible) and plastic (irreversible) deformation of cells and plant tissues, respectively (Nonamy and Boyer, 1990). M3I2 performed better than M2I2 due to reduction of leaf relative water content at first stage of sampling (RWC1), root dry weight and root volume of M2I2 than M3I1 while there is no significant reduction in M3I2 compared with M1I1, M2I1 and M3I3. Maintaining dry forage yield and other traits of M3I2 compared with M2I2 can be attributed to induced root signals due to water stress and their effect on stomatal opening. Drying part of the root system can inhibit stomatal opening, to some degree, to reduce loss of water so that the shoot maintains its turgidity. Partial stomatal closure from maximum status, especially in C_4 plant, can reduce photosynthesis rate more than transpiration rate (Kang et al., 2002). Water saving by alternate irrigation was reported by other researchers in maize (*Zea mays*) (Kang et al., 2002) and green gram (*Vigna radiata*) (Webber et al., 2006). Fixed irrigation of root causes suberization of root epidermis with less sensitivity to the dried soil, more nutrients leaching at wetting part of soil and uneven root distribution at wet and dried zones of soil compared with alternate irrigation of roots (Kang et al., 2000). Only M2I3 had a WUE increase compared with M1I1. Several earlier studies showed that water use efficiency is being increased due to restrained water consumption by crops (Payne et al., 1992; Sasani et al., 2003). Curt et al. (1995) reported that in sweet sorghum, water use efficiency was not changed under different irrigation regimes. Plant height was reduced under sever water stress. Many studies observed reduction in plant height due to water stress (Kang et al., 2000; Heidari Zooleh et al., 2006). This decrease in plant height can be attributed to intelligent response of plant for preventing transpiration from shoot (Karam et al., 2003), reduction of cell size and internodes length and accumulation of Abscisic Acid (Sharp, 1996). LA, leaf number per plant, LDW and SLW measurements showed that LA and LDW was reduced under sever water stress but SLW was increased under water stress and leaf number per plant was not affected by water stress. One of the most obvious effects of water stress on plant growth is the reduced leaf area (Karam et al., 2003). Kang et al (1998) reported that, however alternate irrigation used less water than conventional irrigation, but the leaf area was as large as conventional irrigation. Maintaining leaf relative water content resulted in growth and development of leaf in M2I2 and M3I2 compared with M1I2 (Table 4, RWC1, RWC2, RWC3) and in M2I3 and M3I3 compared with M1I3 (Table 4, RWC2) despite less water consumption. Belaygue et al. (1996) reported that mild water stress did not reduce leaf number per plant in white clover, but severe water stress significantly reduced leaf number per plant. Alyemeny (1998) reported that decreasing shoot biomass like leaf biomass enables plant to tolerate water stress.

Save et al. (1993) reported that water stress reduced cell size and increased solute concentration so SLW increases under water stress. Sever water stress (I3) decreased RWC and alternate irrigation maintained its RWC despite less water consumption. Kang et al. (1998) declared that despite decreasing water consumption under alternate and fixed irrigation, RWC was not reduced that confirms finding of the research. Other researchers reported similar results (Siddique et al., 2000; Abdalla and El-khoshiban, 2007). Overall, it was observed that chlorophyll content was positively affected by water stress and even sometimes its content was increased by water stress. This increase can be attributed to decreasing leaf size and increasing chlorophyll content per area unit under water stress. It takes place under mild water stress. In addition, lack of effect of water stress on decreasing chlorophyll content maybe attributed to resistance of this plant to water stress. Abdalla and El-khoshiban (2007) reported that water stress reduced chlorophyll content that is in contrast with this research. Nezami et al. (2008) reported that mild water stress reduced chlorophyll content but severe water stress increased it. Root dry weight, root volume, root surface area and root length were reduced by sever water stress (I3) and alternate irrigation maintained the traits despite less water consumption. Some parts of the result are confirmed by many researchers (Alyemeny, 1998; Kang et al., 1998; Kang et al., 2000; webber et al. 2006). Apostol et al. (2009) reported that root volume was increased under water stress, while Duruoha et al. (2007) reported that root volume was decreased under water stress. It has been reported that root surface area of chick pea (*Cicer arietinum* L.) and field pea (*Pisum sativum* L.) was not changed under irrigated and dry land conditions but root surface area of soybean (*Glycine max* L. Merr.) was increased by water stress (Benjamin and Nielsen, 2006). Some researchers have shown that water stress reduced root length (Abdalla and El-khoshiban (2007) that confirms the finding of the research, while others have reported that water stress increased root length (Alyemeny,1998). Overall root growth and development was increased by alternate watering. It is due to that alternate watering can reduce soil evaporation area and inhibit stomatal opening to some degree to reduce loss of water through transpiration (Sepaskhah and Ahmadi, 2010). Effect of irrigation method and interval on root to shoot ratio (R/S) of foxtail millet was not significant and water stress had minor effect on root number. Kang et al. (2000) reported that maize R/S was increased**,** fixed and decreased under alternate, fixed and conventional furrow irrigation, respectively. In another study Kang et al. (1988) reported that alternate furrow irrigation had the highest R/S than the other irrigation methods. In the experiment, however root growth was less affected by water stress than shoot but R/S increases were not significant. Maybe it was due to equal reduction in root and shoot dry weight. Kang et al. (2002) reported that alternate furrow irrigation of maize had more root number than conventional furrow irrigation and observed that irrigation water volume had a minor effect on root number, but Abdalla and El-khoshiban (2007) declared that water stress reduced root number in wheat. It is probably due to that root number is a genetic trait that is partially affected by environment.

Conclusion

Overall, there were minor differences among conventional, alternate and fixed irrigation in terms of studied traits. Regarding less water consumption of alternate and fixed irrigation compared with conventional irrigation under mild and severe water stress, these irrigation methods are more water efficient than conventional irrigation. Under mild water stress, alternate irrigation performed better than fixed irrigation (compared with all irrigation methods under non-water stress), so to achieve acceptable yield along with efficient use of water, alternate irrigation under mild water stress is recommended.

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