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Sustainability of Rain-Fed Fig Production (*Ficus carica*) under Supplemental Irrigation in Semi-Arid Regions

Running title: Supplemental irrigation for rain-fed fig

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Abstract

In arid and semi-arid regions, inadequate rainfall necessitates supplemental irrigation to meet crop water requirements. Selecting the appropriate method is crucial for success. A two-years field experiment was conducted in Kharameh Region, Iran, to investigate the effect of different supplemental irrigation methods on fig tree yield, physiological response, and water productivity. Three irrigation methods including flood irrigation, subsurface drip irrigation, micro jet irrigation, and no supplemental irrigation (control) were applied as four treatments in five replications. Results showed that subsurface and micro jet irrigation significantly increased leaves width by 18.2%, shoot length by 27%, and shoot diameter by 13%. Micro jet irrigation also increased the amounts of chlorophyll in fig leaves by 14%, the average of total fruit numbers by 134% and the average of total fruit weight by 54% as compared to the other treatments. **Furthermore, the highest levels of water efficiency were seen in micro jet irrigation techniques, while they dropped by 40% with subsurface drip irrigation. The practical implications of this study involve boosting fig yield, refining water management strategies, bolstering drought resistance, analyzing economic feasibility, gauging sustainability, and supporting the sharing of knowledge and skills for fig cultivation in semi-arid areas.**

Keywords: subsurface irrigation, micro jet irrigation, water scarcity, fig fruit quality, water productivity, Kharameh.

1. Introduction

Water scarcity challenges in both quantity and quality are major problems for agricultural production in Iran (Amiri and Eslamian 2010; Amiri et al. 2015). Supplemental irrigation methods are necessary for the sustainability of agricultural systems, particularly for rain-fed crops (Khozaei et al. 2020). Rain-fed fig orchards are common in arid and semi-arid regions of Iran, producing a country level of approximately 75,910 tons of dry figs annually (Abdolahipour et al. 2019). Despite fig plants' tolerance to water stress, prolonged drought conditions can cause significant loss of yield (Abdolahipour et al. 2018; Karimi et al. 2012). The prolonged drought condition led to soil salinity which has an adverse effect on quality and quantity of rain fed fig (Abdolahipour et al. 2023). Severe drought causes leaf loss and reduces fruit quality and quantity (Tehrani et al. 2016). Previous studies suggest that supplemental irrigation and drought-resistant cultivars can improve water productivity in plant production (Honar et al. 2020; Abdolahipour et al. 2019). Supplemental irrigation effectively maintains soil moisture in the root zone, mitigating water deficit effects on crop yield in arid regions (Moradi et al., 2023). Using the supplemental irrigation in fig orchards has increased in semi-arid regions (Kamyab 2015; Sharifzadeh et al. 2012). Some Studies show that supplemental irrigation improves yield and physiological traits of rain-fed fig trees during drought (Honar and Sepaskhah 2015; Kamgar Haghighi and Sepaskhah 2015). Bagheri and Sepaskhah (2014) recommend March supplemental irrigation for fig trees in low rainfall years. Tapia et al. (2003) found that supplementing 220 mm of water in arid regions results in economically viable fig yields. Al-Desouki et al. (2009) report increased yield and growth of fig trees with supplemental irrigation. Khozaei et al. (2020) observed increased grapevine yield with May supplemental irrigation. Choosing the right supplemental irrigation method impacts rain-fed fig tree yield and morphology (Bouman et al., 2007). Flood irrigation increases apple tree chlorophyll compared to drip and sprinkler irrigation (Chen et al. 2018). Different irrigation methods affect root growth, soil enzyme activity, nutrient uptake, and fruit quality (Wang et al. 2017). Furrow and trickle irrigation methods significantly influence Squash fruit and seed yields (Amer et al., 2011).

Although there are some investigations on the effect of different supplemental irrigation amounts on rain fed fig trees, but limited researches can be found on the effects of supplemental irrigation methods on the quality and quantity of fig fruit and physiological parameters of rain-fed fig trees. Therefore, this study aims to evaluate the impact of various supplemental irrigation methods (flood, subsurface drip, micro jet, and no supplemental irrigation) on soil moisture profile, fruit quality and quantity, and growth and physiological parameters of fig trees (Sabz cultivar) in an arid region.

2. Material and Methods

2.1. Experimental Site

To investigate the effects of different supplemental irrigation methods on fig trees (Sabz cultivar), two years of field experiments were conducted on 2017 and 2018 in Kharameh City, Fars Province, Iran. The area is located on 29° 32″N, 53° 19″ E, 1500 m above the sea level has an arid climate with an average annual rainfall of 200 mm and mean annual temperature of 20°C. The experimental site's soil properties are shown in Table 1.

Table 1. The soil properties of the experimental site.

Soil texture	Depth	Ph	Clay	Silt	Sand	Organic carbon	CaCo3	EC
	(cm)		(%)	(%)	(%)	(%)	(%)	(dS/m)
Loam	0-30	8	21.2	30	49.2	0.49	21	1.18
Sandy Clay loam	30-60	8.2	21.2	25.3	53.5	0.30	41	0.65
Sandy Clay loam	60-90	8.4	21.2	24.4	54.4	0.23	41	0.56
Sandy loam	90-120	8.4	19.3	19.6	61.1	0.21	40	0.54

Growing rain-fed figs require a warm climate with long, hot summers and mild winters, preferably in Mediterranean or semi-arid regions. Figs thrive in well-drained soils with good fertility and a pH level between 6.0 and 6.5 (Jafari and Eslami, 2022). Regular pruning, soil-based fertilization, and pest management are essential for healthy growth and fruit production. The Sabz fig variety used in this study is Iran's most important and expensive dried fig, known for its unique traits, including drought tolerance, extensive roots, and adaptability to different soils. Rain-fed fig orchards need three years of regular irrigation with rooted seedlings. After three years, if rainfall exceeds 200 mm annually, irrigation can be stopped. However, in areas with lower rainfall, supplementary irrigation may be needed for profitable crop production. This combination of high price and low water consumption has led to a shift in regions like Kharamah, Iran, to fig production (Jafari and Eslami, 2022).

2.2. Experimental Design and Field studies

The experimental design consisted of four treatments: 1: flood irrigation using a 10000m^3 tanker for each tree, 2: subsurface drip irrigation using drip tape at 1m distance from the trunk and 50cm depth, 3: micro jet irrigation with one sprinkler per tree and 1.5m spraying radius, and 4: no supplemental irrigation (control), with five replications. Figure 1 shows the irrigation methods used. Measurements were taken on 5 trees with the same condition in each row. The trees were 3 years old and planted 8m×8m apart. Figure 2 shows the experimental treatments. Soil water content was monitored at depths of 0.3, 0.6, 0.9, and 1.2 using a Trime Hygrometer at a distance of 1m from each tree trunk from January to July each year. Based on Honar and Sepaskhah (2015), each tree received a total of 1500 L of supplemental irrigation in three applications (March, May, and August) with 500 L each time. The irrigation water properties are listed in Table (2).

Table 2. Irrigation water properties in the experimental site.

EC (ds/m)	PH	HCO (meq/L)	CL (meq/L)	$SO4^{2-}$ (meq/L)	Ca (meq/L)	Mg (meq/L)	Na (meq/L)
1.2	7	4.6	120	1	31	43	51.9

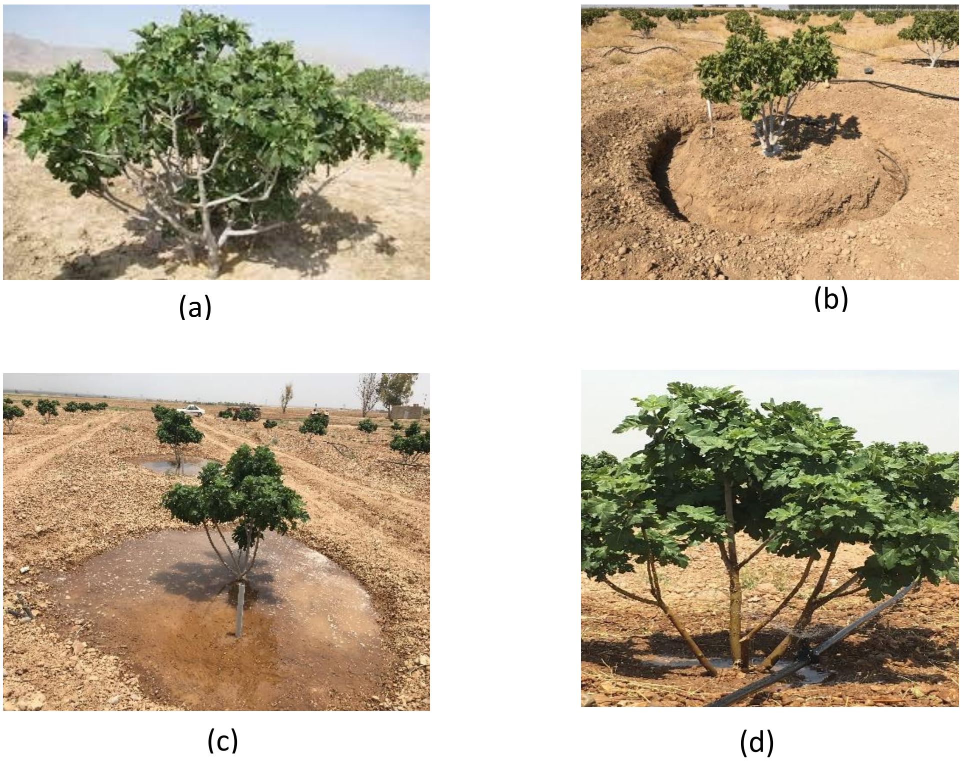

Figure 1. Irrigation treatments, control (a), subsurface drip (b), flood (c) and micro jet irrigation (d).

2.3. Fig Orchard Properties

Different fig cultivars have been planted in Kharameh region, with 'Sabz' being the most common commercial variety (Jafari et al. 2012). Fig shoot growth occurs from mid-April to mid-May, with maximum leaf area observed in May. Flowering and fruiting of fig trees happen from April to July, with fruit maturation starting in August and ending in early October. After this, fig leaves fall and the trees enter dormancy until the next growth period in late October.

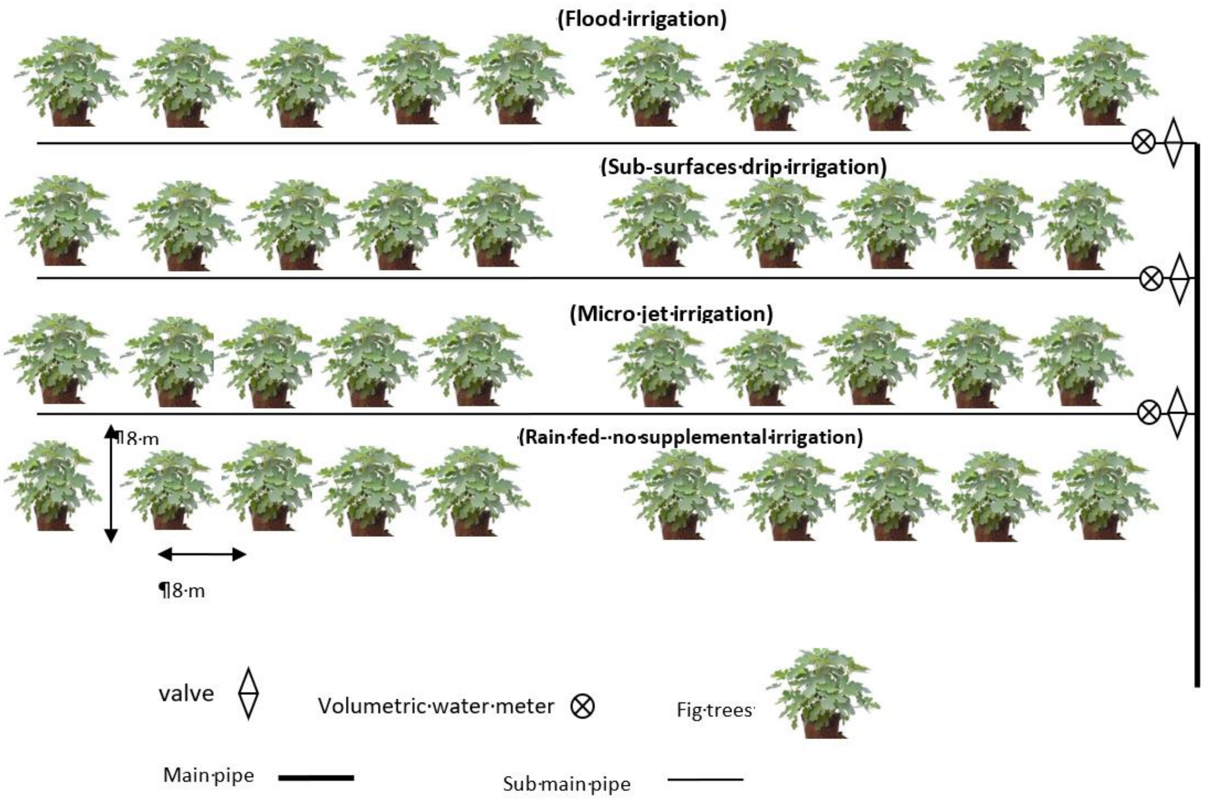

Figure 2. The schematic map of experimental treatments.

2.4. Measurements and Calculations

Growth parameters (shoot length, shoot diameter, node number, internode length, leaf width) were measured in July for two years. Fig fruit number, weight, size, and color were determined at harvest. Fruit size (diameter) was categorized as AA (>22mm), A (17-22mm), and B (<17mm). Fruit color was categorized as light yellow (best), brown (medium), and dark brown (worst).

The irrigation water productivity (*WP*) as the total crop yield divided by the total irrigation water, was determined for each treatment as follow, Fernández et al (2020):

$$WP = \frac{Y}{I}$$

Where Y is the fruit yield (kg/ha), and I is the irrigation depth (m^3/ha).

The content of total chlorophyll, chlorophyll (a), and chlorophyll (b) of the leaves were measured using dimethyl sulfoxide (Hickox and Israelstam 1979) in the middle of August. Fresh and fully matured leaves were collected from the tree at a fixed height and placed in plastic bags before the laboratory analysis. A number of 100 mg of leaf pieces (without veins) were placed in an Erlenmeyer flask and 7 ml of dimethyl sulfoxide (DMSO) was poured on it and kept in an incubator at 65 degrees Celsius for 60 minutes. Then its volume was increased to 10 ml with DMSO and the absorbance of the extract was read at 645 and 663 nono meter wavelengths.

3. Results and Discussion

3.1. Soil Moisture

The availability of water is a significant factor that can limit the growth and productivity of plants (Liu et al., 2021). Soil moisture in different depths and irrigation methods during the growing season is shown in Figure 3. Control treatment had lower moisture percentage than other treatments in all soil layer. The micro jet irrigation method maintained soil moisture at high levels in the 0-30 cm and 30-60 cm soil layers, where the highest density of fig roots is found (Abdolahipour et al., 2021), facilitating water absorption at these depths (Figures 3a and 3b). Also the most significant moisture change with a 5.4% increase, was observed at the 0-30 cm depth, primarily due to evaporation and water movement (Figure 3a). The highest soil moisture in 60-90 cm and 90-120 cm depths were observed in subsurface drip irrigation and flood irrigation, respectively.

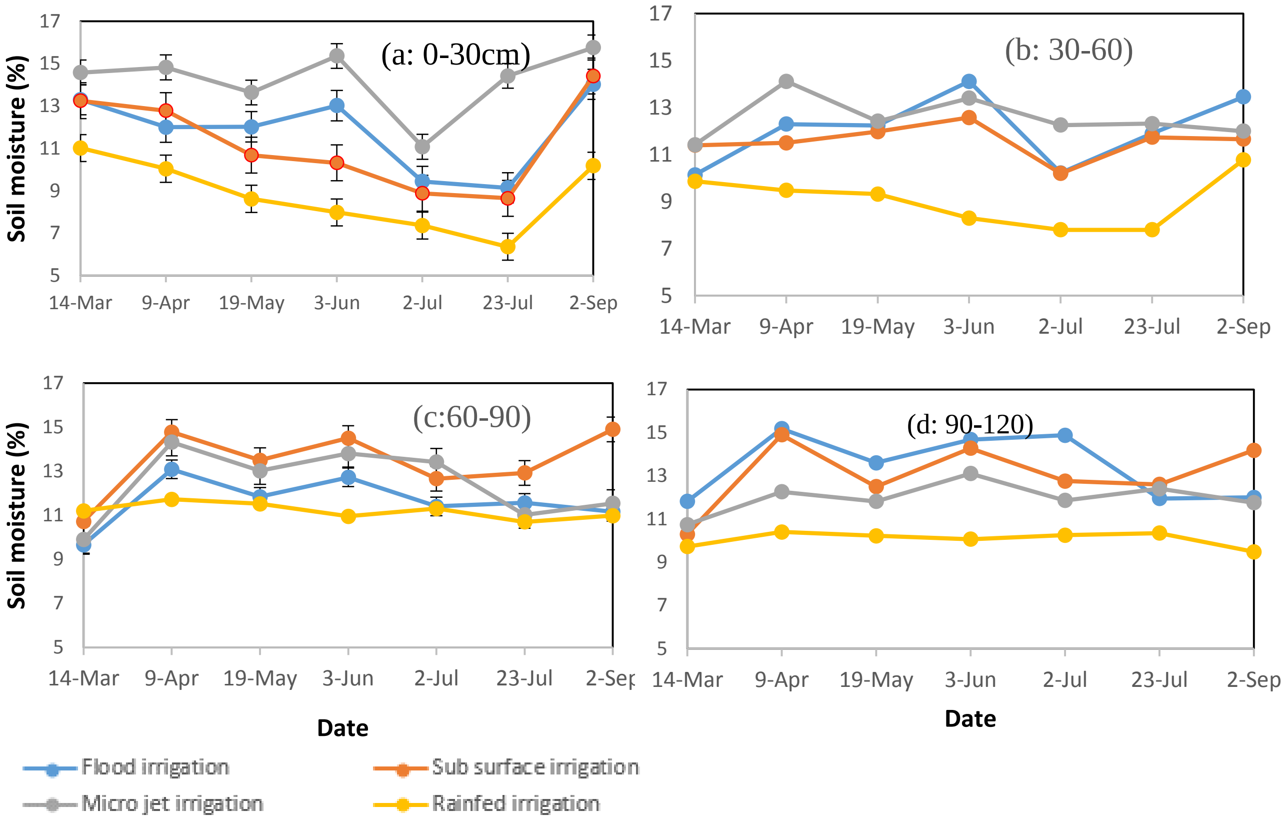

Figure 3. The average of volumetric soil moisture (%) in different supplemental irrigation methods for different soil depths; 0-30cm (a), 30-60cm (b), 60-90 cm (c) and 90-120cm (d) during the growing seasons (2018 & 2019).

3.2. Fig Trees Growth and Physiological Parameters

Table 3 shows that the highest amounts of chlorophyll (a) was observed in the micro jet irrigation treatments (1.645 mg/g) followed by sub surface (1.582 mg/g), flood (1.302 mg/g) and control (1.251 mg/g). Supplementary irrigation had no significant effect on the amount of chlorophyll (b) in the leaves of fig trees. The amounts of total chlorophyll in the leaves of fig trees were affected significantly by supplementary irrigation, and the highest amounts were observed in the micro jet irrigation method (2.201) followed by subsurface, control and flood irrigation treatments (Table 3). These results indicate to the effect of water stress and irrigation system types on water relations parameters such as leaf chlorophyll (a), leaf chlorophyll (b), leaf proline, leaf cell sap osmotic pressure, opened stomata percentage, and leaf bound water content. Generally, leaf chlorophyll (a), leaf chlorophyll (b), as well as opened stomata percentage parameters were increased when water amount increased (Trigueros et al. 2021). Anjum et al. (2011) and Shirbani et al. (2013) indicated that chlorophyll content is positively related to the rate of photosynthesis. Therefore, the decrease in chlorophyll content under drought stress conditions, as a common sign of oxidative stress, may be due to the photo-oxidation of pigments and chlorophyll decomposition. Ammar et al. (2020) found that the deficit irrigation decreased the chlorophyll content and increased the proline in fig plant leaves. Halo et al. (2018) observed higher chlorophyll content in crops resistant to oxidative stress and Chlorophyll (a) decreased more significantly than chlorophyll (b) under drought stress.

Table 3. Effect of supplemental irrigation on the two-year mean of some physiological traits of fig (F. carica cv. Sabz) in 2018 and 2019.

Supplemental Irrigation treatments	Chlorophyll-a	Chlorophyll-b	Total chlorophyll
	(mg/g)	(mg/g)	(mg/g)
Flood	1.302 b	0.438 a	1.740 b
Sub-surface Drip	1.582 a	0.480 a	2.062 ab
Micro jet	1.654 a	0.547 a	2.201 a
Control (Rain-fed)	1.251 b	0.525 a	1.776 b

Means with the same letters in each column are not significantly different using the Duncan test at $P \leq 0.05$.

Table 4 shows that supplemental irrigation significantly affected fig trees' growth parameters. As the results show the highest amounts of leaf width obtained in micro jet irrigation (12.81 cm) with no significant difference by sub surface drip irrigation and decreased in average by about 12% in flood (11.71 cm) and control (10.82 cm) treatments. In this case Chen et al. (2018) found that drip irrigation increased leaf width and weight in apple trees.

Maximum shoot length was observed in flood irrigation (16.3 cm), with no significant difference by micro jet (15.48 cm) and sub-surface drip irrigation (15.14 cm), while the minimum one was observed in control treatment (12.3 cm). Leonel and Tecchio (2010) also showed supplemental irrigation increased shoot diameter and length in fig trees. Increasing irrigation rate caused promotions in many characteristics, which lead to an increment in both vegetative growth and fruiting and finally profitable yield in orange trees (Panigrahi 2023).

Sub-surface drip irrigation had the maximum shoot diameter (8.75 cm) with no significant difference by flood (8.66 cm) and micro jet irrigation (8.58 cm), while the control treatment had the minimum shoot diameter (7.68 cm). The maximum number of nodes and internode length were observed in micro jet irrigation followed by flood and subsurface drip irrigation and the minimum ones were observed in control treatment. These results demonstrate the importance of supplemental irrigation especially micro jet irrigation in improving fig trees' morphological conditions. Most studies show that supplemental irrigation improves vegetative growth compared to non-irrigated rain-fed plants (Varol et al., 2023). Andrade et al. (2014) found significant effects of supplemental irrigation on fig tree node number. Wang et al. (2017) reported significant effects of supplemental irrigation on root development and physiological parameters of trees. Abd-El-Rahman et al. (2017) found significant increases in vegetative growth and fig yield with supplemental irrigation. Moura et al. (2023) reported larger diameter, more branches, and longer internodes in irrigated fig trees. The findings of this study align with Wang et al. (2017), Abd-El-Rhman et al. (2017), and Moura et al. (2023).

Table 4. The average of growth parameters of fig trees under different supplemental irrigation treatments.

Supplemental irrigation treatments	Nod number	Internode length (cm)	Shoot length (cm)	Shoot diameter (cm)	Leaf width (cm)
Flood	10.59 a	6.12 a	16.3 a	8.66 ab	11.71 b
Sub-surface drip	10.49 a	5.93 a	15.14 ab	8.75 a	12.79 a
Micro jet	10.65 a	6.64 a	15.48 ab	8.58 ab	12.81 a
Control (Rain-fed)	9.00 b	4.76 b	12.3 b	7.68 b	10.82 b

The means with the same letters in each column are not significantly different using the Duncan test at $P \leq 0.05$.

3.3. Fig Fruits Quality and Quantity

Fig physiology and growth were affected by different irrigation methods. Quality and quantity of fig fruits can be affected by irrigation management for sustainable production (Si et al, 2023). In Table 5, fig fruit numbers were affected by supplemental irrigation. The number of Light yellow fig fruit increased by 102%, 52%, and 247% in micro jet irrigation as compared to flood, sub-surface drip, and control treatments, respectively. Important polyphenolic compounds in fig fruit are epicatechin, catechin, and chlorogenic acid, reaching peak levels during ripening. Polyphenol oxidase enzyme darkens fig skin by breaking down phenolic substances. Drought stress increases enzyme activity, darkening the fruit at ripening, while sufficient moisture brightens fruit skin (Sedaghat 2018).

The number of grade AA fig fruit increased by 455% and 317% in micro jet compared to flood and sub-surface drip irrigation, respectively, while control treatment had no grade AA fig fruit (Table 5).

Grade A fig fruit was highest in the control treatment, followed by micro jet irrigation, and the lowest number was found in flood irrigation, with no significant difference by sub-surface drip irrigation. The highest number of grade B fig fruit was obtained in control treatment and decreased by 31%, 26% and 22% in flood irrigation, micro jet irrigation and sub-surface drip irrigation, respectively (Table 5). According to Andrade et al. (2014), different supplemental irrigation methods significantly increased fig fruit numbers by about 27% to 47% as compared to control treatment. Sharifzadeh et al (2022) indicated that the supplemental irrigation leads to improve fig fruit yield and quality such as fruit size and color in Estahban city. Gunduz et al. (2011) found that supplemental irrigation increased peach fruit size and quality. Abdolahipour et al. (2019) reported that applying 2000 liters of supplemental irrigation per tree increased fig shoot growth and fruit number. The color and size of fig fruit depend on light intensity, temperature, pollination, fig formation, and soil moisture (Gunduz et al., 2011). Flashman (2016) stated that soil moisture and drought stress affect fig cell division, cell size, growth rate, and cracking. Micro-sprinkler supplemental irrigation increased apple fruit red color, anthocyanin content, firmness, size, and soluble solids concentration (Iglesias et al., 2002). Al-Desouki et al. (2009) observed increased nutrient absorption and improved photosynthetic capacity in rain-fed fig with supplemental irrigation.

Table 5. Effect of supplemental irrigation on the average number of fig fruits (F. carica cv. Sabz) in 2018 and 2019.

Supplemental irrigation treatments	grade AA (Size more than 23 mm)	grade A (Size 17–23 mm)	grade B (Size less than 17 mm)	Light yellow	Brown	Dark brown
Flood	1.8 b	15.4 c	84.4 c	29.2 b	42.3 c	29. 4 a
Sub-surface drip	2.4 b	16.6 c	100.8 b	38.8 ab	65.8 b	37.4 a
Micro jet	10 a	25 b	97 b	59 a	44 c	33.4 a
Control (Rain-fed)	0 b	35 a	123 a	17 c	79 a	37.25 a

The means with the same letters in each column are not significantly different using the Duncan test at $P \leq 0.05$.

According to Table 6, supplemental irrigation significantly affected fig fruit weight. Light yellow fruits had the highest weight in micro jet irrigation, but significantly decreased by about 53%, 35%, and 75% compared to flood, sub-surface drip, and control treatments, respectively. Brown fig fruit weight increased in average by about 55% in subsurface drip and control treatments as compared to micro jet and flood treatments, while there was no significant difference in the weight of dark brown fruits among all irrigation methods (Table 6). Grade AA fig fruit weight was significantly increased in micro jet irrigation by about 78% and 75% compared to flood and sub-surface drip irrigation, respectively. There were no grade AA fig fruits in the control treatment, highlighting the importance of supplemental irrigation in improving fig fruit quality. Micro jet irrigation also significantly increased grade A fruit weight by about 53% and 56% compared to sub-surface drip and control, with no significant difference compared to flood irrigation. The control and sub-surface drip treatments had the highest weight for grade B fruits, while micro jet irrigation had the lowest one. These results demonstrate the effectiveness of micro jet irrigation in increasing both the quantity and quality of fig fruits. Honar et al. (2023) found that supplemental irrigation improved rain-fed fig yield in Estahban, Iran. Ntshidi et al. (2023) reported that water-saving irrigation methods like drip and micro jet are popular in orchards for abundant high-quality fruit. The finding of this study aligns with the results of Ntshidi et al. (2023).

Table 6. Effect of supplemental irrigation on weight (gr) of fig fruits (F. carica cv. Sabz). In 2018 and 2019).

Supplemental irrigation treatments	Grade AA (Size more than 23 mm)	Grade A (Size 17–23 mm)	Grade B (Size less than 17 mm)	Light yellow	Brown	Dark brown
Flood	11.5 b	70.78 a	341.28 b	122.2 b	171.34 b	96.02 a
Sub-surface drip	13.26 b	39.22 b	492.94 a	168.6 b	284.2 a	117.88 a
Micro jet	53.28 a	83.84 a	320.62 b	257.8 a	181.34 b	109.26 a
Control (Rain-fed)	0 b	36.1 b	492.67 a	64.25 c	260.9 a	109.92 a

The means with the same letters in each column are not significantly different using the Duncan test at $P \leq 0.05$.

3.4. Water Productivity

The micro jet irrigation method demonstrated the highest water productivity compared to flood irrigation, with no significant difference observed between the two methods. Subsurface drip irrigation, on the other hand, showed a decrease in water productivity due to lower fig yield. However, this decrease may be compensated in future years as the roots can potentially reach the water source in sub surface irrigation more effectively. Further studies are needed to explore this potential for improved water productivity with subsurface drip irrigation over time.

Moursy et al. (2023) found that sprinkler and drip irrigation improve crop water productivity. Cavalcante et al. (2022) and Sigua et al. (2020) reported the significant role of supplemental irrigation in increasing yield and water productivity of rain-fed fig trees in semi-arid regions. Allam et al. (2007) found a positive effect of supplemental irrigation on fig tree yield and water productivity in Egypt. Supplemental irrigation provides benefits like higher water productivity, lower crop failure risk, and stable yields (Filintas et al. 2021; Wang et al. 2021). Zegbe and Servín-Palestina (2021) showed that implementing supplemental irrigation maintains fruit yield, average mass, and marketable size at the same level as full irrigation, while improving water use efficiency and productivity.

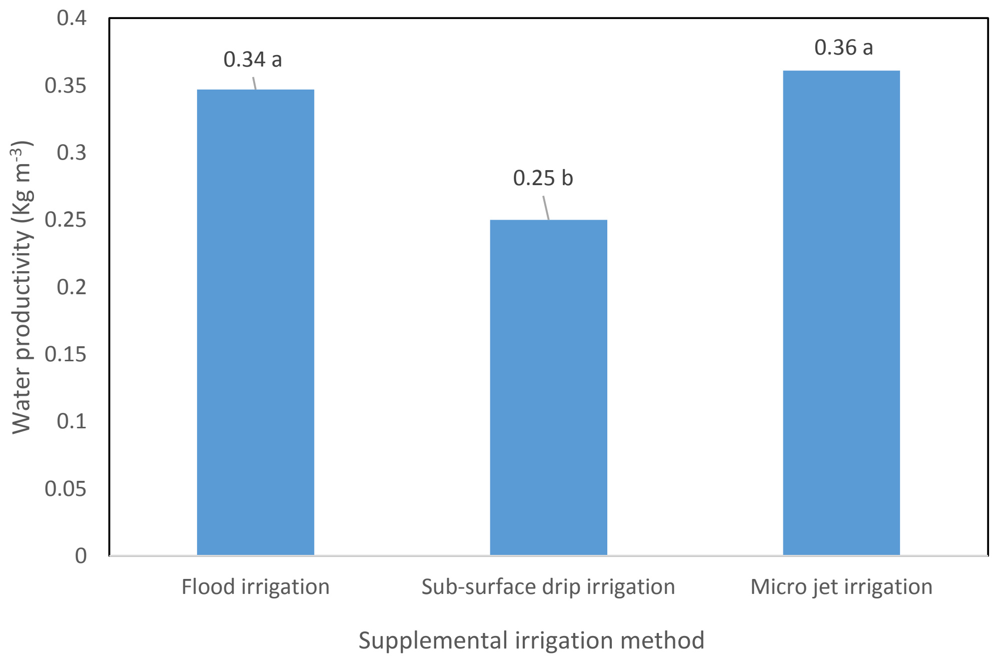

Figure 4. Water productivity in different supplemental irrigation methods.

4. Conclusions

Two years of field experiments in rain-fed fig orchards in the semi-arid Kherameh region showed the effect of different supplemental irrigation methods on fig trees. The results demonstrated that supplemental irrigation greatly affects the quality and quantity of fig fruit.

The highest amounts of total chlorophyll, leaf width, and internode length were observed in micro jet irrigation, which promotes photosynthesis, leading to a significant increase in the number and weight of high quality fig fruits (light yellow and grade AA fig fruit) compared to other irrigation treatments. As the results showed micro jet irrigation resulted in the highest quality, marketability, and water productivity, making it an effective supplemental irrigation method for compensating rainfall deficiency in rain-fed fig cultivation. Future research should focus on determining optimal irrigation levels and schedules for different crops and soils in arid and semi-arid regions, as well as investigating the long-term impacts of irrigation methods on soil health and ecosystem functioning. Assessing the economic aspects of supplemental irrigation can warn policymakers and agricultural practitioners about the potential benefits and trade-offs. These findings can facilitate the development of effective water management, agricultural planning, and investment strategies in regions with insufficient rainfall for rain-fed agriculture

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پایداری تولید انجیر دیم (Ficus carica) تحت آبیاری تکمیلی در مناطق نیمه خشک

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چکیده

در مناطق خشک و نیمه خشک، بارندگی ناکافی نیاز به آبیاری تکمیلی برای برآوردن نیاز آبی محصول دارد. انتخاب روش مناسب برای موفقیت بسیار مهم است. یک آزمایش مزرعه ای دو ساله در منطقه خرامه ایران به منظور بررسی تأثیر روش های مختلف آبیاری تکمیلی بر عملکرد درخت انجیر، پاسخ فیزیولوژیکی و بهره وری آب انجام شد. سه روش آبیاری غرقابی، آبیاری قطره ای زیرسطحی، آبیاری میکرو جت و بدون آبیاری تکمیلی (شاهد) به عنوان چهار تیمار در پنج تکرار اعمال شد. نتایج نشان داد که آبیاری زیرسطحی و میکرو جت به طور معنی‌داری باعث افزایش 18.2 درصدی عرض برگ، 27 درصدی طول شاخساره و 13 درصدی قطر شاخساره شد. همچنین آبیاری میکرو جت باعث افزایش 14 درصدی کلروفیل برگ انجیر، 134 درصد میانگین تعداد میوه و 54 درصد میانگین وزن کل میوه نسبت به سایر تیمارها شد. علاوه بر این، بالاترین سطوح راندمان آب در روش‌های آبیاری میکرو جت مشاهده شد، در حالی که با آبیاری قطره‌ای زیرسطحی 40 درصد کاهش یافت. پیامدهای عملی این مطالعه شامل افزایش عملکرد انجیر، پالایش استراتژی‌های مدیریت آب، تقویت مقاومت به خشکی، تجزیه و تحلیل امکان‌سنجی اقتصادی، سنجش پایداری، و حمایت از اشتراک دانش و مهارت‌ها برای کشت انجیر در مناطق نیمه‌خشک است.