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Water use efficiency and solute transport under different furrow irrigation treatments

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Key words: Alternate Furrow Irrigation, Climatic Conditions of Planted Area, Solute Transport in the Shallow Root Zone, Water Saving, Crop Water Productivity.

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Abstract

Traditional irrigation methods like basin irrigation, border irrigation, and furrow irrigation are commonly employed around the world to irrigate crops,wherethe entire soil surface is almost flooded without giving due consideration to the conservative use and water requirements of the crop. Alternate furrow irrigation (AFI)can save water and result in high grain yield with low irrigation costs, particularly in arid and semi-arid areas. However, despite of this,in several regions of the world,everyfurrow irrigation(EFI) method has been substitutedby AFI.To substantiate this view, field experimentswere conducted during the summer season of 2016 in the experimental field of Anhui Agricultural University, Hefei, China.We investigated the impact of AFIversus EFI on crop (okra)yield, water use efficiency (WUE), performance under the climatic conditions of Anhui (Hefei), irrigation water productivity, and solute transport in the shallow root zone.When irrigation was employed through furrows using AFI or EFI,our results indicated that the total irrigation water use in AFI was lower (370mm/ha)thanEFI (534mm/ha), resulting in 40–43% water savingfrom usingthe AFI method. We conclude that AFI is a significantly betterway to save water in arid and semi-arid areas where okra production relies heavily on repeated irrigation.

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Introduction

Water is indispensable and a fundamental resource for national or regional socio-economic development and ecological environment construction, and it is also a regional strategic resource for sustainable economic development (shi YF and Qu YG 1992). With rapid global economic development and population growth, the demand for water resources has sharply increased. Currently, safety evaluation studies on water resources are mainlyfocusedon the balance between supply and demand.Many different ways of conserving agricultural water have been investigated in the past. Scientists across the world(Stewart *et al* 1981, Musick *et al* 1982, Hodges 1989, Graterol 993, Stone 1993)have employed wide-spaced furrow irrigation or skip-row planting as a means to improve water use efficiency (WUE).

Agriculture is a vital industry in China, employing over 300 million farmers. China ranks first worldwide in farm output, primarily, rice, wheat, potatoes, tomato,sorghum, peanuts, tea, millet, barley, cotton, oilseed, soybeans,etc.(NBSC 2008). Despite of owing only 10 percent of arable land of the world, China produces food for 20 percent of the world's population.To realize self-sufficiency in food production, the Chinese government has undertaken large-scale programs to increase agricultural production. Among these measures, agricultural irrigation program is the largest contributor for increasing crop yield and reducing poverty in rural areas (Huang Q Q *et al* 2006). Agricultural irrigation program is the main source,which helps inthe stabilization of food prices, increased farmer incomes, and food supply to the society. In 2005, the total water use in China was 560 billion m^3, 64% of which was used for agriculture (Wu P *et al* 2007a and 2007b). Thus, agriculture is the largest water consumer in China (Varis O and Vakkilainen P 2001, Wu P and Feng H 2005, Yang H *et al* 2003).

Climate change also spatially and temporally modifies precipitation, placing more stress on the water and food security of China (Kitoh A *et al* 2005, Kharin V V *et al* 2007, Chen H P and Sun J Q. 2009). Therefore, it is essential that crop water requirement be supplemented through irrigation for better crop production. Sustainability of agriculture depends upon timely availability of water. Before the 1990s, most Chinese water channels for irrigation were open soil channels that lacked means of preventing water seepage through the soil. These channels used to result in 50–70% of all water losses before the 1990s(Wu J 2003, Shan L 2004). During this period in China, water lost through soil seepage was more than 170 billion m^3 each year, which was almost one-third of the total water usage.

Alternate furrow irrigation (AFI), is based on the novel partial root drying technique for vegetables which consists of: Irrigating only one side of the plant, i.e., half of the root system, at each irrigation event, while the other side receives water on the next irrigation. Relying on soil moisture regulation of root to shoot signaling and control of stomatal conductance which can reduce water transpiration.Compared to conventional irrigation, alternate furrow irrigation reduces water consumption by 35% with a total biomass reduction of only 6–11%. Alternate furrow irrigation (AFI) was successful in a variety of cropping systemsand climatic conditions to conserve water without loss in production(Bakker 1997). AFI has become an important aspect for improving crop WUE through appropriate irrigation design and management. A higher yield potential and WUE were obtained with AFIthan with every furrow irrigation(EFI) in cotton (Stone *et al* 1982). When AFI was employed, water was saved due to reduced water evaporation from the soil surface(W. J. Davies and Jianhua Zhang 1991).

It is also knownthat differences in soil water content between AFI and EFI methods issmaller for clay loam soil compared to loamy sand(Benjamin *et al* 1994). The lower hydraulic conductivity and subsequentlonger irrigation time allows water to move laterally from under the ridge to beneath the non-irrigated furrow. In other words, AFI in a clay loam soil allows more lateral flow of water, causing more uniform soil water content than in loamy sandbecause of excessive water drainage directly beneath the irrigated furrow. As a result, less irrigation water is required and un-irrigated furrows get water from the adjacent irrigated furrows through the horizontal movement of soil water.Thus, AFItreatment supplies water in a way that considerably reduces the amount of wetted surface,thereby reducing water loss through evapotranspiration and deep percolation. Deep percolation is reduced because less wetted surface of alternate furrow results in lower infiltration.AFI reducesthe amount of water required for irrigation by 20% and also reduces chemical leaching, resulting in higher crop yield(Einsenhaver 1992). In our opinion, if traditional irrigation methodsare integrated with efficient AFI, it will make AFI more acceptable to the farmers. However, AFI needs to be further evaluated under our soil and climatic conditions before we roll out this new technologyto local farmers. Consideringall of the above, the present study was conducted to evaluate the AFI method at the experimental field of Anhui Agricultural University, Hefei, Anhui, China.

Materials and methods

Description of Experimental Site

An experimental plot measuring $330m^2$ (30m×11m) was selected in the “agriculture experimental park” (Nong Cui Yuan) located Northwest of Anhui Agriculture University, Hefei. It is located at a latitude of 31°51’ 32.43” N and Longitude of 117°15’ 21.32” E, at an elevation of about 29m above the mean sea level (MSL) (fig 01).

Fig. 1. Location of plot.

The soil of the planted area is characterized by a clay texture with a water table depth greater than 3 m with irrigation quality ECw 1355 (ds/m),SAR 6.65 and RSC was nil. Average monthly temperature was29.25°C, evaporation was80.1mm, and rainfall was162.25mm during the entire growing season, which spanned from May to August 2016. The mean relative humidity was52% during the aforementioned months. The experimental plot was not in use for any agriculture purposes for more than two and half years resulting inthe soil surfaceto be very hard, requiring plowing using moldboard plow. The resulting big clods were then pulverized with the help of a rotator. The all plotswere then leveled thoroughlyusing spades. Theprepared land was then divided into two seedbeds: T1 (EFI) and T2 (AFI) for each treatment, for comparing the two treatments, respectively, witheach block measuring 165m². Furrows were constructed manually byusing spades. The distance betweentwo adjacentfurrows and two adjacent ridgeswas kept as1m. Total length of each furrow was 7m, while the width of experimental plots was11 m. Thus, 22 furrowseach were used for the alternate furrow irrigation (AFI) treatmentand for every furrow irrigation (EFI) treatment (fig 02).

Agronomic practices

A variety of Okra, *AbelmoschusesculentumL.*, was planted on 15th April, 2016, at an equal distance of 40 cm, andat a growing rate of 20 kg ha^{-1}. Two seeds were planted in each hole ata depth of 2–3 cm. To ensure the germination of every individual plant, all the blocks were irrigated immediately after finishing plantation. Six days after the first complementary irrigation,the seeds started germinatingunder both irrigation treatments. After germination, extra and weak plants were removed to maintain thecorrect distance between the plants. Thus, 54 plants grew on both sides of the 7 m ridge, totaling2376 plants in the experimental plot, where1188were each for AFI and EFI methods. Fertilizerswere applied to both experimental plots as per recommended doses(MINFAL 1997).

The complete dose of phosphorous (P_2O_5, 15.5%) and potassium sulfate (K_2SO_4, 48%) was applied at the time of sowing, and half dose of nitrogen (N_2, 33.5%)was applied after 30days of sowing, followed bythe remaining half dose after 60daysof sowing. The recommended fertilizer rates for okra were adopted by employing nitrogen (N) at 50 kg/acre, and phosphorus (P_2O_5) at 100 kg/acre.Cultural practices like thinning, weeding, and insects, pests and diseases control were carried out as appropriate.

Water application and measurement

Alternate furrowswere irrigated in AFI treatment while each furrow was irrigated in the EFI method. In the AFI method, water was delivered only to 5 odd furrowsduring first irrigation,while the remaining 6even furrows were irrigated during second irrigation, and so on. This practice was continued until the last irrigation was applied.

Waterapplied

Water applied (Wa) was calculated as;

$$Wa = Iw + Re + S \qquad (1)$$

Where,

Iw = irrigation water applied(m3 ha-1)

Re = effective rainfall

S = amount of soil moisture contributing to consumptive use either from stored moisture in the root zone and/or that from shallow water table. Value of S was neglected due to the long duration of the growing season.

Soil physico-chemical properties

In order to determine various physico-chemical properties, such as soil texture, moisture content at Field Capacity (Fc), dry bulk density(g cm^{-3}), soil pH, and electrical conductivity of soil (EC_e), thesamples were collected before sowing and after harvesting the crop, from ridges and furrowsofAFI and EFI treatments at different depths of 0–25, 25–50, 50–75 and 75–100cm (table 01, 02).

Consumptive water use (CWU)

In order to determine crop consumptive water use (CWU), in other words, crop evapotranspiration (ET_c).The soil samples were collected with a screw auger, before each irrigation, and three days after each irrigation. Samples were taken from both the ridge and bottom of the furrows at four different depths: 0–15, 15–30, 30–45 and 45–60cm. Samples were used to measure volumetric soil-water content in the root zone. CWU was calculated as reportedearlier (James, L.G. 1988).

$$CWU = (\theta_2 - \theta_1) \times Bd \times ERZ \qquad (2)$$

Where

CWU= water consumptive use in (mm),

θ_2 = percentage of soil moisture after irrigation,

θ_1 = percentage of soil moisture before the subsequent irrigation,

Bd = bulk density (g cm-3),

ERZ = the effective root zone(cm).

Water Saving (%)

The total water saved in AFI irrigation treatment was calculated by:

Water saving (%) = $\frac{WE-WA}{WE} \times 100$ (3)

Where;

W_E = total water used in EFI (mm)

W_A = total water used in AFI (mm)

Yield of crop

The yield of okra was weighted every time when harvested for AFI and conventional EFI methods. The increase/decrease in yield (%) compared to AFI was computed as under:

Increase in yield (%)= $\frac{YA-YE}{YE} \times 100$ (4)

Where;

Y_A = total yield with AFI (kg/ha)

Y_E = total yield obtained with EFI (kg/ha)

Crop Water Productivity (CWP)

CWP =$\frac{Y}{Wt}$ (5)

Where;

CWP = Crop water productivity (kg/m^3)

Y = Total Grain (kg/block)

Wa = Total water consumed (m^{3}ha^{-1}) including rainfall.

The total expenditure for both AFI and EFI treatments was calculatedconsideringthe total costsincurred in the experiment, starting from conception to conclusion of the experiment. For example:tillage, $35; furrow construction, $45;okra seed, $8; fertilizer and pesticide, $60; labor for weeding,$50,were based on the total planted area. The operating costs for AFI and EFI treatments were the same andtotaled$369. Fluctuation in costs depended on water unit price and the number of irrigation events. The water unit price was estimated to be US$0.05m^{-3}. Total water cost was calculated by multiplying the water unit price with the total amount of irrigation water required for the okra crop. Gross revenue was calculated using the formula:

NR = Gross revenue – Total costs (6)

Statistical analysis

ANOVA was performed with MStatC. Duncan's Multiple Range Test (DMRT) was used to determine significant differences between means at 0.05 probability level.

Results and discussion

The physical properties and bulk density of soil of planted area were examined at four different depth levels (table 2). The soil was medium textured with sand, silt and clay limits from 13 to 22%, 33 to 42% and 36 to 53%, respectively; there were no significant spatial and depth wise variation in sand, silt and clay soil. The soil bulk density of planted area with an average of 1.382 gcm^{-3}. There was no significant spatial and depth-wise trend in soil bulk density.

Table 1. Soil hydro-physical characteristics determined in the experimental field.

Parameters	Adopted Method	Reference	For	Equipment used
Soil texture	Bouyoucos Hydrometer	Bouyoucos(1962)	Soil	Hydrometer
Dry density	Core method	Mcintyre and loveday (1974)	Soil	Core sample, oven, balance
EC_e (dS/m)	1:2 Soil water extract	Rowell (1994)	Soil	Digital EC meter
pH	1:2 Soil water extract	Rowell (1994)	Soil	Digital pH meter

Soil pH & electrical conductivity

Fig 3 & 4; Shows the soil pH and electrical conductivity of saturated soil extract (ECe) were examined before sowing and after harvest of okra by collecting soil samples from four different depth levels of 0–25, 25–50, 50–75 and 75–100 cm under AFI and EFI treatments. Fig3 shows The soil pH values under AFI at different depths 0–25, 25–50, 50–75 and 75–100 cm samples were collected from furrow and ridge before the experiment were between 8.1 to 8.4and 8.0 – 8.2 respectively; and after experiment the values were from 7.9 to 8.2 and 8.0 –

8.3. Similarly, under EFI the soil pH values before experiment were 8.0 - 8.1, 8.3, and after experiment 7.9 – 8.2 respectively. These result indicted that the pH of soil slightly and irregularly increased after crop harvesting when compared to before experiment result due to leaching of salts from upper layers and their accumulation on lower soil layer. Even if soil pH is generally considered a major factor in controlling the soil microbial diversity and composition across a wide range of habitats (Fierer and Jackson, 2006), however in present study, the difference in pH values under both irrigation treatments was not significant.

Table 2. Soil particle distribution and textural classes of the profile before and after the experiment.

Soil depth	Sand %	Silt %	Clay %	Textural Class	FC(cm^3/m^3)	dry density (g/cm^3)	PWP, % ww)	Saturation Capacity (cm3 cm−3)	Infiltration Rate (mm/hr)
0-25	13.2	33.5	53.3	Clay	35.60	1.20	19.98	0.53	23
25-50	21.1	35.0	43.9	Clay	31.52	1.38	19.00	0.40	
50-75	22.0	40.8	37.2	Clay loam	31.50	1.48	18.80	0.42	
75-100	22.0	42.0	36	Clay loam	33.83	1.47	20.00	0.45	

The electrical conductivity of soil saturation extract (EC_e) represents the salinity status in soil (Liu and Yang, 2001). The $EC_e$of soil similarly at different four depths were slightly increased in upper layers under both irrigation treatments illustrated in Fig. 4; however it remained same i.e. 1.27ds/m at the depth of 75-100cm.These results suggest that the concentration of soil after the experiment under EFI method was observed maximum at top of ridge due to capillary action while solute transported downward in soil profile at furrow bottom under AFI and EFI methods.

Table 3. Total irrigation events, depth of irrigation water in every event and grain yield under both irrigation treatments.

Irrigation events	EFI treatment		AFI treatment	
	Water depth(mm)	Grain Yield(Kg)	Water depth(mm)	Grain yield(Kg)
First	120	33.5	115	31.2
Second	60	41.3	58	32
Third	75	44.1	36	36.7
Fourth	72	47.00	35	41.3
Fifth	71	47.00	33	42.2
Sixth	71	43.9	33	40
Seven	65	37.4	29	35.7
Eight		22	31	35
Total	534	316.2	370	294.1

The experimental results were similar to those reported by Xia *et al.* (2010) who concluded that the soil electric conductivity increased in surface soil layer in EFI probably due to high evapotranspiration from soil surface. There was more space for water lateral movement in AFI with lower evapotranspiration pull. Thus, AFI had more space for lateral seepage of soil water and lower loss. The soil surface temperature was higher in AFI treatment, especially in non-irrigated furrow and ridge, which was beneficial for crop growth at the seeding stage. These results are similar to Xia *et al.* (1997). Moisture content at Field Capacity of 33.11 was determined using pressure plate apparatus.

Irrigation water applied and yield

The total volume of irrigation water applied to T1 (EFI) and T2 (AFI) plots is shown in Table 3. The total volume of applied water to T1 and T2 was 534 and 370 mm, respectively. This indicated that the plot under AFI treatment saved approximately 43% of water compared to the plot under EFI treatment. The decrease in applied water for AFI was a result of irrigating only alternate furrows and not every furrow, which likely decreased water evaporation and deep drainage losses. The lower amount of applied water for AFI is probably because of a reduction of wetted surface in AFI; almost half of the soil surface was wetted in AFI as compared with EFI. Our results demonstratethat 40–43% water savings were obtained by using AFI compared with EFI.These findings concordwith earlier reports(Crabtree *et al* 1985, El-Sharkawy 2006, Sepaskhah *et al* 2008, Nelson 2011), which indicated reduced irrigation water use by the AFI method.

Table 4. Otal cost = operating and applied water cost.

	AFI	EFI
Applied water m^{-3}	1708.49	3270.30
Cost of applied water $	85.42	163.51
Total cost $	454.42	532.51
Total yield kg ha^{-1}	15096.96	19163.63
Total gross revenue ha^{-1}	21437	27212
Net revenue ha^{-1}	20982.5	26679.4

Crop yield

The total crop yields of okra obtained with AFI and EFI aredetailed in Table 3. Okra pickingwas carried out around 50 days after planting. The highest yield with AFI and EFI treatments was 15096.96 kg ha^{-1} and 19163.63 kg ha^{-1}, respectively. Grain yield for EFI was higher than AFI by 26.93 kg ha^{-1}. Due to less irrigation water being applied, AFI treatment slightlyreduced grain yield. However, the yield reduction was not statistically significant. Similar yield reductions have also been reported for AFI compared to EFI (Rafiee *et al* 2010), in particular for sorghum and soybeans (Crabtree 1985,Sepaskhah *et al* 2005).

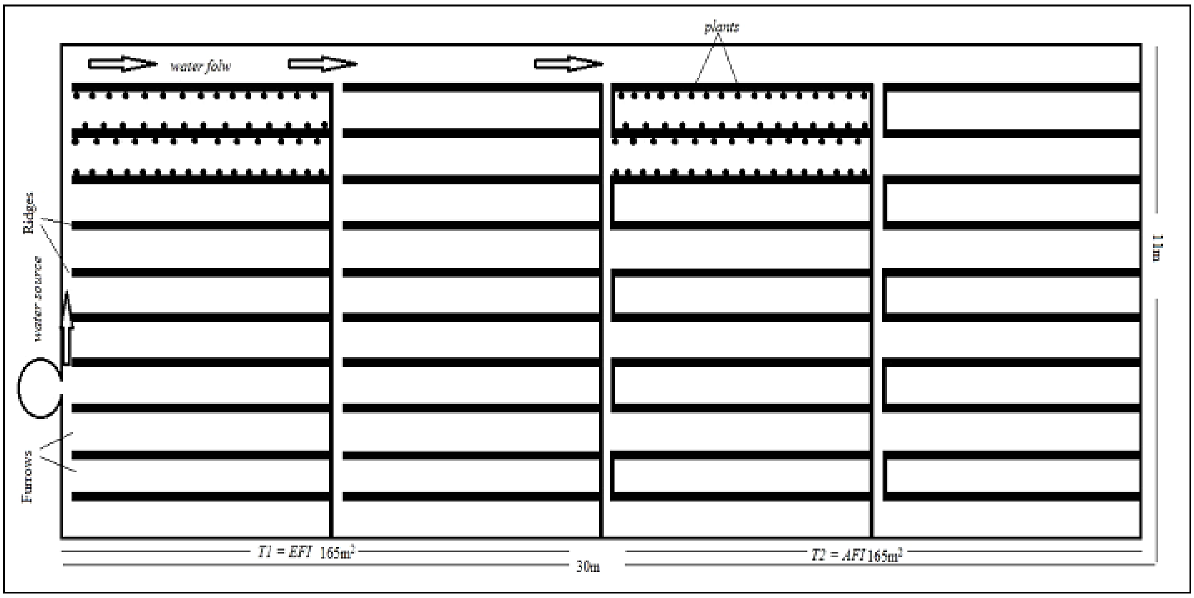

Fig. 2. Experimental site layout.

Yield response of the okra cropfrom AFI versus EFI is shown in Figure 5a, b. T1 (EFI) plot consumed 534mm of irrigation water, and gave a maximum yield of 316.2 kg, which is equivalent to 19163.63kg ha^{-1} of okra. The grain yield in T2 (AFI)increased from 31.2kg at 115mm to a maximum of 42.2kg at 33mm,resulting in a total yield of 294.1kg, which is equivalent to 15096.96kg ha^{-1} at 370mm of irrigation water.In the AFI plots,okra plant rootswere partially wetted, which may have resulted in reduced stomatal conductance, and plant transpiration.However, photosynthesis and dry matter accumulation may have been less affected by this partial stomatal closure(Kang *et al* 2000a). In addition, the roots on the irrigated side of the furrow (wet soil) will continue to take up water to meet the required water demand of the plant(Ahamdi *et al* 2010).

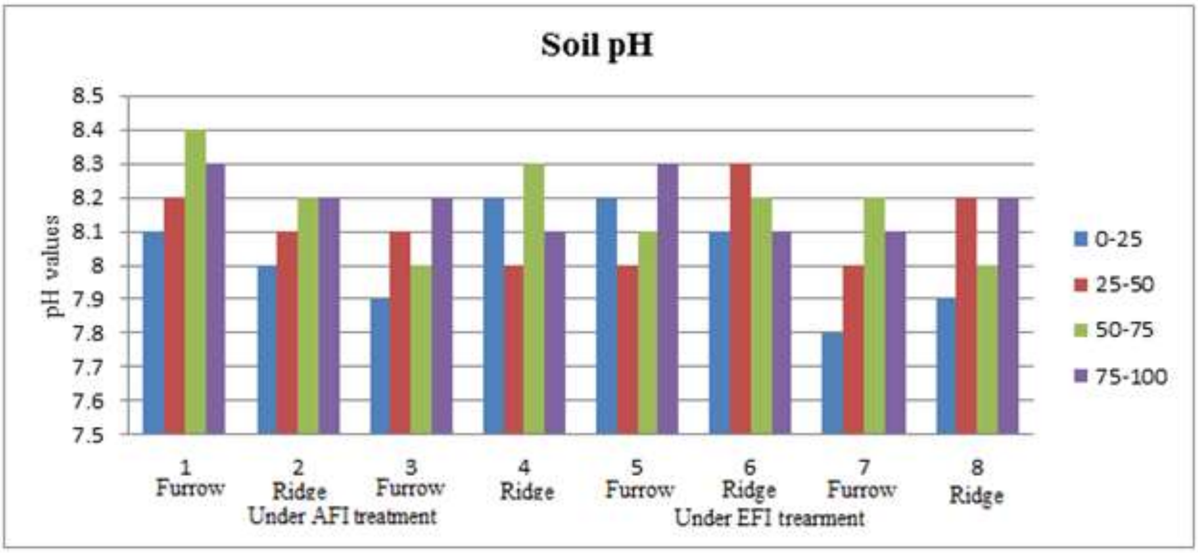

Fig. 3. Illustrate the pH value.

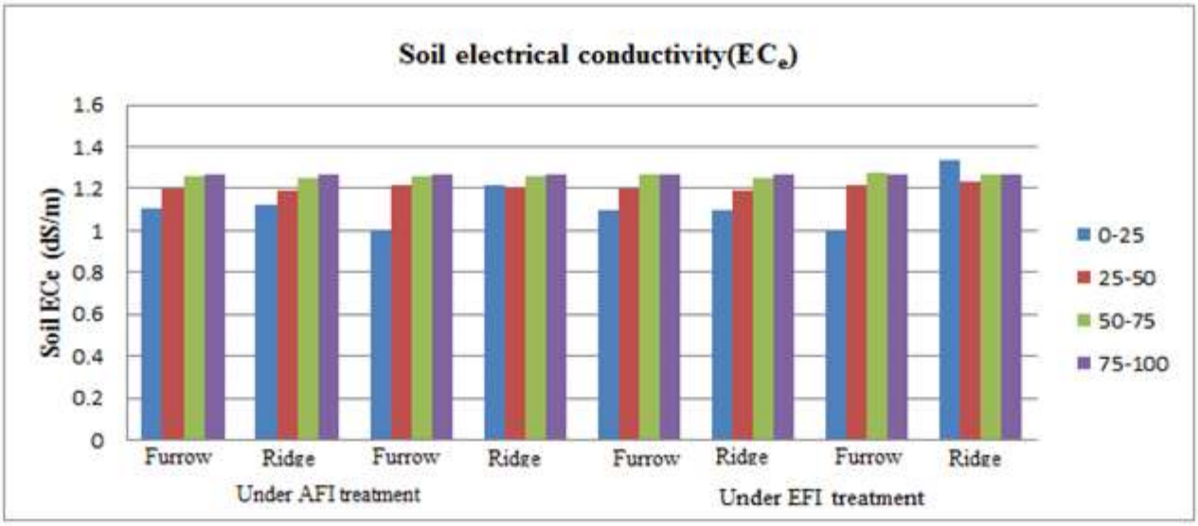

Fig. 4. Soil electrical conductivity under both irrigation treatments.

Partial root zone drying (as seen with AFI) has been reported to yield better fruit quality and crop water productivity in areas with limited water resources(Sepaskhah *et al* 2010). The yield and water use efficiency of okra under AFI and EFI irrigation treatments demonstratedhighercrop water productivity (CWP)of 5.21 kg m^{-3}from AFI compared to EFI (2.93kg m^{-3}).The variation in CWP between the two treatments was highly significant ($p < 0.001$),which highlights the remarkable effectthat method of irrigation has on CWP. This is also in agreement with previous findings (Stone *et al* 1982), whichreported that AFI treatments resulted in a slight decrease in crop yield but increased water productivity. Similarly, others (Rafiee *et al* 2010)have also reportedthat AFI enabled more efficient use of irrigation water but resulted in a lower crop yield, and this was associated with waterstress compared to EFI.

Economic analysis and benefits obtained

The total expenditure and net returns from AFI and EFI treatment is shown in Table 4. As shown,the operating expenditure per hectare was the same between the two treatments. However, crop production per hectare ornet return (NR) was significantly affected by the type of irrigation treatment employed.

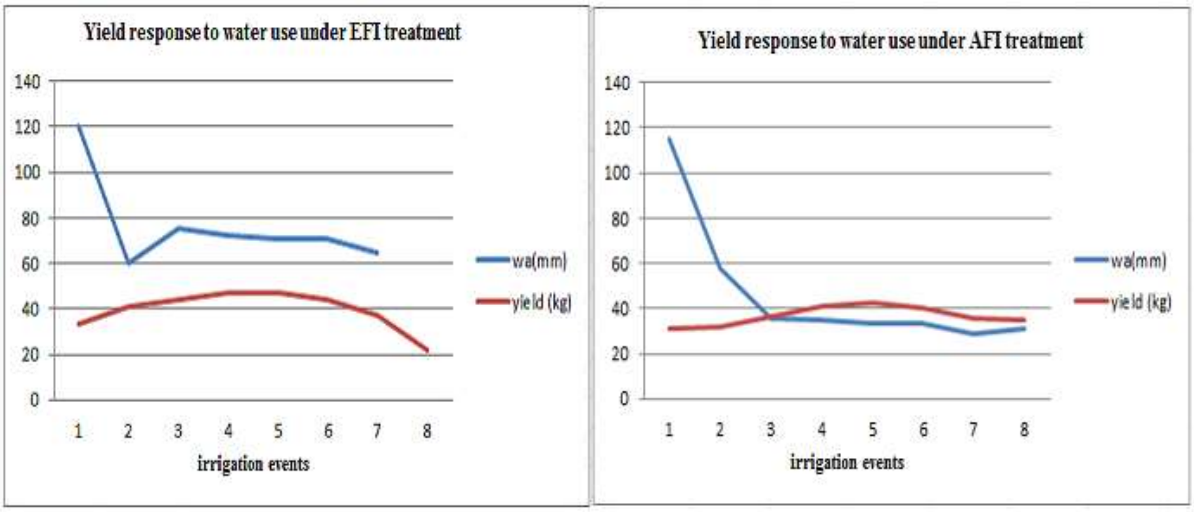

Fig. 5 a,b. Okra yield and water relationship under different irrigation treatments.

The net return with EFI was $26,679.4 ha^{-1}, whereas net return with AFI was only$20,982.5 ha^{-1}.It is to be noted that water charges are based on the type of crop, and the area of crop that is irrigated, and not on the volume of water accessed for irrigation. Our results demonstrate that the farmer who saved 40%of water by using AFI compared to EFI will have reduced NR by 5696 kg ha $^{-1}$, indicating that the farmer who employedAFI compared to EFI will have about 7%less ($416) revenueif they sell their total crop.

Conclusions

In the present field experiment carried out to evaluate the performance of AFI versus EFI, the following are the main advantages we observed: (a) AFI results in water saving of 40-43% compared with EFI, (b) AFI reduced okra yield by 26.93 kg ha^{-1}, which was not statistically different from EFI, (c) AFI resulted in water saving through increased irrigation water use efficiency, leading to a crop water productivity (CWP) of 5.21 kg m^{-3} compared to EFI (CWP, 2.93 kg m^{-3}), and (d) AFI may improve the solute transport in shallow root zone, Based on the results of our field experiment, it will be very difficult to convince the farmer to switch to the AFI method for saving irrigation water, when they know that AFI results in decreased crop yield and net return, compared to the EFI method. A global mind shift is required for enabling substantial changes in water irrigation methods to reap the benefits of AFI.

These lessons are important to consider for other countries too, particularly developing countries who are trying to improve the environmental, social, and economic performance of their irrigation methods. Based on our current observations, we recommend that governments should focus on introducing AFI among their farmers, particularly where irrigation water is very scarce.

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