Water SA 48(3) 264–270 / Jul 2022
https://doi.org/10.17159/wsa/2022.v48.i3.3913

Research paper

Improving water use efficiency and biomass in maize, foxtail millet and bitter vetch by wick irrigation

Hassan Heidari[1], **Zhaleh Zarei**[1] **and Kazhal Mohammadi**[1]

[1]Department of Plant Production and Genetics Engineering, Faculty of Agricultural Science and Engineering, Razi University, Kermanshah, Iran

Water is one of the most important environmental factors in agriculture. Drought annually damages agricultural products. This loss can be reduced by some strategies. Pot and field experiments were conducted to assess the effect of wick irrigation on growth, yield and water use efficiency of maize, foxtail millet, and bitter vetch. Irrigation treatments included wick and surface irrigation (control) methods. Results of the pot experiment showed that wick irrigation had higher total fresh weight, total dry weight, and water use efficiency as compared to surface irrigation in both foxtail millet and bitter vetch. In foxtail millet, wick irrigation also had higher leaf to stem ratio, plant height, leaf relative water content and leaf area compared to surface irrigation. Results of the field experiment showed that wick irrigation increased specific leaf weight, water use efficiency, stem diameter, leaf fresh weight, total fresh weight, leaf dry weight, total dry weight, and leaf to stem ratio, but had similar fresh and dry stem weight and plant height compared to surface irrigation in maize. It is likely that the reduction in surface evaporation, reduced water consumption, and increased dry matter resulted in increased water use efficiency in wick irrigation. Overall, wick irrigation had higher water use efficiency, biomass, and plant growth compared to surface irrigation in maize, foxtail millet and bitter vetch.

CORRESPONDENCE
Hassan Heidari

EMAIL
heidari1383@gmail.com

DATES
Received: 16 June 2021
Accepted: 27 June 2022

KEYWORDS
capillary movement
drought
surface irrigation
water use efficiency
wick irrigation

INTRODUCTION

Drought is one of the main problems of agriculture in arid and semi-arid regions. Drought has restricted almost 25% of the world's land production (Valadabadi and Aliabadi Farahani, 2008). Iran is located in an arid area and water is a vital element for crop growth and development, so strategies that can significantly reduce water consumption, improve water use efficiency and increase the productivity of field crops have been the focus of many researchers. Agriculture is often hampered by insufficient rainfall. Therefore, proper irrigation systems are required since they can guarantee crop yields (Car, 2012).

High evapotranspiration is characteristic of arid and semi-arid regions. There are also limited water resources in these areas (Lehmann et al., 2019). The use of conventional irrigation methods such as surface irrigation results in high moisture losses due to evapotranspiration. The use of subsurface irrigation methods may be able to reduce moisture loss (Hansona, 1997). Wick irrigation is a subsurface irrigation system that relies on capillary flow. In this method, water is moved from a water reservoir directly through a wick to the root zone (Yeager et al., 2004). The wick irrigation system is made of a water reservoir, hose, and wick. The hose protects the wick moisture from evaporation. The main component of the wick irrigation system is the wick, which provides water to the plant root as needed. The wick component draws water from the reservoirs to the plant root zone. The wick can be made of cotton, nylon, blanket materials or polyester cloth materials (Wesonga et al., 2014). The best material in terms of cost, durability, and capillary is glass wool. Plastic materials such as the wastewater bottles or PVC pipe can be used to prepare the water reservoir. If the plants are planted in pots, then after filling the pot with soil and planting the plant in the pot, about 10 cm of the wick should be placed in the soil to bring water to the root zone. Water will be conducted to the root zone by capillary movement so the soil is not flooded and gradual moisture is provided to the soil and roots of the plant. The gradual consumption of water in the soil reduces the evaporation level and the plant will have constant access to water. The wicks provide water and nutrients from the solution in which they are placed as needed by the plant. Therefore, this irrigation method is an automatic irrigation system that reduces the need for labour (Joseph, 2016).

There is currently much research interest in small-scale irrigation systems for small farmers. Laboratory studies have been performed to investigate the hydraulic properties and efficiency of cotton materials for use as wick emitters. In addition, greenhouse studies have been performed to simulate the movement of water and elements in the eggplant root zone (Muhammed, 2016). Eggplant was grown in the greenhouse in two growing media (peatgro and sandy clay loam) under the wick irrigation system in Malaysia. The simulation of water distribution showed that wetted zone extension depended on water application periods and the hydraulic properties of the medium (Rowshon et al., 2019). In a study on turnip, some clay pitchers had holes drilled in the bottom and wicks placed in them (W1), some other pitchers had holes drilled in the middle of the pitcher (W2) while the rest were used without drilling and without wick (P1). The crop water productivities in treatments of P1, W1, and W2 were 29.2, 16.9, and 24.32 kg/m^3, respectively (Bhayo et al., 2018).

Among the various subsurface irrigation systems, a wick irrigation system is a suitable method for controlling the use of fertilizers, water and pesticides, and improving production efficiency, and is widely used in places with high evapotranspiration (Oh et al., 2007). In a study conducted by Semananda et al. (2018), the results showed that traditional capillary irrigation systems had higher crop yield and water use efficiency compared to conventional irrigation methods. In the experiment, a nutrient film technique (NFT) hydroponic system had an 83% lower leaf area in greenhouse lettuce (*Lactuca sativa* L.) than a wick irrigation system with wicks made of either pine bark (WPB) or coconut coir (WCC) (Ferrarezi and Testezlaf, 2014). The fresh and dry shoot weights with NFT were 58% and 24% lower than with WPB and WCC, respectively. Wick irrigation had a yield increase of 54.6% in tomato (*Solanum lycopersicum*) when compared to the basin irrigation method; and an 82.43% water-saving was obtained using wick irrigation (Bhatt and Kanzariya, 2017). Increased yield by wick irrigation occurs because water is applied directly to the roots, thus minimizing drainage and evaporation losses and ensuring that water is more efficiently provided to the plant than with the basin irrigation method.

In a study on three methods of irrigation – sprinkler, subsurface, and wick – it was reported that wick irrigation is an effective method for producing high quality azaleas (Million et al., 2007). In another study, soil substrates made of Smart Capillary Barrier Wick (SCB-W), containing silt loam blocks enclosed in sand-sheathes and watered with a sand wick cylinder had higher water storage (by 44.3–52.4%) than control substrates (homogenous soil irrigated by the same wick system). SCB-W can be suggested as a method to improve water conservation in home gardens (Al-Mayahi et al., 2020). Water productivity of green pepper (*Capsicum annuum* L.) grown in the field under wick irrigation system (36.6 g/L) was higher than with drip irrigation (9.9 g/L). A similar trend was observed for eggplant (*Solanum melongena* esculentum) (Orge and Sawey, 2019).

One type of irrigation system that works similarly to wick irrigation, in that water is provided below the surface, is subsurface drip irrigation. Subsurface drip irrigation has been shown to lead to a quantitative and qualitative increase in yield and water use efficiency compared to surface irrigation (Thompson et al., 2009). Sub-surface drip irrigation has resulted in crop water productivity and irrigation water productivity increases of 24.95% and 19.59%, respectively, when compared to flood irrigation. Plants irrigated by the sub-surface method showed higher water use efficiency and lower transpiration rates compared to those subjected to flood irrigation. Sub-surface irrigation optimized seed yield and reduced water loss to defeat drought in winter wheat (Umair et al., 2019). The benefits of sub-surface irrigation include a reduction in deep percolation, soil salinity control, and net income increase (Hanson and May, 2003). In a study by Singh et al. (2009), drip irrigation had the greatest effect on growth parameters such as plant height, leaf area index, and dry matter compared to surface irrigation.

Due to the lack of water resources in arid and semi-arid regions, it is necessary to make maximum use of available resources. In arid and semi-arid regions, the rate of evapotranspiration is higher than rainfall. Due to the high evapotranspiration potential, the use of surface irrigation methods is not advised, and subsurface irrigation could be more appropriate. Wick irrigation is one of the methods that has not received much attention from researchers. There has been little research on water use efficiency and dry matter production under wick irrigation, and the research that has been done in this field has often been preliminary and focused on wick construction. This research therefore aimed to conduct a comprehensive study, including measuring plant growth traits, plant physiological traits, and water use efficiency under wick irrigation conditions, and specifically examining the water use efficiency and dry matter production of foxtail millet, bitter vetch, and maize under the wick irrigation method.

MATERIALS AND METHODS

Pot experiments

The pot experiment was conducted at the greenhouse at the Agricultural and Natural Resources Campus, Razi University, Kermanshah, in 2016. Foxtail millet (Poaceae) and bitter vetch (Fabaceae) were selected as test crops and tested separately. The experimental layout was a completely randomized design with 3 replications. Experimental treatments included wick irrigation and surface irrigation (as control). On 8 November 2016, for each crop type, 6 pots with a diameter of 15 cm and a height of 20 cm were prepared and filled with field soil and kept in the greenhouse. After emergence, the weak seedlings were removed, and the healthy seedlings were thinned to 10 plants per pot. In surface irrigation, the water requirement of the plant was determined visually with the help of soil colour and plant symptoms such as leaf turgor. Before the experiment, a pot containing soil only was placed in the greenhouse and irrigated before the soil dried out completely, to determine the appropriate irrigation interval. The field capacity of the pot was determined visually with the help of the soil colour change due to wetting. Water was gradually added to the pot, until it was observed that the soil was completely wet. In the surface irrigation pots, water consumption was based on atmospheric demand, and the timing of irrigation was determined visually by plant and soil symptoms, while aiming not to expose the plant to drought stress during the growing season. In wick irrigation, water consumption was based on atmospheric demand and the water reservoir was refilled before the water in the water reservoir ran out. The water consumption of each plant is given in Tables 1 to 3. Greenhouse air relative humidity and temperature were 50% and 20°C, respectively.

Field experiment

The field study was conducted at The Research Field, Agriculture and Natural Resources Campus, Razi University, Kermanshah, Iran (34°21' N, 47°09' E, and elevation 1 319 m amsl) in 2015. The field experiment was performed as a randomized complete block design with 3 replications. Experimental treatments included a surface irrigation regime and wick irrigation regime. The seedbed was prepared uniformly. In this study, maize (CV. SC. 704) was used. The distance between experimental plots was 1 m and, due to the limited water transfer by wicks, the dimensions of each experimental plot were small, at 1 m × 2 m. Each plot included 3 rows of maize plants. For the first month after planting, all treatments were surface-irrigated every 2 days. After this period, the wick system was designed and applied in the wick irrigation treatment. The water reservoir in the wick system was regularly filled up. Water consumption for the wick and surface irrigation treatments was recorded. In the surface irrigation treatment, (control) water was applied conventionally using the basin irrigation method. The soil around the plots was raised so that there was no run-off. Water was then applied to each plot and the soil was flooded, once a week. Soil and water electrical conductivity (dS/m) were 1.6 and 0.6, respectively. Figure 1 shows the basic climatic data which applied during the plant growth period (Weatherunderground, 2022).

Wick irrigation system

A tool was made for wick irrigation, which consisted of a reservoir, a hose and a wick. The reservoir included a water inlet valve, an inlet valve cap and a hole for interring the wick. The hose acts as a protector for the wick and conducts the wick from water reservoir to below the surface of the soil and to the plant root zone. It also protects the wick and moisture of the wick against sunlight and wind. Wick draws water from the reservoir to the root zone by capillary movement. The wick was made of cotton to easily absorb water and make it available to the plant roots. As can be seen in Figs 2 and 3, each water reservoir has 3 outlets for wick irrigation; each outlet was allocated to one pot in the pot experiment or one plot in the field experiment. The field experiment was conducted on a small scale, the reason being that water transfer with wicks from the water reservoir to the field soil can be disrupted. At the end of each wick, about 10 cm of the wick was outside its protection, the hose, so that the wick was in direct contact with the soil. The wicks were placed at a depth of 10 cm in the soil to provide moisture to the roots of the plants and so that less moisture reached the soil surface, thus reducing soil evaporation. During the experiment, the outflow from the wicks was checked (the soil around the wicks was inspected) to ensure that the wicks were working.

Plant trait measurements

On 22 December 2016, when foxtail millet and bitter vetch plants reached the desired growth, pots were transferred to the laboratory. Four plants per pot were randomly selected and stem fresh weight, leaf fresh weight, total fresh weight, stem dry weight, leaf dry weight, total dry weight, leaf to stem ratio, plant height, leaf relative water content, leaf area, leaf number, specific leaf weight, and water use efficiency were measured. In the field experiment, 6 maize plants per plot were randomly selected to measure stem fresh weight, leaf fresh weight, total fresh weight, stem dry weight, leaf dry weight, total dry weight, leaf to stem ratio, stem diameter, plant height, leaf relative water content, leaf area, specific leaf weight, and water use efficiency. Plants were cut before tasseling.

A ruler was used to measure plant height and main stem length. The leaf numbers were also recorded. To determine the relative water content of the leaf, one of the plants was cut and its leaf blades were separated. Leaves were weighed immediately to measure fresh weight. Then leaves were saturated in distilled water

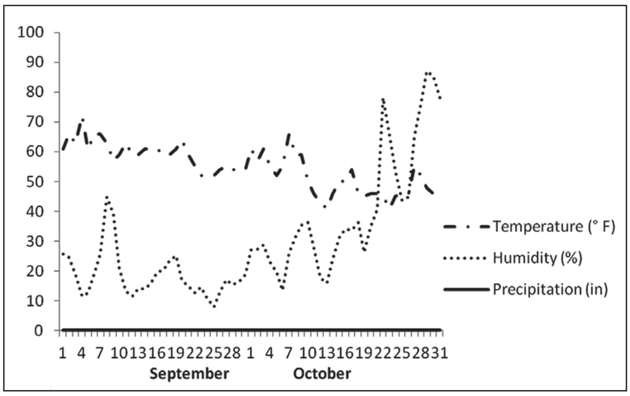

Figure 1. Climatic data for Kermanshah where the field experiment was conducted

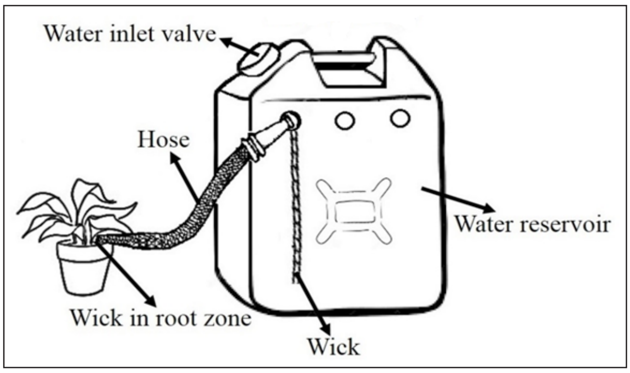

Figure 2. A view of the wick irrigation system in the pot experiment

for 16 to 18 h to measure turgid weight. The leaves were then laid in an oven at 70°C for 24 h and their dry weights obtained. Finally, the relative water content of leaves was calculated based on Eq. 1 (Turner and Kramer, 1980).

$$\text{RWC\%} = (\text{FW-DW}) / (\text{TW-DW}) \quad (1)$$

where RWC is relative water content of leaf (%), FW is leaf fresh weight (grams per plant), DW is leaf dry weight (grams per plant), TW is leaf turgid weight (gram per plant).

For measuring parameters such as leaf fresh weight, stem fresh weight, stem dry weight, leaf dry weight and total dry weight, an accurate electronic scale with a precision of 0.001 g was used. Foxtail millet and maize leaf area (LA) were calculated from Eq. 2 (Heidari, 2012).

$$\text{LA (cm}^2) = \text{leaf width (cm)} \times \text{leaf length (cm)} \times 0.75 \quad (2)$$

Specific leaf weight (SLW, g/cm^2) was calculated using leaf dry weight (LDW, gram per plant) and leaf area (LA, cm^2) according to Eq. 3 (Heidari, 2012).

$$\text{SLW}=\frac{\text{LDW}}{\text{LA}} \quad (3)$$

Water consumption was measured using a graduated container, i.e., before pouring water into the soil in the surface irrigation method, the volume of water used was measured. In the wick irrigation method, the volume of water poured into the wick irrigation reservoir was measured with a graduated container, and if the reservoir water ran out, the required amount was added from the graduated container. Water consumption was calculated cumulatively for the whole growth period.

Water use efficiency (WUE) was calculated based on Eq. 4 (Farre and Faci, 2006):

$$\text{WUE} = \frac{\text{Bi}}{W_{\text{ap}}} \quad (4)$$

where Bi is produced biomass (g) and W_{ap} is water consumption (m^3).

Statistical analysis

The data were analysed using SAS software (Version 9.2). The means were compared using LSD test at $p = 0.05$.

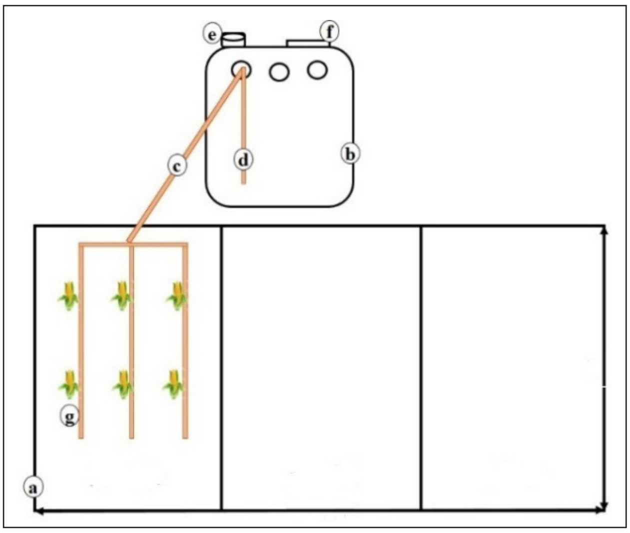

Figure 3. A view of the wick irrigation system in the field experiment. a: Experimental plot, b: water reservoir, c: hose, d: wick, e: water inlet valve, f: water reservoir handle, g: location of the wick in the root environment

RESULTS AND DISCUSSION

Leaf, stem and total fresh weight

Comparison of means showed that wick irrigation increased the leaf, stem, and total fresh weight in both foxtail millet and bitter vetch plants compared to surface irrigation (Tables 1 and 2). In maize, there was no significant difference between irrigation methods in terms of stem fresh weight, but wick irrigation increased leaf and total fresh weight compared to surface irrigation (Table 3). In surface irrigation, the water is periodically available for the plant; the plant is therefore exposed to drought during each irrigation interval. Under drought conditions, dehydration occurs and cell size reduces. The shoot is more sensitive to these occurrences than the roots, so more photosynthetic reserves are allocated to the roots and the weight of the aerial parts is reduced (Nakhaei et al., 2013). Increasing stress reduces the leaf area index and turgor pressure in the cells. Reduction in turgor pressure causes less water to remain inside the cells, resulting in reduced cell volume, cell weight, and ultimately forage yield (Haji-Hasani-Asl et al., 2010). It has been reported that fresh weight loss by increasing irrigation intervals may occur due to lower photosynthesis and too much water loss from leaves (Rauf, 2008). Drought decreases photosynthesis and decreases plant growth by closing stomata and decreasing leaf area (Moosavi et al., 2011).

One of the problems of surface irrigation is runoff. Some nutrients, especially nitrate and phosphate, enter water resources through runoff and cause pollution of groundwater and surface water (Ferrarezi et al., 2015). Subsurface irrigation improves plant growth by maintaining leaf water, causing early maturity, and reducing weeds, pests, and disease damage (Fanish, 2013). Probably, wick irrigation has minimized water loss to the depths of the soil as well as wetting the soil surface, which could reduce surface evaporation. Despite less water consumption during wick irrigation, more water is available for the plant root so drought is postponed and plant fresh weight is maintained.

Leaf, stem and total dry weight

Comparison of means showed that wick irrigation compared to surface irrigation increased leaf dry weight, stem dry weight, and total dry weight in both foxtail millet and bitter vetch plants (Table 1, 2). In maize, there was no significant difference between irrigation methods in terms of stem dry weight, but wick irrigation increased leaf and total dry weight compared to surface irrigation (Table 3). Access to soil water is the most important factor in determining crop yield in semi-arid areas (Stone et al., 2001). High evapotranspiration and water resource restriction reduce the growth period and decrease the yield of crops (Payghozar et al., 2009). In a study on millet, it has been declared that with increasing irrigation intervals and drought, the growth rate and yield components of millet decreased significantly and eventually caused a significant decrease in biological yield (Hayati et al., 2012).

Reasons for increased plant growth in subsurface irrigation include less water consumption (James and Van Iersel, 2001), ease of use of pesticides (Rouphael et al., 2006), reduced growth period (Pennisi et al., 2005), and reduced disease (Oh and Son, 2008). In subsurface irrigation water is supplied at depth and is directly available to the root. As a result, the water in the plant root zone is less susceptible to wind loss and evapotranspiration (Kieffer and Campbell, 2009). In wick irrigation, water is constantly available to the plant. This can improve plant growth and thus increase dry yield compared to surface irrigation.

Low water flow in wick irrigation can improve plant rhizosphere ventilation and control runoff and soil erosion. One of the problems of surface irrigation is soil crusting. Soil crusting can restrict plant growth and increase evaporation (Lal and Stewart, 2012). In surface irrigation, it appears that high water volumes cause the soil pores to be filled with water, which can be a factor in reducing oxygen availability, and hindering the development of the plant root and shoot (Brisson et al., 2002).

Leaf to stem ratio

Comparison of mean values showed that wick irrigation increased the leaf to stem ratio of foxtail millet and maize compared to surface irrigation (Tables 1 and 3). But in bitter vetch plants there were no significant differences between the two irrigation methods in terms of the leaf to stem ratio (Table 2). The high leaf to stem ratio in the millet plant represents plant investment in the leaves.

Table 1. Comparison of mean values for foxtail millet traits under wick and surface irrigation

Irrigation method	Stem fresh weight (g)	Leaf fresh weight (g)	Total fresh weight (g)	Stem dry weight (g)	Leaf dry weight (g)	Total dry weight (g)	Leaf to stem ratio	Plant height (cm)	Leaf relative water content (%)	Leaf area (cm²)	Leaf number	Specific leaf weight (g/cm²)	Water consumption (mL)	Water use efficiency (g/m³)
Wick	0.39 a	0.29 a	0.68 a	0.05 a	0.07 a	0.12 a	1.70 a	16.86 a	90.63 a	195.4 a	10.0 a	0.003 a	24	5 066 a
Surface	0.24 b	0.18 b	0.42 b	0.03 b	0.05 b	0.08 b	1.26 b	14.79 b	70.06 b	117. 6 b	9.3 a	0.004 a	83	960 b

Means in each column with the same letter have no significant difference based on LSD test

Table 2. Comparison of mean values for bitter vetch traits under wick and surface irrigation

Irrigation method	Stem fresh weight (g)	Leaf fresh weight (g)	Total fresh weight (g)	Stem dry weight (g)	Leaf dry weight (g)	Total dry weight (g)	Leaf to stem ratio	Plant height (cm)	Leaf relative water content (%)	Leaflet number	Water consumption (mL)	Water use efficiency (g/m³)
Wick	0.85 a	0.48 a	1.33 a	0.11 a	0.19 a	0.30 a	2.39 a	12.49 a	78.02 a	36.33 a	25	11 998 a
Surface	0.31b	0.39b	0.71b	0.06b	0.10b	0.16b	2.41a	13.55a	69.45a	38.66a	82	1 959b

Means in each column with the same letter have no significant difference based on LSD test

Table 3. Comparison of mean values for maize traits under wick and surface irrigation

Irrigation methods	Stem fresh weight (g)	Leaf fresh weight (g)	Total fresh weight (g)	Stem dry weight (g)	Leaf dry weight (g)	Total dry weight (g)	Leaf to stem ratio	Stem diameter (mm)	Plant height (cm)	Leaf relative water content (%)	Leaf area (cm²)	Specific leaf weight (g/cm²)	Water use efficiency (g/m³)	Water consumption (L)
Wick	7.66 a	8.38 a	16.05 a	1.17 a	1.38 a	2.55 a	1.24 a	8.01 a	13.30 a	72 a	51.10 a	0.03 a	127.58 a	19.99
Surface	6.32 a	4.34 b	10.67 b	0.80 a	0.87 b	1.68 b	1.08 b	6.05 b	14.33 a	67 a	62.37 a	0.01 b	101.90 b	16.49

Means in each column with the same letter have no significant difference based on LSD test

This can be attributed to the timely and sufficient supply of water to the plant in wick irrigation. It has been argued that drip irrigation minimizes water loss by reducing surface evaporation and increasing penetration depth (Fanish, 2013). One of the reasons for the non-significant difference in bitter vetch leaf to stem ratio between the two irrigation methods could be the uniform effect of drought on dry matter compartmentation and dry weight loss in all above-ground parts (Nakhoda et al., 2000).

Plant height, leaf number, and stem diameter

In foxtail millet, wick irrigation increased plant height compared to surface irrigation (Table 1). Comparison of means showed that there was no significant difference between irrigation methods in terms of leaf number of millet, plant height and leaf number of bitter vetch and plant height of maize (Tables 1–3). Wick irrigation had a higher stem diameter than surface irrigation in maize (Table 3). In surface irrigation, water is available periodically and this may cause water stress to the plant between irrigation intervals. Hence, a reduction in plant height due to drought can be attributed to the disruption of photosynthesis. In this condition, dehydration occurs and the production of photosynthetic materials for aerial and growing parts of the plant is reduced. Finally, these conditions cause a failure to reach the genetic potential for plant height (Jamshidi et al., 2012; Jabbari et al., 2015). Other studies have also shown that drought reduces plant height (Moaveni et al., 2009) and stem growth and development (Payero et al., 2009). It has been reported that drip irrigation resulted in greater plant height in tomato plants than surface irrigation (Subba Reddy et al., 2015). One study concluded that stem diameter under subsurface irrigation was greater than that under surface irrigation (Davis et al., 2011).

Leaf relative water content

Comparison of means showed that wick irrigation increased the leaf relative water content of foxtail millet compared to surface irrigation (Table 1). In bitter vetch and maize, there was no significant difference between irrigation methods in terms of leaf relative water content (Table 2, 3). Since the leaf relative water content indicates the moisture content of the plant, the plant was likely exposed to moisture stress in surface irrigation. In a review by Fazeli Rostampour et al. (2010), it has been reported that the leaf relative water content is decreased under water stress. However, in wick irrigation, due to constantly keeping the moisture in the root zone, the plant was not exposed to moisture stress. High leaf relative water content may be due to mechanisms such as reducing water loss through the closing of the stomata, or because of greater water absorption through the roots and the ability to suck more moisture from the soil (Jiang and Huang, 2001). Subsurface irrigation keeps the soil water content in the root zone at a desirable level. Also, the water required for the plant is slowly released and consumption can be controlled. This causes the soil water potential to be relatively high and water absorption becomes easy (Fanish, 2013). Under these conditions, the plant had a relatively good moisture content.

Leaf area and specific leaf weight

Comparison of means showed that wick irrigation resulted in a higher leaf area than surface irrigation in foxtail millet (Table 1). There was no significant difference between the two irrigation methods in terms of specific leaf weight in foxtail millet (Table 1). Wick irrigation had a higher specific leaf weight than surface irrigation in maize (Table 3). There was no significant difference between the two irrigation methods in terms of leaf area in maize (Table 3). Moisture deficit reduces leaf area index through reducing production and increasing leaf aging (Cakir, 2004). Also, reduction of leaf area is probably due to the reduction of cell size, leaf relative water content, cell division, leaf growth, leaf number, accelerated aging, and leaf loss (Lobato et al., 2008). Leaf area reduction is a plant response to stress as a result of water shortage. This response can reduce cell turgescence, leaf growth and development, and transpiration (Moosavi et al., 2011). Drought reduces water loss and transpiration and subsequently reduces leaf area and leaf number per plant (Khurana and Singh, 2000).

Water use efficiency

Comparison of means showed that wick irrigation increased water use efficiency compared to surface irrigation in foxtail millet, bitter vetch, and maize plants (Tables 1–3). Water use efficiency is an important tool for evaluating the productivity of a water consumption unit (Vimalendran and Latha, 2014). It seems that in wick irrigation the plant is less susceptible to drought. Thus applying moderate stress can lead to improved water use efficiency, but severe stress has an adverse effect on water use efficiency and causes a significant reduction (Mehrpuoyan and Faramarzi, 2011). In subsurface irrigation, water use efficiency increases compared to surface irrigation due to lack of surface evaporation and runoff, a decrease in deep percolation (Jiang and Huang 2001), and improvement of plant growth and soil moisture (Elhindi et al., 2016). Increased water use efficiency has also been reported in subsurface irrigation due to transpiration reduction, deeper growth of roots (Kieffer and Campbell, 2009), and efficient use of water and fertilizer (Reddy et al., 2017). In one study, the high water use efficiency in drip irrigation was mainly due to significant saving in the amount of irrigation water applied, increased yield of crops, and better nutrient use efficiency (Vimalendran and Latha, 2014). In addition, it has been reported that wick irrigation reduced water consumption by 86% compared to sprinkler irrigation, while plant growth was not reduced (Bryant and Yeager, 2002). Surface irrigation can reduce water use efficiency due to water loss by deep percolation, nutrients leaching out of the plant root zone, and reducing soil ventilation (Singh et al., 2009).

CONCLUSIONS

In this study, the wick irrigation method resulted in higher water use efficiency, biomass, and plant growth compared to surface irrigation in maize, foxtail millet, and bitter vetch. In the case of maize, wick irrigation resulted in water use efficiency and biomass increases of 25% and 52% compared to surface irrigation, respectively. In bitter vetch, wick irrigation resulted in water use efficiency and biomass increases of 512% and 87% compared to surface irrigation, respectively. In the case of foxtail millet, wick irrigation resulted in water use efficiency and biomass increases of 428% and 50% compared to surface irrigation, respectively. Wick irrigation is a new irrigation method for crop plants. Using this method can reduce water consumption, especially in arid and semi-arid areas. One of the possible reasons for the improvement in biomass and water use efficiency under wick irrigation compared to surface irrigation is that the water is provided directly to the roots of the plant. As a result, water in the root zone of the plant is less susceptible to evaporation due to factors such as wind. The low water flow in wick irrigation can improve plant rhizosphere ventilation and control runoff and soil erosion. One of the advantages of the wick irrigation method is its implementation with minimal facilities by smallholder farmers. In this method of irrigation, there is no need for a technically skilled workforce to maintain it, it saves time and labour, and is to an extent a form of automatic irrigation. The effect of wick diameter and length will be the subject of further study, along with other effects of wick irrigation such as soil capping, weed, erosion and salinity control, and pumping energy.

REFERENCES

AL-MAYAHI A, AL-ISMAILY S, AL-MAKTOUMI A, AL-BUSAIDI H, KACIMOV A, JANKE R, BOUMA J and SIMUNEK J (2020) A smart capillary barrier-wick irrigation system for home gardens in arid zones. *Irrig. Sci.* **38** 235–250. https://doi.org/10.1007/s00271-020-00666-3

BHATT NJ and KANZARIYA BR (2017) Experimental investigations on wick Irrigation: An indigenous irrigation technique to suit small-land holders. *Int. J. Adv. Eng. Res. Dev.* **4** (8) 138–144. https://doi.org/10.21090/IJAERD.22713

BHAYO WA, SIYAL AA, SOOMRO SA and MASHORI AS (2018) Water saving and crop yield under pitcher and wick irrigation methods. *Pak. J. Agric. Agric. Eng. Vet. Sci.* **34** (1) 57–67.

BRISSON N, REBIERE B, ZIMMER D and RENALT D (2002) Response of the root system of winter wheat crop to water logging. *Plant Soil.* **243** 43–55. https://doi.org/10.1023/A:1019947903041

BRYANT H and YEAGER T (2002) Production of *Spathiphyllum* using three irrigation methods. *SNA Res. Conf. Proc.* **47** 596–599.

CAKIR R (2004) Effect of water stress at different development stages on vegetative and reproductive growth of corn. *Field Crops Res.* **89** 1–16. https://doi.org/10.1016/j.fcr.2004.01.005

CAR MKV (2012) *Advances in Irrigation Agronomy: Plantation Crops* (1st edn). Cambridge University Press, Cambridge. 360 pp. https://doi.org/10.1017/CBO9780511998263

DAVIS AS, PINTO JR and JACOBS DF (2011) Early field performance of Acaciakoa seedlings grown under subirrigation and overhead irrigation. *Native Plants J.* **12** (2) 94–99. https://doi.org/10.3368/npj.12.2.94

ELHINDI K, EL-HENDAWY S, ABDEL-SALAM E, ELGORBAN A and AHMED M (2016) Impacts of fertigation via surface and subsurface drip irrigation on growth rate, yield and flower quality of *Zinnia elegans*. *Bragantia*. **75** (1) 96–107. https://doi.org/10.1590/1678-4499.176

FANISH SA (2013) Micro irrigation of millets – a review. *Angew. Biol. Forsch.* **1** (2) 1–8.

FARRE I and FACI JM (2006) Comparative response of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) to deficit irrigation in a Mediterranean environment. *Agric. Water Manage.* **83** 135–143. https://doi.org/10.1016/j.agwat.2005.11.001

FAZELI ROSTAMPOUR M, SEGHATOLESLAMI MJ and MUSAVI SGH (2010) The study of drought stress effect and superabsorbent on relative water content and leaf chlorophyll index and its relationship with seed yield in corn (*Zea mays* L.). *Crop Physiol.* **2** (1) 19–31.

FERRAREZI RS and TESTEZLAF R (2014) Performance of wick irrigation system using self-compensating troughs with substrates for lettuce production. *J. Plant Nutr.* **39** (1) 147–161. https://doi.org/10.1080/01904167.2014.983127

FERRAREZI RS, WEAVER GM, VAN IERSEL MW and TESTEZLAF R (2015) Subirrigation: Historical overview, challenges, and future prospects. *HortTechnology.* **25** (3) 261–276. https://doi.org/10.21273/HORTTECH.25.3.262

HAJI-HASANI-ASL N, MORADI AGHDAM A, SHIRANIRAD AH, HOSSEINI N and RASAEIFAR M (2010) Effect of drought stress on forage yield and agronomical characters of millet, sorghum and corn in delay cropping. *J. Crop Prod. Res.* **2** (1) 63–74.

HANSON B and MAY D (2003) Drip irrigation increases tomato yields in salt- affected soil of San Joaquin Valley. *Calif. Agric.* **57** (4) 132–137. https://doi.org/10.3733/ca.v057n04p132

HANSONA BR, SCHWANKL LJ, SCHULBACH KF, PETTYGROVE GS (1997) A comparison of furrow, surface drip, and subsurface drip irrigation on lettuce yield and applied water. *Agric. Water Manage.* **33** 139–157. https://doi.org/10.1016/S0378-3774(96)01289-9

HAYATI A, RAMROUDI M, and GALAVI M (2012) Effect of timing of potassium application on millet (*Setaria italica*) yield and grain protein content in different irrigation regimes. *J. Crop Prod. and Process.* **1** (2) 35–44.

HEIDARI H (2012) Effect of irrigation by contaminated water with cloth detergent on plant germination traits of maize (*Zea mays*). *Life Sci. J.* **9** (4) 1587–1590.

JABBARI H., AKBARI GA, KHOSH KHOLGH SIMA NA, SHIRANI RAD AH, ALAHDADI I and TAJODINI F (2015) Study of agronomical, physiological and qualitative characteristics of canola (*Brassica napus*) under water stress. *J. Environ. Stresses Agric. Sci.* **8** (1) 35–49.

JAMES E, VAN and IERSEL MW (2001) Ebb and flow production of petunias and begonias as affected by fertilizers with different phosphorus content. *HortScience.* **36** 282–285. https://doi.org/10.21273/HORTSCI.36.2.282

JAMSHIDI N, SHIRANI RAD AH, TAKHT CHIN F, NAZERI P and GHAFARI M (2012) Evaluation of rapeseed genotypes under drought stress condition. *J. Crop Ecophysiol.* **6** (3) 323–338.

JIANG Y and HUANG B (2001) Osmotic adjustment and root growth associated with drought pre-conditioning enhanced heat tolerance in Kentucky bluegrass. *Crop Sci.* **41** (4) 1168–1173. https://doi.org/10.2135/cropsci2001.4141168x

JIUSHENG L, JIANJUN Z and REN L (2003) Water and nitrogen distribution as affected by fertigation of ammonium nitrate from a point source. *Irrig. Sci.* **22** (1) 19–30. https://doi.org/10.1007/s00271-003-0064-8

JOSEPH K (2016) Wick irrigation – A smart and user-friendly irrigation method for container grown plants. *SB Acad. Rev.* **XIX.OA1** 17–21.

KHURANA E and SINGH JS (2000) Influence of seed size on seedling growth of *Albizia procera* under different soil water levels. *Ann. Bot.* **86** 1185–1192. https://doi.org/10.1006/anbo.2000.1288

KIEFFER DL and CAMPBELL T (2009) Effect of sub-surface drip irrigation and shade on soil moisture uniformity in residential turf. Annual irrigation show, San Antonio, TX, 2–4 December 2009. 1–10.

LAL R and STEWART BA (2012) *Soil Water and Agronomic Productivity.* CRC Press, Boca Raton. https://doi.org/10.1201/b12214

LEHMANN P, BERLI M, KOONCE JE and OR D (2019) Surface evaporation in arid regions: Insights from lysimeter decadal record and global application of a surface evaporation capacitor (SEC) model. *Geophys. Res. Lett.* **46** 9648–9657. https://doi.org/10.1029/2019GL083932

LOBATO AKS, OLIVEIRA NETO CF, SANTOS FILHO BG, COSTA RCL, CRUZ FJR, NEVES HKB and LOPES MJS (2008) Physiological and biochemical behavior in soybean (*Glycine max cv. Sambaiba*) plants under water deficit. *Aust. J. Crop Sci.* **2** 25–32.

MEHRPUOYAN M and FARAMARZI A (2011) The effect of different water deficit levels on yield and water use efficiency of forge millet and sorghum. *Plant Ecosyst.* **7** (26) 60–71.

MILLION J, YEAGER T and LARSEN C (2007) Water use and fertilizer response of azalea using several no-leach irrigation methods. *HortTechnology.* **17** (1) 21–25. https://doi.org/10.21273/HORTTECH.17.1.21

MOAVENI P, HABIBI D and ABBASZADEH B (2009) Effect of drought stress on yield and yield components of four wheat cultivars in Shahr-E-Gods. *Iran. J. Agron. Plant Breeding.* **5** (1) 69–85.

MOOSAVI SGR, SEGHATOLESLAMI MJ, JAVADI H, and ANSARI-NIA E (2011) Effect of irrigation intervals and planting patterns on yield and qualitative traits of forage sorghum. *Adv. Environ. Biol.* **5** (10) 3363–3368.

MOUSAVI SGHR, MIRHADI SMJ, SIADAT SAE, NOURMOHAMMADI GH and DARVISH F (2009) The effect of drought stress and nitrogen levels on yield and water use efficiency of forage millet and sorghum. *J. New Agric. Sci.* **5** (15) 101–114.

MUHAMMED HHA (2016) *Modeling of Wick Irrigation System.* LAP Lambert Academic Publishing, Bergisch Gladbach.

NAKHAEI A, ABBASI MR and ARAZMJOO E (2013) Evaluating yield and morphological traits response of some millet accessions to stopping off irrigation at flowering stage. *J. Crop Ecophysiol.* **7** (2) 115–128.

NAKHODA B, HASHEMI DEZFOULI A and BANISADR N (2000) Water stress effects on forage yield and quality of pearl millet [*Pennisetum americanum* (L.) Leek. Var. Nutrifeed]. *Iran. J. Agric. Sci.* **31** (4) 701–712.

OH MM, CHO YY, KIM KS and SON JE (2007) Comparisons of water content of growing media and growth of potted Kalanchoe among nutrient-flow wick culture and other irrigation systems. *HortTechnology.* **17** (1) 62–71. https://doi.org/10.21273/HORTTECH.17.1.62

OH MM and SON JE (2008) Phytophthora nicotianae transmission and growth of potted kalanchoe in two recirculating subirrigation systems. *Sci. Hort.* **119** 75–78. https://doi.org/10.1016/j.scienta.2008.07.026

ORGE RF and SAWEY DA (2019) Field performance of the capillary wick irrigation (capillarigation) system for rice-based crops. *Int. J. GEOMATE.* **17** (61) 41–49. https://doi.org/10.21660/2019.61.4636

PAYERO JO, TARKALSON DD, IRMAK S, DAVISON D and PETERSEN JL (2009) Effect of timing of a deficit-irrigation allocation on corn evapotranspiration, yield, water use efficiency and dry mass. *Agric. Water Manage.* **96** 1387–1397. https://doi.org/10.1016/j.agwat.2009.03.022

PAYGHOZAR Y, GHANBARI A, HEYDARI M and TAVASSOLI A (2009) Effect of foliar application of micronutrients on qualitative and quantitative characteristics of pearl millet (*Pennisetum glacum*) under drought stress. *J. Crop Ecophysiol.* **3** (10) 67–79.

PENNISI SV, VAN IERSEL MW and BURNETT SE (2005) Photosynthetic irradiance and nutrition effects on growth of English Ivy in subirrigation systems. *HortScience.* **40** 1740–1745. https://doi.org/10.21273/HORTSCI.40.6.1740

RAUF S (2008) Breeding sunflower (*Helianthus annuus* L.) for drought tolerance. *Commun. Biometry Crop Sci.* **3** (1) 29–44.

REDDY ARG, SANTOSH DT and TIWARI KN (2017) Effect of drip irrigation and fertigation on growth, development and yield of vegetables and fruits. *Int. J. Curr. Microbiol. Appl. Sci.* **6** (2) 1471–1483. https://doi.org/10.20546/ijcmas.2017.602.165

ROUPHAEL Y, CARDARELLI M, REA E and BATTISTELL AC (2006) Comparison of the subirrigation and drip-irrigation systems for greenhouse zucchini squash production using saline and non-saline nutrient solutions. *Agric. Water Manage.* **82** 99–117. https://doi.org/10.1016/j.agwat.2005.07.018

ROWSHON KM, HAMAAZIZ MH, ABDUL MM, RUEDIGER A and AMIN MSM (2019) Two-dimensional modeling of water distribution under capillary wick irrigation system. *Pertanika J. Sci. Technol.* **27** (1) 205–223.

SEMANANDA NPK, WARD JD and MYERS BR (2018) A semi-systematic review of capillary irrigation. The benefits, limitations, and opportunities. *Horticulturae.* **4** 23. https://doi.org/10.3390/horticulturae4030023

SINGH R, KUMAR S, NANGARE DD and MEENA MS (2009) Drip irrigation and black polyethylene mulch influence on growth, yield and water-use efficiency of tomato. *Afr. J. Agric. Res.* **4** (12) 1427–1430.

STONE LR, GOODRUM DE, JAFFAR MN and KHAN AH (2001) Rooting front and water depletion depths in grain sorghum and sunflower. *Agron. J.* **95** (5) 1105–1110. https://doi.org/10.2134/agronj2001.9351105x

SUBBA REDDY GV, PATIL DV, SPIHARI RAO B and NAGENRAPRASAD B (2015) Effect of different types of irrigation and growing methods on growth, yield and water – use efficiency of tomato (*lycopersicon esculentum miller*). *The Bioscan.* **10** (1) 243–246.

THOMPSON TL, HUAN- CHENG P and YU-YI L (2009) The potential contribution of subsurface drip irrigation to water-saving agriculture in the western USA. *Agric. Sci. China.* **8** (7) 850–854. https://doi.org/10.1016/S1671-2927(08)60287-4

TURNER NC and KRAMER PJ (1980) *Adaptation of Plants to Water and High Temperature Stress.* Wiley Interscience, New York.

UMAIR M, HUSSAIN T, JIANG H, AHMAD A, YAO J, QI Y, ZHANG Y, MIN L and SHEN Y (2019) Water-saving potential of subsurface drip irrigation for winter wheat. *Sustainability.* **11** 2978. 3–15. http://doi.org/10.3390/su11102978

VALADABADI SA and ALIABADI FARAHANI H (2008) Effect of potassium application on quantitative characteristics and root penetration of corn, sorghum and millet under drought stress. *Iran. J. Agron. Plant Breeding.* **4**(2) 37–49.

VIMALENDRAN L and LATHA KR (2014) Yield, water use and water use efficiency of pigeon pea [*Cajanus cajan* (L.) Millsp.] under drip fertigation system. *J. Appl. Nat. Sci.* **6** (1) 457–462. https://doi.org/10.31018/jans.v6i2.482

WEATHERUNDERGROUND (2022) Weather underground. URL: https://www.wunderground.com/history/monthly/ir/kermanshah/OICC/date/2015-10 (Accessed 27 February 2022).

WESONGA JM, WAINAINA C, OMBWARA FK, MASINDE PW and HOME PG (2014) Wick material and media for capillary wick based irrigation system in Kenya. *Int. J. Sci. Res.* **3** (4) 613–617.

YEAGER TH and HENLEY RW (2004) Irrigation and fertilization for minimal environmental impact. *Acta Hortic.* **638** 233–240. https://doi.org/10.17660/ActaHortic.2004.638.30