

Irrigation Water Use Efficiency and Yield of Pistachio under Aerated Subsurface Drip Irrigation System

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ABSTRACT

Improving yield and Irrigation Water Use Efficiency (IWUE) is important for pistachio cultivation in Iran. Subsurface Drip Irrigation (SDI) is a novel irrigation system that is used by pistachio farmers. Oxygen deficiency could occur in the soil under crops irrigated by SDI, especially in heavy clay soils, due to creation of sustained wetting fronts around emitters. The focus of this work was to evaluate aerated water irrigation (oxygation) under SDI to overcome hypoxia in saline loam silt soil environments on 15 years old pistachio trees in desert climate. Two treatments including F₃ (irrigation frequency once every 3 days without air injection) and F_{3-oxygation} (irrigation frequency once every 3 days by air injection) were investigated in two years. The injection of 18% by volume air into irrigation water by SDI resulted in a beneficial effect on yield and IWUE in the second year of experiment; with yield values of 4.9 ton ha⁻¹ for F_{3-oxygation} against 4.4 ton ha⁻¹ for F₃; and IWUE values of 4.2 kg ha⁻¹ mm⁻¹ for F_{3-oxygation} against 3.7 kg ha⁻¹ mm⁻¹ for F₃. Decreases in yield and IWUE in the F_{3-oxygation} in comparison with F₃ were 33.3 and 28.2% in the first year, respectively; but yield and IWUE due to F_{3-oxygation} were 11.1 and 13.5% greater in the second year compared to F₃, respectively. At the end of the irrigation season, the nitrogen content of the nuts removal in F₃, and F_{3-oxygation} were 1.9 and 2.1% in the first year and 1.4 and 1.6% in the second year, respectively. The leaf K⁺ and nut Fe²⁺ concentrations in F_{3-oxygation} were about 24 and 44% more than F₃, respectively. Leaf area was larger in aeration treatment compared with the control. Overall, these results indicate positive effects of oxygated SDI system on pistachio trees and merit further investigation for improving yield and IWUE.

Keywords: Hypoxia, Leaf area, Oxygation, Oxygen deficiency, *Pistacia vera*.

INTRODUCTION

Water scarcity in hot and dry climate areas, such as central part of Iran, will be gradually and progressively aggravated by climate change, drought, growing population, and urban, tourism, and industrial activities (Galindo *et al.*, 2018). Furthermore, in hot-arid areas of Iran, the crops water requirements are often influenced by high evapotranspiration, water and soil salinity, and restricted water availability. Therefore, Water Use Efficiency (WUE) needs to be increased by developing new irrigation systems (El Jaouhari *et al.*, 2018).

Several irrigation strategies have been

proposed by researchers to reduce water use in agriculture, maintain an adequate yield, and improve the irrigation water use efficiency (IWUE) of crops (Namara *et al.*, 2007; Çolak *et al.*, 2018). Some typical micro-irrigation techniques, such as Subsurface Drip Irrigation (SDI), have nearly 100% efficiency (i.e. 100% of the water delivered is used by crop as evapotranspiration) and have shown great potential for saving water, improving IWUE, and reducing negative environmental impacts of irrigation (McHugh *et al.*, 2008; Yan *et al.*, 2019). In recent years, application of SDI system has been widely accepted by many pistachio growers. This system can uniformly distribute adequate water around the root

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activity area, reduce evapotranspiration and percolation, decrease risks of soil salinity, and prevent soil degradation (Karlberg and Frits, 2004).

Pistachio is one of the most important crops in Iran, which is cultivated in arid regions with limited water resources and poor water quality. Although pistachio cultivation in Iran goes back to ancient times, today's pistachio production has not increased to the predicted levels and yield per tree is still low (Ünlü *et al.*, 2005). For instance, the average yield is 1 ton ha⁻¹ in the well managed orchards that have 18-20 years old trees. Whereas in the USA, where they only began to cultivate pistachio after the 1960s (Tekin *et al.*, 1990; Ak *et al.*, 1999), modern production, irrigation, and fertigation management techniques are used and the average yield is 3.5 ton ha⁻¹ at orchards with 12 years old trees. Also, although the area of pistachio orchards in USA is less than one-fifth of that in Iran, the total production is 1.5 times more than Iran. Pistachio trees are drought tolerant and are able to survive and even produce modest yields with very little water. However, drought tolerance does not mean that pistachio trees require little water for optimal performance; these trees use water at a faster and quicker rate than the other fruit and nut trees (Goldhamer, 2005).

Although the SDI systems improve crop yield and production efficiency, development of sustained wetting fronts during and after irrigation using SDI in fine-texture soils causes temporal hypoxia that has negative effect on root aeration (Chen *et al.*, 2010). The high frequency irrigation by SDI may increase water content of soil and, consequently, decrease the oxygen availability in the root zone (Klaring and Zude, 2009). It has usually been observed that the near-saturated conditions around drippers during irrigation cause the supply of oxygen to be insufficient (Bhattarai *et al.*, 2010). Friedman and Naftaliev (2012) illustrated that orchards planted on fine-textured soils usually had lower yields than orchards planted on coarse-textured soils in similar climatic conditions, probably due to poor soil aeration. Also, reduced aeration decreases uptake rates of N, P, K, Ca, and Mg by root (McLaren and

Cameron, 1996), and the impacts of salinity become severe in hypoxia soils (Kuz'yakov and Cheng, 2001). The unfavorable effects of hypoxia on root performance of different plants have been widely documented (Shi *et al.*, 2007).

Several techniques have been proposed for improving soil aeration, whereas the most important one is sucking air (bubbles) into the irrigation water entering the drip lines (Bhattarai *et al.*, 2013; Bonachela *et al.*, 2005). The simple technique to transfer aerated water to the root zone by SDI is called oxygation (Bhattarai *et al.*, 2004). In this technique, air and oxygen as micro-bubbles can continuously be entered into water along the drip line and discharged to a hypoxic root zone (Bhattarai *et al.*, 2006). Oxygation can potentially prevail over inherent problems related to low oxygen (such as flooding, salinity, and sodicity) in the rhizosphere (Bhattarai *et al.*, 2004). Several studies attributed the enhanced WUE for many crop species in SDI systems to oxygation of irrigation water (Goorahoo *et al.*, 2002; Huber, 2000; Bhattarai, 2005; Bhattarai and Midmore, 2009; Pendergast *et al.*, 2014). Therefore, irrigation and oxygation strategies must be considered to avoid water deficiency and to prevent happening of hypoxic conditions in the root zone (Chen *et al.*, 2010).

Based on previous studies, oxygation increases the IWUE and yield, but the efficiency of oxygation is quite possibly affected by many factors such as soil type, crop type, and different ways of introducing air into the irrigation system (Chen *et al.*, 2010). On the other hand, by the authors' knowledge, benefits of aeration on trees planted on saline soil in dry region are not known. Therefore, the primary objective of this study was to quantify the effects of oxygenated water in SDI system on plant response, yield, nutrient uptake, quality, and IWUE for pistachio tree.

MATERIALS AND METHODS

Study Area, Weather, Soil, and Irrigation System Details



Figure 1. (a) Experimental site in Kerman Province (Sirjan City), (b) Experimental trees rows and the private weather station at 90 ha pistachio orchard, (c) Water flow from subsurface emitters, (d) Soil moisture measurement using TDR, (e) Surface wetting pattern from subsurface emitters, and (f) Air injection measurement .

Field experiments were carried out through installed Subsurface Drip Irrigation (SDI) on one ha pistachio (*Pistacia vera* cv. *Ahmad Aghaei*) orchard ($55^{\circ} 82' N$, $29^{\circ} 30' E$) of 15

years old that was part of a 90 ha farm, located in Kerman Province (Sirjan City) (Figure 1), over two cropping seasons. The pistachio trees were spaced 1×6 m within and between rows,

**Table 1.** Soil physical properties.

Layer thickness (cm)	San d (%)	Silt (%)	Clay (%)	Textural class	Bulk density (g cm ⁻³)	Field capacity (cm ³ cm ⁻³)	Wilting point (cm ³ cm ⁻³)
0-110	42.8	51.2	6	silt loam	1.34	32.8	15

respectively. Pistachio is the main plant cultivated in Sirjan using saline water (Talebiniya *et al.*, 2019).

The experimental area has a desert climate with no summer rains. The meteorological parameters were measured directly in the private weather station in the experimental field site. The total precipitation from April to September was 79.8 and 35.1 mm in first and second year of study, respectively. Furthermore, the precipitation distribution was non-uniform along the growing season. The mean temperature (°C), relative humidity (%), wind speed (m s⁻¹), and sunshine (hr) from April to September were 23, 28, 1.4, and 10.4 in the first year of study and 27, 29, 1.5, and 10.7 in the second year, respectively. The combined SDI pipe and an air injection system delivered mixture of water and air into the root zone.

The soil samples were collected at five different positions and five depths, within experimental field site (Iniesta *et al.*, 2008), and it is classified as a silt loam. Physical properties of the experimental soil are given in Table 1. Irrigation water, with average electrical conductivity of 0.83 dS m⁻¹ and pH 7.6, was obtained from a deep well located in the experimental area (Ucan *et al.*, 2007).

The lateral pipes with pressure-compensated emitters were placed at the both sides of the trees row. During the irrigation period, drip rate was regulated to 2.0 L hr⁻¹ per emitter by controlling hydraulic pressure. Subsurface laterals were placed 40 cm beneath the soil surface and 110 cm from trees row. The external

diameter and length of the laterals were 16 mm and 100 m, respectively, with emitters spaced 80 cm apart.

The nutrient requirement of the tree was supplied through fertigation. Fertilizers (kg ha⁻¹) consisted of 295 urea, 30 Ca(NO₃)₂, 40 KNO₃, 145 (NH₄)₃PO₄, and 131 ultrasolmagnum phoscal in the first year of study, and 260 urea, 35 Ca(NO₃)₂, 70 KNO₃, 115 (NH₄)₃PO₄, and 120 ultrasol magnum phoscal in the second year of study.

Air Injection

The treatments consisted of one irrigation interval (once every 3 days) without air injection (F₃) and by oxygation (F_{3-oxygation}) to investigate the effect of oxygation on pistachio trees. An air compressor was used for oxygation. It was fixed near the weather station and was connected with a 16 mm ID pipe fitted with a gate valve for each treatment. A pressure gauge was installed at the inlet of the air pipe for each treatment (Figure 2). Aerated water was delivered to the soil through emitters. The air delivery from emitters along dripline was measured following the method described by Torabi *et al.* (2013) and Torabi (2010).

Soil Moisture Monitoring

The active root zone depth in the soil volume was estimated using the moisture changes pattern that was determined by the Time Domain Reflectometry (TDR). Soil moisture content was measured daily using TDR (IMKO, Model: TRIME-FM3), which was calibrated by gravimetric method. Eight TDR tubes per treatment were installed at the beginning of the first season of study, arranged at fixed intervals from trees row in the wetted zone (50, 100, 150, and 200 cm from the tree row). The soil water content was measured at depths of 15, 30, 45, 60, 75, 90, and 100 cm through all access tubes. Irrigation was carried out on three days interval based on the TDR readings. The soil profile under each tree was divided into control volumes and the soil moisture in each control volume was measured (Figure 3). The soil water content for the whole tree was computed using weighted average of all control volumes under each tree. Also, it was assumed that there was a continuous wetted strip at the around the tree row. The application efficiency parameter was measured in the study field using Vermeiren and Jobling (1986) method and was equal to 76%. Irrigation gross volume

was calculated using the following equation:

$$V_n = \sum_{j=1}^n \left(\sum_{i=1}^m (W_{FCi} - W_{BIi}) \times CV_i \right) / E_a \quad (1)$$

Where, V_n is irrigation net Volume (cm^3), W_{FC} is soil Water content in Field Capacity ($\text{cm}^3 \text{cm}^{-3}$), W_{BI} is soil Water content Before Irrigation ($\text{cm}^3 \text{cm}^{-3}$), m is total soil layers in root depth, n is total measurement points, cv_j is control volume (cm^3) (Figure 2), and E_a is application efficiency.

Plant Growth and Yield

Leaf Area (LA) was measured by Leaf Area Meter in six trees per treatment (two trees per replicate). The leaves were picked from several trees in different locations of trees row and at distance of approximately 10 to 30 m along rows. Ten leaves per tree were picked from the north, south, east, and west faces near the trunk. The data for LA was derived from May to final plant harvest. Relative leaf growth was calculated as (Final-Initial)/Initial leaf area values.

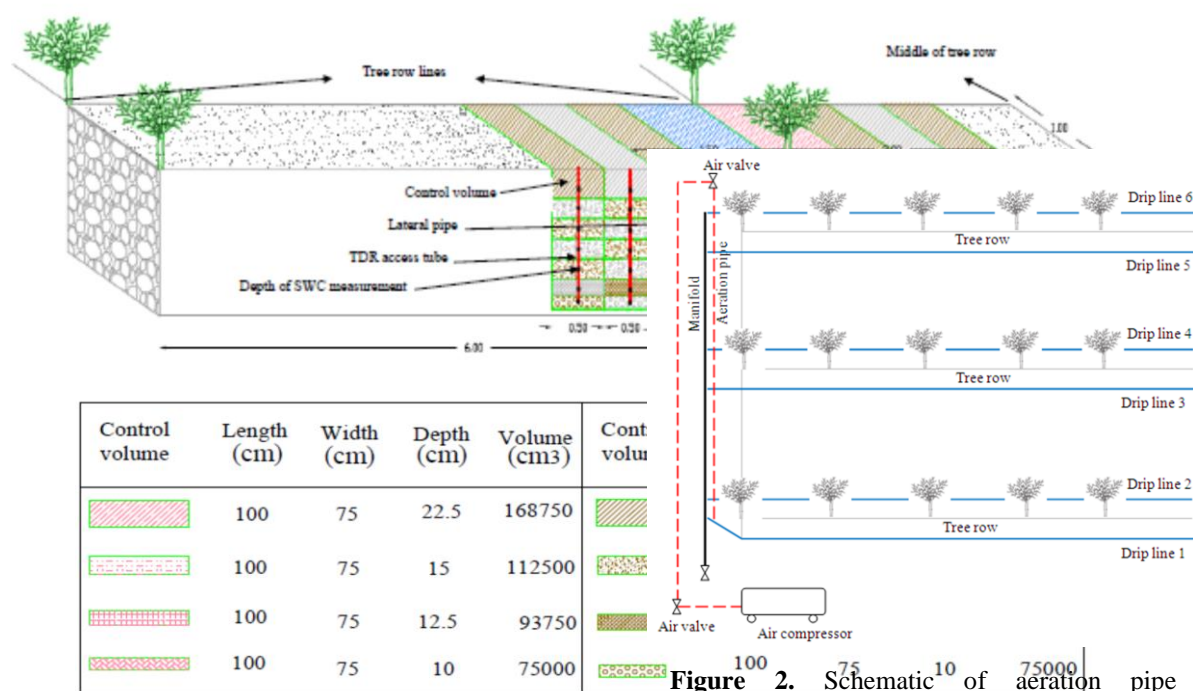


Figure 3. Schematic of the control volumes for calculating irrigation depth.

Figure 2. Schematic of aeration pipe connection from air compressor to driplines at



Also, three leaf samples per tree from six trees in each treatment were analyzed for the determination of K^+ , Fe^{2+} , and N_2 concentration. Before attempting to measure, leaf samples were first rinsed with double distilled water and then dried with paper towel (Barone *et al.*, 1997; Hajiboland *et al.*, 2014).

Harvest was carried out in commercial pickings in October. All nuts from nine experimental trees per treatment were harvested and average weight of fresh nut was determined. One sample was taken from harvested fresh nuts and was weighed. Quality traits such as percentage of blank nuts and split nuts were determined after shelling fresh nuts. Nuts were dried using sun drying method during four days, then, dry yield weight was measured. Pistachio ounce was determined by counting the number of dry nuts at 28.35 g (Panahi and Khezri, 2011).

Irrigation Water Use Efficiency (IWUE) values ($kg\ ha^{-1}\ mm^{-1}$) were calculated by Equation (2) (Yang *et al.*, 2013).

$$IWUE = \left(\frac{E_y}{I_r} \right) \times 100 \quad (2)$$

Where, E_y is the yield ($kg\ ha^{-1}$) and I_r is the amount of Irrigation water plus rainfall during the growing season (mm).

Statistical Analyses

The experiment was done using a randomized block design with three replications and statistical analyses were performed using the SPSS 16.0 for Windows. The treatments were compared using Duncan test at 5% level. At least three replicates were used for each laboratory and field measurement (Panahi and Khezri, 2011).

RESULTS AND DISCUSSION

Meteorological Data, Applied Irrigation Water, Air Injection

The weather data during the two growing seasons including precipitation and evapotranspiration are illustrated in Figure 4. The total precipitation from April to September was 79.8 mm in the first year and 35.1 mm in the

second year of study. Furthermore, a non-uniform precipitation distribution along the growing season is shown in Figure 4. The variation trend of Penman-Monteith evapotranspiration was approximately similar during the two growing seasons, but it was higher in the second year because of higher air temperature. The total Penman-Monteith evapotranspiration from April to September was 1,050 mm in the first year and 1,168 mm in the second year of study. On the other hand, the second experimental year was the driest and warmest. The air temperature increased from mid-March to mid-July, then decreased to late-September. The trend in evapotranspiration changes coincided with changes in mean air temperature. The Penman-Monteith evapotranspiration was almost $3\ mm\ d^{-1}$ since early March and reached about $8\ mm\ d^{-1}$ in mid-July in the first year, and $10\ mm\ d^{-1}$ in mid-July in the second year, then decreased.

The number of irrigations during experiment was 34 in both treatments. Total applied irrigation water during the irrigation period (22 May-22 September) was 1,189 mm in F_3 and 1,171 mm in $F_{3-oxygenation}$ in the first year of study. Applied irrigation water was increased to 1,356 mm for F_3 and 1,304 mm for $F_{3-oxygenation}$ in the second year of study as a consequence of weather conditions and evapotranspiration (Table 2). The applied irrigation water for trees increased over the 2 years of study due to canopy growth. A similar result was presented also by Gijon *et al.* (2009). The highest amount of irrigation water was measured in July for both treatments. The oxygenation treatment received the lower cumulative applied irrigation water than the control treatment.

Galindo *et al.* (2018) data on the pistachio water requirements varied in the range of 842–1,000 mm when calculated based on Testi *et al.* (2008) or Goldhamer (1995) methods. The high irrigation water requirement of pistachio was reported by many researchers. Goldhamer (2005) calculated water requirement for pistachio trees grown in the San Joaquin Valley under clean cultivated conditions during a normal weather year. The values of applied irrigation water from April to September were calculated equal to 38.76 inch (equivalent to 984.5 mm). Ünü *et al.* (2005) investigated the two irrigation intervals (every 7 or 14 days) of pistachio through a drip

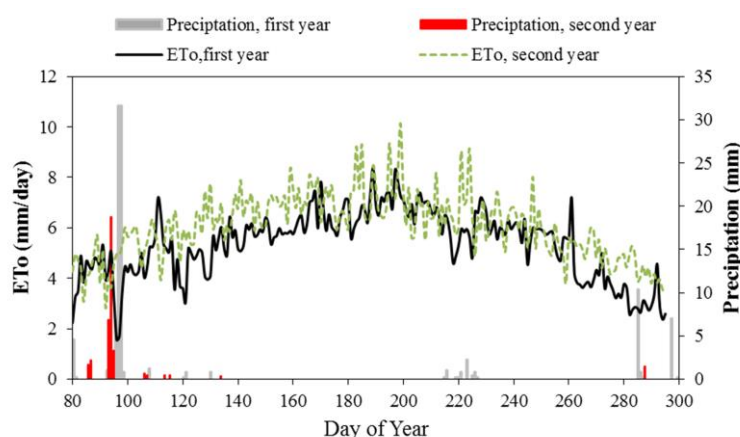


Figure 4. The Penman-Monteith evapotranspiration and precipitation during the two experimental growth seasons.

Table 2. Irrigation depth for pistachio tree under both treatments in two growing seasons.

Date	Day of year	First year		Second year	
		F ₃ (mm)	F _{3-oxgygation} (mm)	F ₃ (mm)	F _{3-oxgygation} (mm)
22May- 5June	143-157	73	66	139	125
6June- 21June	158-173	156	144	152	139
22June- 6July	174-188	226	216	222	212
7July- 22July	189-204	180	187	177	184
23July- 6August	205-219	155	153	151	148
7August- 22August	220-235	182	189	176	183
23August- 6September	236-250	116	100	209	177
6September- 22September	251-265	100	105	137	136
22 May- 22 September	143-265	1189	1170	1356	1304

system in Gaziantep City of Turkey with clay soil texture. Irrigation depth was calculated equal to 907 mm for interval of 7 days. Memmi *et al.*, (2016) performed daily irrigation for pistachio using a drip irrigation system in the Mediterranean climate with an average rainfall of 397 mm. The value of irrigation water was calculated as 750 mm in 2014 for the control treatment. Marino *et al.* (2019) investigated water use of micro-irrigated pistachio orchards under saline and non-saline soils condition in San Joaquin Valley of California. The total applied irrigation water according to soil control ranged from 1,125 to 1,222 mm in the period of 25 May–10 October. Although, differences in the reported levels of applied irrigation water could be attributed to differences in climate, soil texture, irrigation system (Özmen *et al.*, 2015), and the age of trees.

The average water flow rate was 2.5 L hr⁻¹ in pipes, which was close to water flow rate

specified by manufacturer. The average amount of air ingress into the driplines was approximately 18.8% air by volume of water. There was non-uniform air distribution and a decreasing trend was observed with distance along the driplines. Torabi (2010) reported that when air bubbles arrived into the driplines, the continuous air flow proceeds in upper part of dripline, and some air bubbles were released from upstream emitters. Therefore, the pressure gradient was created between the air injection point and primary emitters on the driplines. Increased pressure gradient creates the relatively low-pressure zones, which may enforce the biggest air bubbles to move toward this zone. Therefore, air bubbles flow decrease in downstream emitters.

Soil Moisture Content



Monitoring soil moisture content throughout the whole profile around the plant is important for effective scheduling for supplying sufficient irrigation water (Pendergast *et al.*, 2019). The soil moisture variations at different depths (0-22.5, 22.5-37.5, 37.5-52.5, 52.5-82.5, and 82.5-105 cm) measured at four locations from the tree row are shown in (Figure 5a-d). The soil water content was maintained between 27 and 33 mm for both treatments. In the top layer (0-22.5 cm), the soil moisture was low due to evaporation. Also, soil moisture profile of the control treatment stayed wetter at all depths during the season compared with the oxygated treatment. On the whole, moisture was largely distributed within the soil beneath the dripline and increased with increasing soil depth in all soil layers due to reducing root activities. The transverse distribution of soil moisture was affected by oxygation and it was uniform in $F_{3\text{-oxygation}}$. The soil moisture in the control treatment was lower than the oxygated treatment at 200 cm distance from tree row. At a distance of 0-75 cm from tree row, a decrease in soil water content of $F_{3\text{-oxygation}}$ compared to the F_3 treatment can be explained by high concentration of air in soil pores under irrigation pipe.

The difference between soil water content of treatments was clear at the beginning of the experiment. However, during the irrigation period, the soil water content of treatments in depth and distance from tree row were similar, probably because of variability in soil packing and chimney effect.

Plant Response to Air Injection

Relative leaf growth from May to September was 39.4 and 45.5% in the first year of study and 55 and 36.1% in the second year of study for F_3 and $F_{3\text{-oxygation}}$, respectively. Positive effect of oxygation was observed on leaf area per plant where the oxygation treatment had the highest leaf area per plant (not significantly) at the end of season (Figure 6). The positive effect of oxygation on leaf area in the low irrigation interval may be due to a relief of O_2 shortage in the rhizosphere (Bhattarai *et al.*, 2006).

Concentrations of K^+ in the nut and leaf were not affected significantly by oxygation, although the concentration of K^+ in the nut and leaf in the

oxygation treatment was higher than the control in both years. K^+ concentration of the pistachio leaf in $F_{3\text{-oxygation}}$ was 10 and 33.3% higher than F_3 in the first and second years of study, respectively. Also, concentration of K^+ in the pistachio nut at harvest in $F_{3\text{-oxygation}}$ was 10% more than control treatment in the first year and it was 22.2% higher in the second year (Figure 7). Distribution of K^+ in leaves and nuts of pistachio under oxygation showed an increase in movement toward leaves and nuts (Bagheri *et al.*, 2012). As presented in Fernando *et al.* (1992), the K^+ is transferred from vacuole to the cytosol of roots and then to the shoot and leaves. Furthermore, oxygation may improve nutrient uptake by modifying soil pore space of fine texture soils.

Concentration of Fe^{2+} in the nut and leaf increased with oxygation in $F_{3\text{-oxygation}}$ compared to the control treatment. Differences in Fe^{2+} concentrations between oxygation and control treatment in nut were significant in the second year (Figure 7). The rate of Fe^{2+} accumulation in leaf was 10.1 and 22.2% more than the control in $F_{3\text{-oxygation}}$ in the first and second year, respectively, while it was 14.3 and 77.8% more in pistachio nuts of $F_{3\text{-oxygation}}$ compared with control. The results of current study illustrated the positive role of oxygation in Fe^{2+} uptake.

The N concentration in the leaves did not seem to be affected by oxygation (Figure 7). The variation of N concentration in nuts was not clear, while a slight increase in N uptake by leaves was observed in $F_{3\text{-oxygation}}$ compared to the control treatment.

Pistachio Yield and Quality and Irrigation Water Use Efficiency

As is shown in Table 3, a reduction of 34.5, 14.9, and 28.2% was seen in, respectively, total yield, percentage of split nut, and IWUE in the $F_{3\text{-oxygation}}$ treatment compared to the F_3 in the first year of study. But no significant differences were seen between the $F_{3\text{-oxygation}}$ and F_3 during the second year of study for the parameters of total yield, percentage of split nuts, percentage of blank nuts, and IWUE. However, the total yield and IWUE in oxygation treatment were, respectively, 11.3 and 13.5% greater than in the control. Also, a reduction of 3.4% in

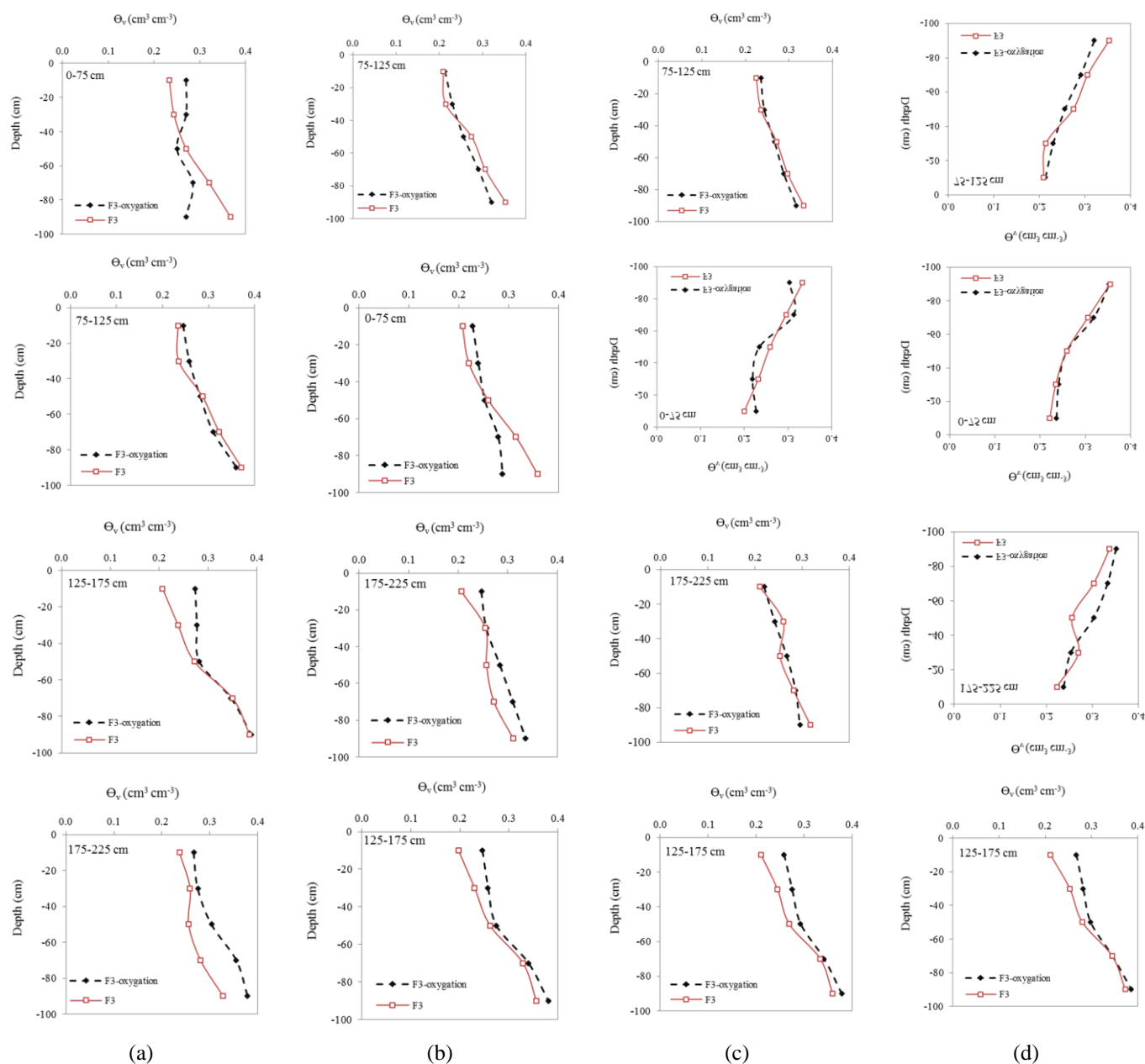


Figure 5. Variation of average soil moisture in 0-100 cm soil depth at different distances from the trees row (distances are written in the upper left side of the chart), (a) from 22 May to 21 June, (b) from 22 June to 21 July, (c) from 22 July to 21 August, and (d) from 22 August to 21 September.

percentage of split nuts and 17.6% in percentage of blank nuts occurred in oxygation compared to the control.

Pistachio yield was 3.3 and 2.2 kg tree⁻¹ in the first year, and 2.7 and 3 kg tree⁻¹ in the second year for F₃ and F_{3-oxgyation}, respectively. The mean pistachio yield per tree in F_{3-oxgyation} (2.6 kg tree⁻¹) was significantly lower than in F₃ (3kg tree⁻¹)

treatment (33.3%). It is well known that the distribution and amount of precipitation, differences in soil conditions, and temperature are the important factors affecting nut yield and quality traits for pistachio in arid and semi-arid areas (Nath *et al.*, 2001). Unusual rainfall happened in the spring 2013 that was harmful for pollination and led to abnormal growth and loss



of flower buds. Also, Bhattarai *et al.* (2005) noted low oxygen under FC on a heavy clay soil leading to lower cotton crop yields compared to

drier soils. In our study, yield in treatments was more

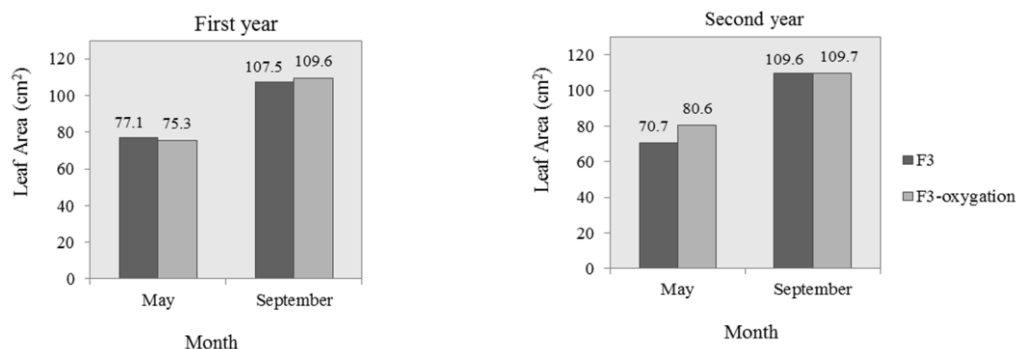


Figure 9. Effects of oxygation on pistachio leaf area.

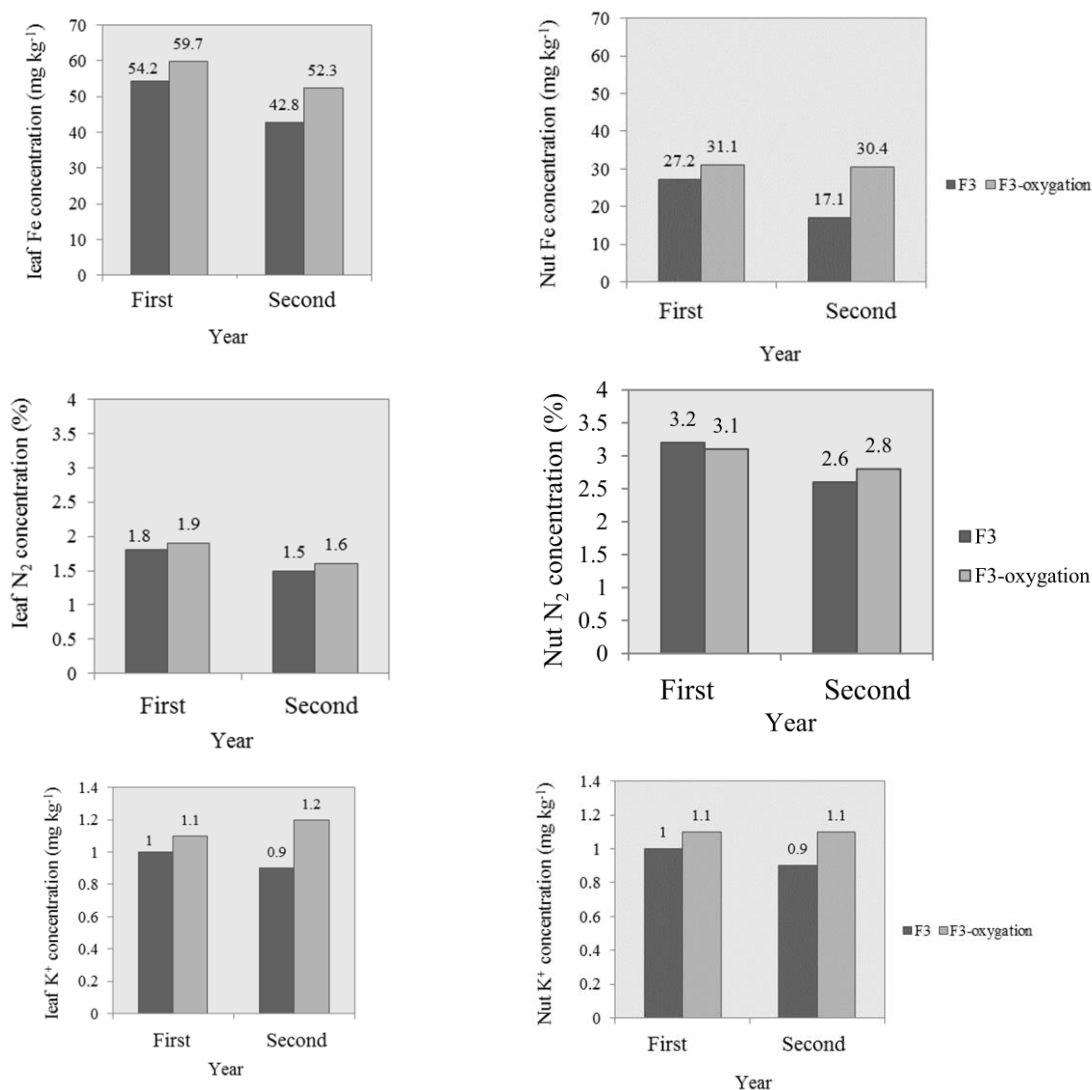


Figure 10. Effects of oxygation on ion concentrations of pistachio leaf and nut (the mean concentrations were calculated from several samples).

**Table 3.** Yield, irrigation water use efficiency, and quality traits for pistachio under different treatments in two growing seasons.

Parameter	First year		Second year	
	F ₃	F ₃ -oxygation	F ₃	F ₃ -oxygation
Yield (kg tree ⁻¹)	3.3 ^a	2.2 ^b	2.7 ^a	3 ^a
Total yield (ton ha ⁻¹)	5.5 ^a	3.6 ^b	4.4 ^a	4.9 ^a
Adjusted yield (ton ha ⁻¹)	5.1 ^a	3.2 ^b	4.3 ^a	4.8 ^a
Ounce (number of nuts per 28.35 g)	24 ^a	24.3 ^a	26.3 ^a	26.3 ^a
Percentage of split nuts	84.2 ^a	71.6 ^a	58.7 ^a	56.7 ^a
Percentage of blank nuts	14.1 ^a	17.4 ^a	5.1 ^a	4.2 ^a
IWUE (kg ha ⁻¹ mm ⁻¹)	3.9 ^a	2.8 ^a	3.7 ^a	4.2 ^a

dependent on blank nuts rather than the size of the nuts. Therefore, the adjusted yield calculated based on the parameters percentage of blank nuts and nut weight. To calculate the corrected yield, weight of hundred nuts was calculated using pistachio Ounce (number of pistachio nuts per 28.35 g) and weight of hundred blank nuts was measured (equal to 65 g). Statistical analysis showed significant difference in adjusted yield of pistachio among control and oxygation treatments in the first year; whereas in the second year, oxygation did not significantly affect pistachio yield. Clearly, the yields in second year for oxygation treatments were higher than those in first year. The adjusted yield of oxygated treatment was higher than the control by 10.4% in second year. Difference between oxygation and control could be due to wetting fronts and hypoxia conditions in the root zone of no-oxygation treatment that affected root and shoot growth and leaf water potential (Rhoades and Loveday, 1990). The average marketable adjusted yield of pistachio in the current study was calculated based on split nuts equal to 3.4 ton ha⁻¹ in F₃ and 2.5 ton ha⁻¹ in F₃-oxygation for both cropping seasons. These values are much higher than the 1 ton ha⁻¹ of dried marketable yield in the Iranian pistachio orchard that was irrigated fully. Also, the dried marketable split nuts of a fully irrigated Californian pistachio orchard was reported as 2.5 ton ha⁻¹ (Marino *et al.*, 2019). This result approves the benefit and potential of SDI systems application in the pistachio orchards, although the needed water volume to achieve this yield by SDI system and full irrigation with 3 days interval (10,500 m³ ha⁻¹) is higher than that required for common pistachio production in Iran (9,000 m³ ha⁻¹).

The pistachio ounce is a marketing index to indicate the weight and size of pistachio nuts. The lower number of pistachio nuts per ounce shows the larger nut size (Panahi *et al.*, 2011). The number of pistachio nuts per ounce of treatments was close and there was no significant difference between control and oxygation treatments in both experimental seasons. At the last harvesting date, the number of pistachio nuts per ounce was 24 in F₃ and 24.3 in F₃-oxygation in the first year of study. The number of pistachio nuts per ounce in the second year (26.3 for both treatments) was greater than first year. Panahi *et al.* (2011) reported the number of nuts per ounce of 26.2 for “Ahmad-Aghaii” cultivar harvested on 13 September at Rafsanjan (Iran).

The IWUE did not differ significantly between treatments and the two growing seasons. IWUE in the treatments with the high total water application and low total yield were commonly low. The greater IWUE in the second year was obtained by oxygation treatment. It was 4.7 kg ha⁻¹ mm⁻¹ in air injection treatment versus 3.7 kg ha⁻¹ mm⁻¹ in control treatment in the second year of study. In the current trial, the elevated IWUE with oxygation was achieved by positive influence on the rhizosphere environment. The IWUE results in the second year reflected the trends of more yield and IWUE improvements by oxygation that is encouraging over the results of the first year. It is an indication that air injection into SDI system has the potential to increase pistachio production efficiencies. Increasing IWUE of pistachio using oxygation of SDI provides benefits to invest for upgrading irrigation systems.

The effect of oxygation was not significant for pistachio ounce (nut size). Percentage of split nut was significantly higher in both treatments in

first year than second year. The effect of irrigation on pattern of split nut was not clear. A decrease in the percentage of split nuts occurred at the end of two growth seasons, but the extent was high and depended on irrigation treatment. This parameter was greater for control than the oxygation in both experimental years. This parameter may be related to environmental conditions more than water status. Sedaghati and Alipour (2005) suggested that the splitting is depended on plant water status from late April to early June. However, Gijón *et al.* (2009) stated that splitting incidence was not related to plant water status but was affected by temperatures below 13°C. Also, Kanber *et al.* (1993) and Memmi *et al.* (2016) reported that irrigation had no effect on percentage of split nuts.

The percentage of blank nut followed the same trend with split nuts, i.e. the pistachio nuts had lower blank nuts in the second experimental year. In the second year, the percentage of blank nut of F₃ treatment was higher than F_{3-oxygation}. According to the Goldhamer *et al.* (1985) and Gijón *et al.* (2009) studies, irrigation did not increase fruit weight, but it could affect the number of total nuts (Marino *et al.*, 2018). Rather, oxygation increased the number of total nuts and decreased the number of blank nuts in the second year of experiment.

There is obviously an indication that oxygation has an improvement potential to increased pistachio production efficiencies. This positive result deserves further investigation on the benefits of oxygated pistachio under SDI.

CONCLUSIONS

Two years of field experiments were carried out in Southeast Iran (Kerman Province, Sirjan City), on 15 years old pistachio trees grown on silt loam soil and irrigated by Subsurface Drip Irrigation (SDI), to study the effects of SDI with air injection on tree growth, nut yield, and mineral uptake by pistachio. Two treatments including F₃ (irrigation frequency once every 3 days without air injection), and F_{3-oxygation} (irrigation frequency once every 3 days by air injection) replicated three times were applied to one-hectare block of a 90 ha farm in two years. An air compressor was used for oxygation and irrigation was done based on the soil water

content reading with TDR sensor at depths of 15, 30, 45, 60, 75, 90, and 100 cm. The results showed that application of oxygation can reduce the mean applied irrigation water by about 3%, although the soil moisture pattern in the oxygation treatment was wider than control. The oxygation treatment had the highest leaf area per plant at the end of experimental seasons. Uptake of K⁺ and Fe²⁺ by nuts and leaves were affected by oxygation and these nutrients accumulated more in nuts and leaves compared with the control. The average concentration of K⁺ and Fe²⁺ of pistachio nuts in both experimental years in the oxygation treatment was almost 22 and 46% more than the control treatment, respectively; while these increased concentrations were 16 and 16.1% for leaves. This result exhibits the positive role of oxygation on nutrient availability from soil to pistachio tree. The results illustrated the oxygation potential to increase yield and water-use efficiencies of pistachio on a silt loam soil in the second experimental year. The non-uniform distribution of air bubbles along the aerated experimental lateral pipes led to insufficient supply of oxygen to the root zone and hence difference between nut yield between the aerated and control treatments was insignificant. In the second year, the highest yield (4.8 ton ha⁻¹) was obtained in oxygation treatment and the IWUE increased when oxygation was used. Air injection compared with no-oxygation increased blank nuts in the first year of study, but blank nuts decreased by oxygation treatment in the second year. The percentage of split nuts was not affected by water status and oxygation, but seemingly, it varied with climate conditions. The positive results of this study indicate that intensive monitoring is needed to investigate the long time effects of oxygation of irrigation water in SDI on pistachio tree. Therefore, the increased yield and improvement in IWUE could improve the profitability of SDI systems in pistachio farms. Based on the results, and growth parameters, tree yield, and nut quality characters were improved with oxygation in high frequency irrigation. Therefore, air injection into water in the SDI system can be used for improving SDI efficiency in heavy soils.

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راندمان استفاده از آب آبیاری و عملکرد پسته تحت تأثیر هوادهی در سیستم آبیاری قطره‌ای زیرسطحی

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چکیده

بهبود عملکرد و راندمان استفاده از آب موضوعی مهم در کشاورزی پسته در ایران می‌باشد. آبیاری قطره‌ای زیرسطحی، سیستم جدید آبیاری است که اخیراً مورد توجه کشاورزان پسته قرار گرفته است. کاربرد آب آبیاری به صورت متناوب در خاک تحت آبیاری این سیستم‌ها و به ویژه در خاک‌های رسی سنگین می‌تواند شرایط کمبود اکسیژن به دلیل ایجاد جبهه‌های خیس‌شدگی پایدار اطراف قطره‌چکان را بوجود آورد. در تحقیق حاضر، تأثیر هوادهی آب در سیستم آبیاری قطره‌ای زیرسطحی (اکسیژن-آبیاری) در غلبه بر شرایط

کمبود اکسیژن در خاک سیلت لومی و شور درختان پسته ۱۵ ساله در شرایط اقلیم بیابانی ارزیابی شد. دو تیمار شامل دور آبیاری ۳ روز در حالت بدون تزریق هوا: F_3 و دور آبیاری ۳ روز با اکسیژن-آبیاری: $F_{oxygation}$ در مدت دو سال مورد بررسی قرار گرفتند. تزریق ۱۸٪ درصدی حجم هوا به آب آبیاری سیستم آبیاری قطره‌ای زیرسطحی باعث اثرات مفیدی در عملکرد و راندمان استفاده از آب پسته در سال دوم آزمایش شد. به طوری که در سال دوم، عملکرد پسته در تیمار اکسیژن-آبیاری برابر با ۴/۹ تن در هکتار و در تیمار کنترل ۴/۴ تن در هکتار و راندمان استفاده از آب برابر با ۴/۲ کیلوگرم پسته خشک در هکتار بر میلی‌متر آب در تیمار اکسیژن-آبیاری و ۳/۷ کیلوگرم پسته خشک در هکتار بر میلی‌متر آب در تیمار کنترل اندازه-گیری شد. در سال اول، عملکرد و راندمان استفاده از آب در تیمار اکسیژن-آبیاری به ترتیب به مقدار ۳۳/۳٪ و ۲۸/۲٪ کمتر از تیمار کنترل بود اما در سال دوم به ترتیب به ۱۱/۱٪ و ۱۳/۵٪ افزایش یافت. پس از برداشت دانه‌های پسته، جذب نیتروژن در تیمار اکسیژن-آبیاری و کنترل به ترتیب برابر با ۱/۹٪ و ۲/۱٪ در سال اول و ۱/۴٪ و ۱/۶٪ در سال دوم اندازه‌گیری شد. همچنین، جذب پتاسیم برگ و آهن دانه پسته در تیمار اکسیژن-آبیاری به ترتیب در حدود ۲۴٪ و ۴۴٪ بیشتر از تیمار کنترل بود. مساحت سطح برگ اندازه‌گیری شده در تیمار اکسیژن-آبیاری بزرگتر از تیمار کنترل بود. نتایج حاصل، اثرات مثبت اکسیژن-آبیاری در سیستم آبیاری قطره‌ای زیرسطحی بر کشت پسته را نشان می‌دهد و لازم است تا بررسی‌های بیشتری برای ارزیابی اثرات پایدار اکسیژن-آبیاری در بهبود عملکرد و راندمان استفاده از آب پسته انجام شود.