A decade-long study on the effect of furrow and subsurface drip irrigation using unconventional water on soil salinity and the growth of pistachio trees

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Highlights

- *A subsurface drip irrigation (SDI) system consumed 50% less water than a furrow irrigation system.*
- *The two irrigation methods did not significantly differ in terms of their influence on the growth of pistachio trees (height, crown width, and trunk circumference) and yield.*
- *There was the greatest dispersion and spread of roots in SDI from 60 to 140 cm, and furrow irrigation at a depth of 50 cm.*
- *The average water use efficiency was 0.09 kg m^3 for SDI and 0.06 kg m^3 for surface irrigation.*
- *The overall trend in terms of salinity in the soil was increasing in both irrigation methods. However, in the surface layer (0-30 cm) of the subsurface drip irrigation (SDI) method, it initially increased from 34.7 dS m^{-1} to 110 dS m^{-1} and then decreased to 65.5 dS m^{-1} over the ten years.*

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Abstract

Furrow irrigation is the most common method of irrigating pistachio orchards in Iran. Water use efficiency using this method of irrigation is close to 35%. Ten years ago, a subsurface drip irrigation (SDI) project was initiated with highly saline and alkaline water for the first time in Iran at the Feyzabad pistachio research station, at 34° 54′ 15″ N, 58° 45′ 37″ E, located in the northeast of Iran, at an altitude of 850 meters from the sea. The water salinity and sodium adsorption ratio were 11.5 dS m^{-1} and 15.5 at the beginning of the project, and they reached 16.25 dS m^{-1} and 17.7 in 2021. The amount of SDI water consumption in the first year of the project (2012) was 1640 m^3 ha^{-1} yr^{-1}, and as the trees aged, water consumption reached 3000 m^3 ha^{-1} in 2022. The amount of water utilized for furrow irrigation was about 6912 m^3 ha^{-1} in 2022. Salt entering the soil through irrigation water differed by about 41 t ha^{-1} in 2022 between the two methods. After ten years of project implementation, the root development layer was more than 100 cm and less than 50 cm, respectively, for SDI and furrow. The trend of soil salinity has changed from 2012 to 2022: it went from 34.7 dS m^{-1} in 2012 to 110 dS m^{-1} in 2018, and then decreased to 65 dS m^{-1} in 2022 in the surface layer of the SDI method. In contrast, salinity increased almost twofold within the root development layer (60-140 cm) in the SDI. In the last two years (2021 and 2022), the height, crown width, trunk circumference, and yield of the pistachio trees were not significantly different between the two irrigation methods. However, there was a significant difference in the irrigation treatments during the two last years (2021 and 2022) in the annual growth, the average number of flower buds in the branch, and the average number of flower buds abscised. The branch vegetative growth in 2022 had decreased by almost 50% compared to 2021 in both methods. The results showed that the lowest annual growth was achieved in the SDI in 2022. Overall, the efficiency of water consumption in the SDI and furrow was equal to 0.09 and 0.06 kg m^3, respectively. SDI net income was 1284 $ higher after expenses were deducted

from 2012 to 2022. Therefore, due to severe climate change and excessive salinity increase in soil and water resources, a well-managed SDI can provide a more sustainable production method for salt-affected soils for pistachio orchards by reducing water consumption and salt entry into the soil.

Introduction

The importance of the implementation of the subsurface drip irrigation method

Population growth has increased demands on food production worldwide. However, the amount of water of appropriate quality for economic exploitation and production of agricultural products is limited throughout the world, and in particular in countries with a high proportion of semi-arid land such as Iran (Abedi *et al.*, 2002). To compensate for the lack of water needed for agriculture and food production in many regions of Iran, saline to highly saline water (Table 1) is inevitably used (Figure 1). The use of these waters can destroy the soil structure, reduce water penetration in the soil, and limit the spread of roots to the deep layers of the soil. Saline water also reduces the vegetative growth and yield of pistachios by increasing the toxicity of sodium and chlorine elements while reducing the absorption of essential nutrients and water for plant growth (Khorsandi *et al*., 2010; Fiezy, 2013). Currently, large parts of Iran's pistachio orchards (Figure 2) are irrigated using the furrow method with saline to highly saline water (Ahmadi and Baaghideh, 2020; Mousavifazl *et al*., 2021). In furrow irrigation, a large percentage of the water given to the trees is lost through evaporative losses due to the specific climatic conditions in the region and intense sunlight. For this reason, the use of subsurface irrigation systems is proposed as a solution to this problem (Sedaghati *et al*. 2012).

Classification of water quality

The most important parameter determining water quality is the total dissolved solids in mg l^{-1}, or its ability to conduct an electric current proportionate to its ion concentration in dS m^{-1}(Corwin and Yemoto, 2020). The American classification, the Food and Agriculture Organization, and Iran are very different in determining water quality (Table 1) (Abedi *et al*., 2002). There are many water sources in Iran whose salinity is higher than 12 ds m^{-1} but they are still used to irrigate pistachio orchards (Eskandari and Sherafati, 2021). The water used in this research was about 16 dS m^{-1}; which is much more than the maximum range of salinity in the common classification for water quality in agriculture (Table 1) (Abedi *et al*., 2002).

Common irrigation methods of pistachio orchards in Iran

Iran's pistachio orchards have traditionally used basin or furrow irrigation (Dastorania *et al*., 2007).

In the basin irrigation method, a large part of the garden surface is irrigated, and the roots grow in different directions. A tree's resistance to salinity and drought stress increases as its roots

Figure 1. Accumulation of salt in the soil surface of pistachio orchard, south of Bardaskan City, Khorasan Razavi, Iran (Sherafati, 2011).

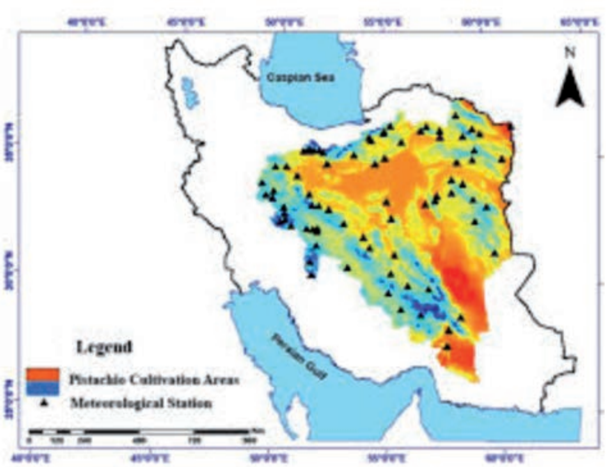

Figure 2. Pistachio cultivation areas in Iran (Ahmadi and Baaghideh, 2020).

Table 1. Comparison of American and Iranian classification of water quality based on dS m^{-1} (Abedi *et al*., 2002).

Water quality (dS m^{-1})	American classification	Iranian classification
Fresh water	0.25>	1>
Brackish water	0.25-0.75	1-4
Moderately saline water	0.75-2.25	4-8
Saline water	2.25-4	8-12
Highly saline water	4<	12<

expand. In recent years, this method has almost been abandoned due to the increasing amount of agricultural land under cultivation and associated higher water consumption (Seifi and Mirlatifi, 2020). The furrow irrigation method is used in two ways: i) in conditions where the water quality is suitable (low salinity), pistachio trees are mainly placed on the ridges. A portion of the area between the rows is irrigated by this method, which does not come into contact with the tree trunks (Figure 3A); ii) in this method, contrary to the first method, the trees are placed in the middle of the channels (in the water) and the ridges are formed between the two rows (Figure 3B).

Pistachio water requirements

The net irrigation requirement of pistachio orchards (m^3 ha^{-1}) for the traditional (furrow) and subsurface drip irrigation (SDI) methods was 6570 m^3 ha^{-1} and 4500 m^3 ha^{-1} respectively based on a study conducted in the Feyzabad region (Mousavifazl *et al.*, 2021). This is even though the volume of water used by the gardeners was 5671 m^3 ha^{-1} in the traditional method, 4230 m^3 ha^{-1} in the surface drip method, and 6100 m^3 ha^{-1} in the bubbler method. (Mousavifazl *et al*., 2021). Although, from the beginning of cultivation to nine years after planting, the water requirements of the pistachio trees differed (Table 2). According to the study conducted by Sedaghati *et al*. (2012), three irrigation treatments of 40, 60, and 80% of the pistachio tree's water requirements were implemented with surface drip irrigation and SDI on 30-year-old pistachio trees of the Ohadi variety. As a result of SDI, 0.29 kg dry yield was produced per cubic meter of water with a consumption of 4398 m^3 ha^{-1} (60% of the water requirement), at a salinity of 4.7 dS m^{-1}. Additionally, it was more efficient than SDI by saving 25% in water consumption (Sedaghati *et al*., 2012).

The purpose of this research was to investigate: i) the possibility of using unconventional water through an SDI system for pistachio orchards; ii) the long-term evaluation and comparison of the water consumption, vegetative growth, and yield of pistachio trees in the SDI and furrow irrigation. A final objective was to determine if the SDI method could be applied and exploited on a large scale in pistachio orchards by identifying the technical and operational challenges and providing solutions.

Materials and Methods

Land preparation and cultivation

To prepare it, the land was leveled first. In the next step, the cultivation plan was implemented, which had a six-meter row spacing between trees and a three-meter tree spacing between rows. Holes 80 cm deep and 50 cm wide were dug to plant seedlings. An equal amount of sand and soil was then used to refill the hole. Then irrigation was performed once using the traditional

Figure 3. A) Furrow method, the trees are placed on the ridge and water move between the rows, Feyzabad, Khorasan Razavi, Iran (Sherafati, 2012); **B**) Furrow method, trees are placed in the water, Feyzabad, Khorasan Razavi, Iran (Sherafati, 2020).

Table 2. Water requirement for the two methods (Farshi *et al.*, 1997).

No.	The age of the pistachio tree	Reduction coefficient	Water requirement (m^3) Furrow method	SDI method
1	From planting to 3 years old	0.4	2800	1260
2	From 4 to 6 years old	0.7	4900	2160
3	From 7 to 9 years old	0.9	6300	2835
4	More than 9 years old	1.0	7000	3150

SDI, subsurface drip irrigation.

method. After the soil preparation, the two-year-old seedlings of the Badami Zarand variety (rootstock), which were planted in plastic bags with dimensions of 40 cm long and 7 cm wide, were transferred to the farmland in the middle of March 2012. Irrigation was done immediately after planting. In the first year of planting (2012), the whole orchard was irrigated using the traditional method (furrow) to allow the seedlings to establish. Since the second year, the SDI system has been implemented in the orchard.

Technical specifications of the project

The SDI project was conducted at the pistachio research station, at 34° 54′ 15″ N, 58° 45′ 37″ E, located in the northeast of Iran, at an altitude of 850 meters above sea level. This irrigation method was implemented for the first time in 2012 with water with a salinity of 11.5 dS m^{-1} on two-year-old pistachio seedlings. The 16 mm diameter septic pipes, with in-line drippers and a self-cleaner, were installed at a depth of 70 cm in the soil and a distance of 120 cm on both sides of the seedlings (Figure 4). The drippers were located at a distance of 100 cm from each other on septic pipes. And their flow rate varied between 5-5.5 l h^{-1} depending on the pressure (1 to 2 atmospheres).

Irrigation schedule and amount of water used

During the growing season from mid-March to mid-October, irrigation was performed seven times (once every 20 days). Moreover, it should be mentioned that during the period from the first of April to mid-May, lower temperatures, high soil moisture, and the possibility of rain reduce the water requirement of the pistachio trees. During this period, irrigation can stimulate vegetative growth and interfere with the processes of pollination and pistachio fruit formation (Ferguson *et al*., 2016). As a result, the irrigation interval in this period is about 40 days (Mehrnejad and Javanshah, 2010). Consequently, only seven irrigations were performed between mid-March and mid-October. As per the study conducted by Farshi *et al*. (1997), it was estimated that pistachio trees during their bearing age would require almost 7000 to 7500 cubic meters of water per hectare in the surface method. However, the water requirements of juvenile pistachio trees of one to nine years of age were determined by the correlation coefficients in Table 2 (Farshi *et al*., 1997). Following the results of Sedaghati *et al*. (2012), the pistachio water requirement was 40-50 percent of the surface irrigation requirement (7500-7000 m^3 ha^{-1} yr^{-1}) in the SDI method. On average, 360 liters of water were consumed per tree in the first two years of implementing this method. With 555 trees per hectare, about 199 m^3 of water was used in each circuit during the growing season, and nearly 1400 m^3 of water was used in total. Water consumption per hectare per year reached about 1640 m^3 due to heavy irrigation in the dormant season (late November-early February) (Figure 5). This amount reached nearly 2400 and 3000 m^3 ha^{-1} $year^{-1}$in the eighth (2020) and tenth (2022) years, respectively. Surface irrigation calculations showed that 6912 m^3 of water were consumed per hectare per year.

Water salinity trend

The salinity of irrigation water has gradually increased since the implementation of the SDI method from 2012 until 2022. The elemental composition of water was measured by the soil and water lab of the Khorasan Razavi Agricultural and Natural Resources Research Center each year (Table 3). Electrical conductivity (EC) and pH were measured by the EC and pH meter (EW-35414-00 model) (Rayan *et al*., 2001). The soluble calcium and magnesium were determined by the 0.01 normal titration method

Figure 4. The 16 mm diameter septic pipes, in a 70 cm depth, Feyzabad Pistachio Research Station (2018).

Table 3. Salinity trend and other properties of water used in the subsurface drip irrigation (2012-2022).

Year	EC (dS m^{-1})	pH	$(CO^3)^{2-}$	HCO^3	Cl^-	Ca^{2+}	Mg^{2+}	Na^+	SAR
2013	11.5	7.4	0	0.115	3.03	0.494	0.168	1.567	15.5
2015	11.7	7.6	0	0.183	3.01	0.480	0.184	1.855	18.2
2017	12.2	7.3	0	0.195	3.24	0.513	0.174	1.807	17.6
2019	14.2	7.5	0	0.109	4.80	0.721	0.243	1.956	16.1
2021	16.23	7.3	0	0.189	4.78	0.721	0.246	2.158	17.7

EC, electrical conductivity; SAR, sodium adsorption ratio.

(Rayan *et al*., 2001), soluble sodium by a Flame Photometer (JENWAY PFP 7 Model), carbonate and bicarbonate by 0.01 normal H_2SO_4 titration method (Klute, 1986), and soluble chloride by 0.01 normal $AgNO_3$ titration method (Klute, 1986).

Soil chemical properties before the implementation of the subsurface drip irrigation method (2012)

Before implementing the SDI method, soil sampling was performed from the surface (0-50 cm) and subsurface (50-100 cm) layers according to the pistachio root depth; the results of its analysis are presented in Table 4. To investigate the process of soil salinization during the years of the project, soil samples were collected at two depths (0-30 and 30-60 cm) using the furrow method and at three depths (0-30, 30-60, and 60-140 cm) using the SDI method in three replicates for each depth. Since the pistachio roots did not grow deep enough in 60 to 140 cm in the first two years (2012 and 2013) of the project, soil sampling from this depth was not conducted using the SDI method. Some soil chemical properties were measured in the soil and water lab of the Khorasan Razavi Agricultural and Natural Resources Research Center (Table 4). The total neutralizing value was measured by normal titration with NaOH 1 (Klute, 1986). Other soil sample parameters were measured in the soil saturation extract (Aliehyaei and Behbahanizadeh, 1993). The methods for soil analysis were the same as previously described.

Management of the surface layer of the soil

The movement of agriculture equipment and humans on the soil surface causes the surface layer of the soil to be compressed (Nawaz *et al*., 2013). As a result, air infiltration into the soil could be gradually reduced. Two solutions were proposed and implemented to solve this problem. First, the surface layer of the soil, which contained a large amount of salt according to the results of Table 4, was collected and transported outside the orchard by the agricultural equipment at the end of the growing season (late October) and before the fall and winter rains. Hence, while salt is reduced in the soil surface layer, it is prevented from entering the lower layers and root development zone. Second, every winter before the rains, the soil was plowed at a depth of about 50 cm by a cultivator to reduce soil density and allow air to penetrate deeper layers (Figure 6).

Trees nutrition in the subsurface drip irrigation method

Nutrition and supplying the required nutrients were done in two ways: fertigation and foliar nutrition.

In fertigation, all kinds of water-soluble chemical fertilizers (liquid or solid) are used (Table 5). The following fertilizer compounds were used to provide macronutrients (Table 5): nitrogen (two sources of fertilizers, including urea and ammonium sulfate, are used to supply the required nitrogen); phosphorus (the main

Table 4. Some chemical soil properties before the implementation of subsurface drip irrigation (2012).

Depth, cm	pH	ECe, dS m^{-1}	TNV, %	Ca^{2+}, g l^{-1}	Mg^{2+}, g l^{-1}	Na^{+}, g l^{-1}	Cl^{-}, g l^{-1}	SAR
0-50	7.3	47.5	17.1	2.32464	0.729	6.239	9.0397	28.9
50-100	8	3.35	18.1	0.0721	0.074	0.6138	1.2053	16.5

TNV, total neutralizing value; EC, electrical conductivity. ECe was measured in soil-saturated paste extract; TNV is the percentage of the material that can neutralize acid expressed as the calcium carbonate equivalence (CCE) of the product.

Table 5. Nutrition schedule of pistachio trees in the subsurface drip irrigation and furrow methods in 2022.

Nutrition method	Date	Trade name	Nutrient weight (%)	Kg or L per hectare	
				Subsurface drip irrigation	Furrow irrigation
Fertigation	2022-3-12	Liqufos®	5-30-2	20 l	24 l
Fertigation	2022-3-12	fertinox®	5-5-40	25 kg	30 kg
Fertigation	2022-3-12 2022-6-5	Urea	N:46	130 kg	220 kg
Fertigation	2022-3-12 2022-6-5	Mega humat®	Humic acid:12, K:6, N:1, Zn:0.05	15 l	36 l
Fertigation	2022-6-5 2022-3-12 2022-6-5	Soluptasse®	K:51	20 kg	30 kg
Fertigation	2022-6-5	Ammonium sulfate	N:21, S:24	25 kg	40 kg
Foliar nutrition	2022-3-11 2022-10-2	Fruti Max fs®	N:4.35, Zn:3.25, B:0.43, Ca:0.043, Mo:0.0043 Fulvic Acid:2.6 and Seaweed: 8.7	12 l	12 l
Foliar nutrition	2022-3-11 2022-5-26	Fruti Max pis®	4.3-4.3-4.3 Along with all the micronutrients and amino acids, seaweed and fulvic acid	12 l	12 l
Foliar nutrition	2022-6-15	Silinox®	SiO_2:20 K:10	4 l	4 l

source of phosphorus was the liquid compound under the trade name Liqufos and mono potassium phosphate); and potassium (the main source of potassium was potassium sulfate under the trade name Soluptasse).

To provide micronutrients and growth stimulants, foliar nutrition was the priority of the work schedule. In the middle of March, at the same time as the flower buds swelled, foliar spraying (fruit set) was performed. After fruit formation on May 20, June 5, June 25, and October 10, 2022, leaves were fed with the compounds listed in Table 5.

In comparison to furrow irrigation, SDI consumed relatively small amounts of fertilizer. In the furrow, manure was applied by ring organic fertilizer method every four years, or splashed on the soil surface and then mixed with the soil using a rotavator. But in the SDI, organic fertilizer was not consumed at all.

Precipitation amount

One of the important climatic parameters that directly affect the growth of pistachio trees is the amount of rainfall (Table 6).

Statistical analysis

The data were statistically analyzed in two parts: i) a randomized complete block design (RCBD) for some parameters, including tree height, crown width, trunk circumference, the number of lateral branches on a two-year branch, and yield; ii) a RCBD arrangement in time (combined analysis over the years in RCBD) for the average annual growth, the average number of flower buds and the average number of abscission buds by MSTAT-C software and analysis of variance tables were obtained. Then the means' comparison of the data was performed by the least significant difference test (at a 5% probability level). Excel 2007 was also used to calculate and show Y error bars in the graphs.

Results and Discussion

Salinity distribution in different soil layers

One of the important matters in the SDI with highly saline water is the accumulation of salt in different layers of the soil. To investigate the trend in soil chemical properties and distribution of salinity, the results of the soil analyses before the implementation of the SDI project (2012) were first considered (Table 4). This soil was intact and had no crops cultivated on it before the implementation of this project. The degree of salinity was very high in the soil surface layer and very low at a depth of 50 to 100 cm. On the contrary, the pH in the subsurface layer was higher than in the surface layer before the implementation of the SDI (2012). After six years of the project (2018), to investigate the chemical changes in the soil, 3 profiles with a depth of 2 meters were dug at a distance of 1.5 meters from the tree and in the vicinity of the septic pipes, and sampling was carried out from the surface (0-30 cm), semi-deep (30-60 cm), and deep soil layers (60-140 cm), which results are given in Table 7. 10 years after the implementation of the project (2022), sampling of the above three layers was also performed, the results of which are shown in Table 8. Further, soil samples were collected from two depths (0 to 30 and 30 to 60 cm) during the project years (2012 to 2022) to determine the trend in soil EC in the furrow method (Figure 7). Also, in the SDI treatment, soil samples were collected at the same two depths (0-30 and 30-60 cm) in 2012 and 2013, as well as at a depth of 60 to 140 cm between 2014 and 2022 (Figure 8).

Six years after the project began, the accumulation of salinity and toxic elements, including sodium and chlorine, in the soil surface layer had increased (Table 7). So that the salinity in the sur-

Figure 5. The appearance of moisture on the soil surface in the path of the septic pipes, after heavy irrigation, Feyzabad Pistachio Research Station (winter of 2018).

Figure 6. Surface plowing of the soil using a cultivator, Feyzabad Pistachio Research Station (2015).

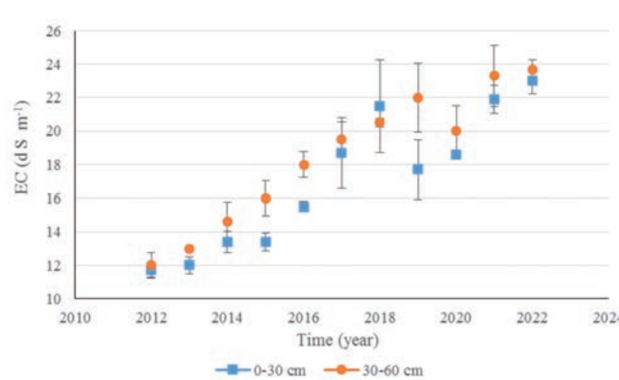

Figure 7. Electrical conductivity of soil in two depths (0-30 and 30-60 cm) in the furrow method from 2012 to 2022.

face layer of the soil (0-30 cm) reached 110 dS m-1 and the salinity elements including sodium and chlorine reached 15.20 and 27.47 g l-1, respectively. However, the salinity was 47.5 and 3.35 dS m-1 for the 0-50 and 50-100 cm layers before the SDI implementation (2012) (Table 4). Also, the concentrations of sodium were 6.2 and 0.61 g l-1 for these two layers and chlorin concentrations were also 9.03 and 1.20 g l-1 for 0-50 and 50-100 cm layers respectively (Table 4). These conditions not only destroy soil structure but can also be highly toxic and dangerous to roots. In the two lower layers, 30-60 and 60-140 cm, the degree of salinity and the toxic elements were very low (Table 7), and the root had no limit to absorbing water and nutrients. However, soil analysis (Table 8) after 10 years of using this irrigation method (SDI) showed that soil chemical properties changed significantly. Therefore, soil surface salinity decreased and increased almost two-fold at depths of 30-60 cm and 60-140 cm (root development zone) (Tables 7 and 8 and Figure 8). It is important to measure the salinity conditions in the soil layers to determine the presence of roots. The salinity intensity in different soil layers was completely different between furrow irrigation and SDI. In the SDI method, from 2012 to 2022, the salinity front expanded toward the surface layer (Figure 8), and the root growth moved toward the subsurface soil. The degree of salinity in the root development zone (30 -60 and 60 -140 cm) reached its lowest level in 2018 and then gradually increased. But in the furrow method, the degree of salinity in the two soil layers (0 to 30 and 30 to 60 cm) did not differ greatly (Figure 7). Unlike the SDI method, where salt accumulation occurred mostly in the surface layer of the soil, in the furrow method, a lot of salt accumulation was observed on the ridges (Supplementary Figure 1).

Distribution of roots in the soil

It is not easy to calculate the root growth and distribution of pistachio due to its deep and phreatophyte roots (Ferguson and Haviland, 2016). There are four characteristics that determine root growth in general: soil texture, soil salinity (Sepaskhah and Maftoun, 1982), irrigation method, and water consumption (Ryugo, 1988). As trees aged, more water entered the soil, so moistened soil volume increased from 2012 to 2022. The SDI method increased the zone with moisture more than twice as much as the furrow method with an increase in water input to the soil (Figure 9). The volume of root zone development based on water consumption in a 10-year period for the furrow method reached from 1.4 to 3.2 m^3 and in the SDI method from 3.8 to 7.0 m^3 (Figure 9). The lateral and deep dispersal of roots were directly related to the soil moisture range determined by digging the profile. With SDI irrigation, roots grew 160 cm in 2022 but were restricted to 60-70 cm with furrow irrigation (Supplementary Figures 2 and 3).

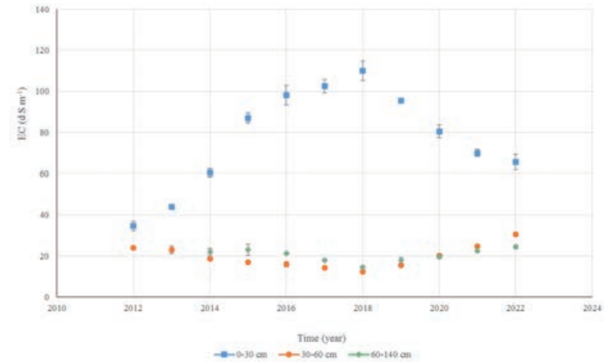

Figure 8. Electrical conductivity of soil in three depths (0-30, 30-60 and 60-140 cm) in the subsurface drip irrigation method from 2012 to 2022. There was no soil sampling conducted between 60 cm and 140 cm during the first two years of the project (2012 and 2013).

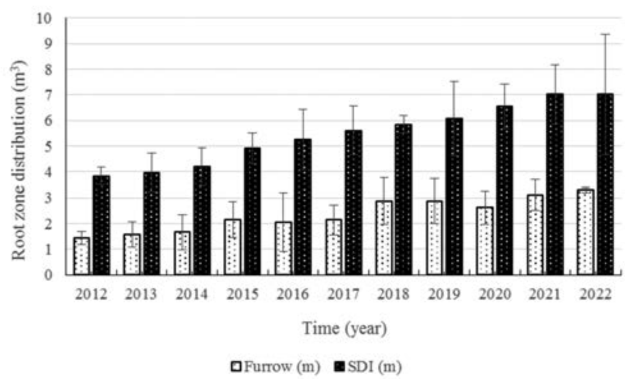

Figure 9. Estimation of root zone distribution based on soil moisture zone distribution.

Table 6. The amount of rainfall and evaporation rate in Feyzabad meteorological station from 2012 to 2022.

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Average
Rainfall amount, mm	188.5	133.5	83	104.6	91.2	100.4	67.3	214.1	244.6	122	57	127.8
Evaporation, mm	2232.8	2396.6	2523.2	2472	2480.2	2468.1	2350.7	2332.3	2279.9	2613.7	2570.6	2453.8

Table 7. Some important chemical soil properties six years after the implementation of the subsurface drip irrigation method (2018).

Depth, cm	pH	EC, dS m-1	TNV, %	Ca^{2+}, g l-1	Mg^{2+}, g l-1	Na^{+}, g l-1	Cl^{-}, g l-1	SO_4^{-2}, g l-1	SAR
0-30	7.1	110	15.3	3.60	1.64	15.20	27.47	13.44	52.7
30-60	7.8	12.33	14.3	0.400	0.243	1.83	3.19	0.960	17.8
60-140	7.8	14.52	16.5	0.440	0.243	2.31	3.54	1.53	21.9

EC, electrical conductivity; SAR, sodium adsorption ratio.

Based on the soil profile results, at a distance of 1.5 meters from the tree trunk (Table 7), it was found that: i) no secondary roots had grown from the soil surface to a depth of 30 cm; ii) the main root had spread horizontally at a depth of about 60 cm, after passing through the soil surface layers; iii) the roots were scattered to a depth of more than 140 cm, but the largest area of root dispersion was at 100 cm; iv) contrary to expectations, roots did not gather in the region of the dripper outlet and they appeared to be uniformly dispersed throughout the volume of soil under the dripper area (Supplementary Figure 2). While in furrow, the roots mainly started from the soil surface layer and reached maximum density at an average depth of 50 cm (Figure 3A).

Comparison of vegetative growth and fruiting between subsurface drip irrigation and furrow irrigation

After 10 years of the SDI project (Supplementary Figure 4), traits such as tree size, including tree height (Supplementary Figure 5), annual growth, and the ability to produce lateral branches were measured. Reproductive traits were also measured and recorded, including flower buds, abscission buds, and yield in 2022 (Supplementary Figure 6). As part of the study, the same traits were measured in furrow irrigation for trees of the same age, and statistical comparisons were conducted between the two irrigation methods to understand the impact of SDI on pistachio tree growth in highly saline soil and water.

Based on the analysis of variance results (Table 9), there was no significant difference between the two irrigation methods in height, crown width, and trunk circumference. Also, the number of lateral branches on the two-year-old branch and yield did not show any significant difference. However, according to the results of the mean comparison, there was a difference between the last two years (2021 and 2022) in the SDI in the average annual growth of the branch, the average number of flower buds, and the average number of abscission buds in the branch (Table 10).

The branch's annual growth in 2022 was almost 50% lower than in 2021 (Table 11). The mean comparison of traits in the interaction effects of the irrigation method in the year (Table 12) showed that the lowest annual growth (6.60 cm) was in the SDI method in 2022. As shown in the analysis of variance results, there was no significant difference in tree size (height, crown width, and trunk circumference) between the two irrigation methods (Table 9). But since 2022, the annual growth of trees in the SDI method experienced a significant decrease compared to the previous year and also compared to furrow irrigation (Table 12). These results were consistent with the results obtained by Ferguson *et al*. (2002) who stated that with the increase in salinity the root zone, vegetative growth and pistachio nut development decreases, but the percentage of sunburn increases. The soil analysis results (2022) in Table 8 indicated that the salinity in the root development zone had increased by approximately 2.5 times compared to the year 2018 with the SDI method (Table 7).

Comparison of water consumption, yield, water use efficiency, production costs and net income in two irrigation methods

The trend in the amount of water used over the past decade (Figure 10) showed that the furrow method (3000 to 6912 m^3 ha^{-1}) consumed almost twice as much water as the SDI method (1640 to 3000 m^3 ha^1). Climate fluctuations affected water consumption more in the furrow method than in the SDI (Figure 10).

Between 2012 and 2017, neither irrigation method produced a yield in the juvenile stage (Figure 11). In 2018, a little dry yield was produced, but it had no economic value. Both methods have shown economic production yields since 2019 when the trees

Table 8. Some important chemical soil properties ten years after the implementation of the subsurface drip irrigation method (2022).

Depth, cm	pH	EC, dS m^{-1}	TNV, %	O.C, %	Sand, %	Silt, %	Clay, %	$(Ca+Mg)^{2+}$, g l^{-1}	Na^+, g l^{-1}	SAR
0-30	7.3	65.5	17.3	0.32	42	36	22	2.8	10.2	48.7
30-60	7.4	30.6	16.3	0.19	48	30	22	1.69	4.31	27.4
60-140	7.3	24.5	14.5	0.15	34	42	24	1.72	3.34	21

Table 9. One-way analysis of variance of investigated traits in furrow and subsurface drip irrigation methods.

Source	df	Tree height				Crown width				Trunk circumference				Number of lateral branches on 2-year branch				Yield			
		MS	SS	F	P	MS	SS	F	P	MS	SS	F	P	MS	SS	F	P	MS	SS	F	P
Irrigation method	1	350	350	1.9091	0.2163	644.643	644.643	0.9748	-	23.143	23.143	1.5453	0.2602	0.046	0.046	0.0292	-	42.875	42.875	1.261	0.3044
Error	6	183.3	1100	-	-	661.310	3967.857	-	-	14.976	89.857	-	-	1.566	9.394	-	-	34	204	-	-

Table 10. Two-way analysis of variance of investigated traits in furrow and subsurface drip irrigation methods.

Source	df	Average annual growth (cm)				Average number of flower buds				Average number of abscission buds			
		MS	SS	F	P	MS	SS	F	P	MS	SS	F	P
Year	1	199.289	199.289	29.0958	0.0002	0.013	0.013	0.0452	-	0.756	0.756	5.1401	0.0427
Irrigation method	1	55.160	55.160	3.8314	0.0740	0.463	0.463	0.5905	-	0.070	0.070	0.1386	-
Year×irrigation method	1	15.303	15.303	1.0630	0.3229	1.201	1.201	1.5328	0.2394	1.201	1.201	2.3796	0.1489
Error	12	14.397	172.761	-	-	0.784	9.406	-	-	0.505	6.059	-	-

df, degree of freedom; MS, mean of squares; SS, sum of squares; F, F values; P, P-values.

reached maturity (Figure 11). There was an increase in water consumption efficiency in both irrigation methods, but the SDI had a twofold increase over the furrow irrigation method (Figure 12). The trend towards reduced water use efficiency for the furrow irrigation approach was clear in 2022 (Figure 12). Furrow irrigation had higher production costs than SDI, but neither of the methods had a significant difference in net income (Figure 13). Although, there were fewer fluctuations in net income for the SDI method during the study period, and the net income of the furrow irrigation method declined in the last year (2022) (Figure 13). Due to the

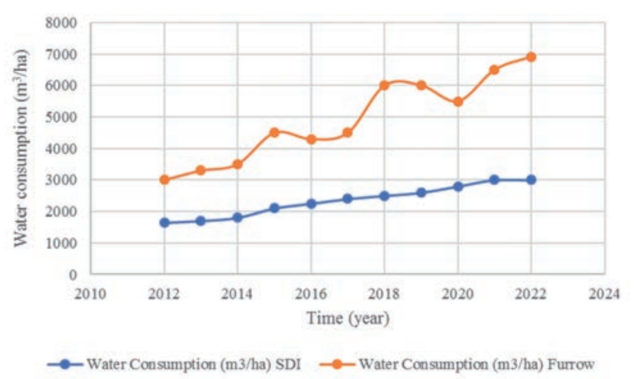

Figure 10. A comparison of water consumption (m^3 ha^{-1}) between two irrigation methods (furrow irrigation and subsurface drip irrigation) from 2012 to 2022.

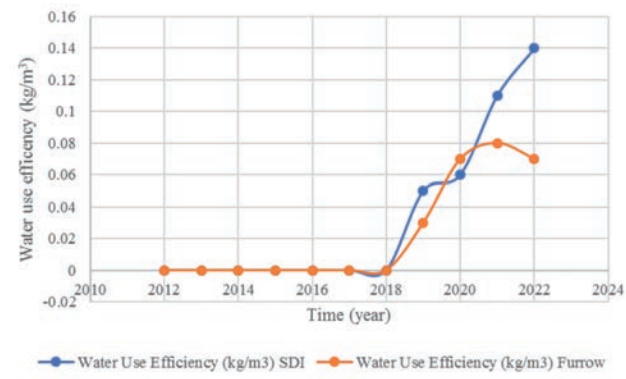

Figure 12. A comparison of water use efficiency (kg m^{-3}) between two irrigation methods (furrow irrigation and subsurface drip irrigation) from 2012 to 2022.

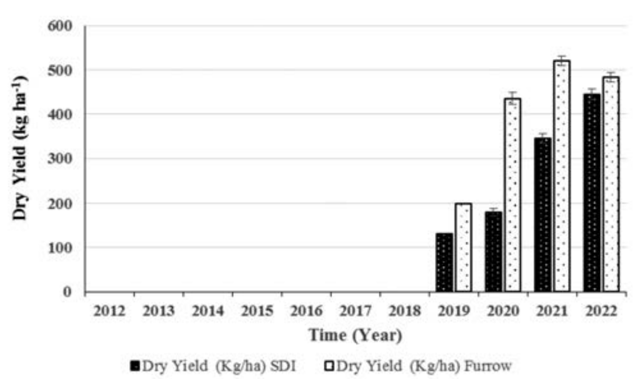

Figure 11. A comparison of dry yield (kg ha^{-1}) between two irrigation methods (furrow irrigation and subsurface drip irrigation) from 2012 to 2022.

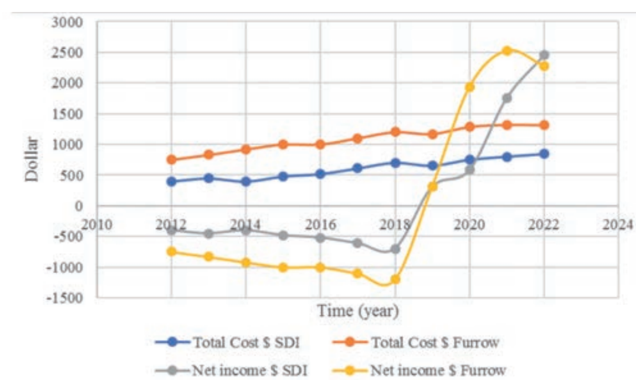

Figure 13. A comparison of production costs and net income between furrow irrigation and subsurface drip irrigation from 2012 to 2022.

Table 11. Mean comparison of the growth traits for the two years 2021 and 2022 in the subsurface drip irrigation and furrow irrigation.

Year	Average annual growth, cm	Average number of flower buds	Average number of abscission buds
2021	14.07[a]	1.293[a]	1.414[a]
2022	8.74[b]	1.250[b]	1.086[b]

Means followed by the same letters are not significantly different ($p \leq 0.05$) based on the least significant difference test.

Table 12. Mean comparison of the interaction effects of a year in the irrigation method.

Treatments	Average annual growth, cm	Average number of flower buds	Average number of abscission buds
2021× subsurface drip irrigation	13.41[a]	0.95[b]	1.57[a]
2021× furrow	14.74[a]	1.62[a]	1.25[a]
2022× subsurface drip irrigation	6.60[b]	1.32[a]	0.82[b]
2022× furrow	10.88[ab]	1.17[a]	1.34[a]

Means followed by the same letters are not significantly different ($p \leq 0.05$) based on the least significant difference test.

higher production costs in the furrow method, the net income of the two methods was equal because the yield of pistachio trees was lower in the SDI treatment. However, the trend in the net income of the furrow method in the last year produced different results (Figure 13).

The results reported in Table 13 show that water use efficiency was 0.09 and 0.06 kg m^{-3} for SDI and furrow irrigation methods, respectively. A significant finding is the one-third increase in water consumption efficiency (Figure 12) in the SDI method compared to the furrow method, taking into account the increasing trend in water salinity in the area (Table 3) and its different volume consumption of water in both irrigation methods (Figure 10). As a result of the higher water use efficiency of the SDI method, its net income was also higher (1284 $) from 2012 to 2022, although its yield was lower.

The production costs and income used in the furrow and SDI per hectare are shown for the last year (2022) in Table 13). The costs have been calculated based on the price of inputs such as labor, fertilizers and water in 2022 (Table 13). The yield in the two irrigation methods did not differ significantly based on the results of the analysis of variance (Table 9). However, the average fresh yield per tree for SDI and furrow irrigation methods was 3.6 kg and 4.8 kg, respectively. The yield in 2022 was a 1998 kg fresh yield equivalent to 444 kg of dry yield based on 555 trees per hectare, and 2664 kg fresh yield equivalent to 484 kg of dry yield based on furrow irrigation (Table 13).

Conclusions

A large portion of agricultural water sources have become saline to highly saline over the past two decades. Increasing salinity has led to increased water consumption, increased production costs, and reduced water efficiency. A decrease in investment and production is inevitable under these critical conditions. As a result, any method that reduces water loss in hot, dry regions, such as the studied area with an average annual evaporation of 2453.8 mm and an average annual rainfall of 127.8 mm (Table 6) is crucial. In this research, over the last 10 years, the SDI has achieved many valuable outcomes, some of the most important of which are listed below. In the SDI method, as mentioned in the results section, the roots of the pistachio tree developed deeply. Salinity levels decreased by 12 to 14 dS m^{-1} in the area of root expansion between 2012 and 2018; therefore, water and nutrient uptake were unlimited and trees grew well. Although the salinity in the surface layer of the soil had reached 110 dS m^{-1}.

During the period 2018-2022, the salinity trend in different soil layers changed; therefore, in 2022, salinity levels in the surface layer gradually decreased and in the root development layer almost doubled in the SDI method. The salinity level in the root growth zone exceeded the plants' tolerance levels, affecting vegetative growth and yield directly, so that branch growth decreased from 13.41 cm in 2021 to 6.60 cm in 2022. A simple count after 10 years of the project's implementation also showed that 16% of trees died under furrow irrigation and 14% under SDI irrigation. No significant difference in yield was observed between the two methods despite the use of organic fertilizer in the furrow method.

This severe reduction in growth was primarily dependent on the salinity increase in the root zone. Due to the deep root growth in the SDI irrigation method, climatic changes (severe decrease in rainfall) in 2022 (Table 6) could not significantly reduce tree growth. It may be concluded that the growth reduction in 2022 was caused by insufficient provision of water to the trees through SDI. But according to Figure 10, the amount of water consumption was the same in 2021 and 2022, while the tree's growth in 2021 was acceptable. Leaves emerge on new branches each year. In 2022, the average annual growth of the branches was only 8.74 cm, compared to 14.07 cm in 2021 (Table 11). As a result, there are fewer leaves, less leaf area, and lower rates of evapotranspiration. Consequently, growth reduction was probably not related to evapotranspiration, but to salinity increase in the rhizosphere zone (60 to 140 cm) in the SDI method as shown in Figure 8. Based on the comparison of furrow and SDI methods, the results indicated that even though the water use was doubled compared to the SDI method, there was an almost equal increase in salinity in the root development zone over 10 years. Although more salinity was expected using furrow irrigation, the salinity was distributed almost uniformly throughout the irrigated area up to 60 cm deep, with the greatest accumulation occurring on the ridge of the rows and in unirrigated soil. In the SDI method, as the soil depth increased, the salinity decreased (Figure 1).

The reason that the distribution and dispersal of salts in different layers of the soil changed in the SDI from 2018 to 2022 can be attributed to a huge increase in sodium, which destroyed the soil structure at the surface layer (0-30 cm). The collapse of the soil structure caused the pores of the soil surface layer to be blocked, and the movement of harmful elements such as sodium and chlorine, which occurs along with the ascent of water from the depths to the surface layer, was reduced. As a result, salinity and sodium concentration gradually increased in the 30-60 and 60-140 cm layers (root development zone) (Figure 8). The consequence of the salinity increase was a decrease in the absorption of water and mineral nutrients, which directly reduced the annual growth.

It can be concluded from the obtained results and additional explanations that to improve tree growth, achieve acceptable results and provide a more economical method, the following improvements should be made: i) leach from the surface layer of the soil - in the 10 years that have passed since the implementation of this project, leaching from the surface layer has not been done. For this purpose, the soil of the surface layer will be removed about 1.5 m from each side of the tree, and then leaching will be performed; ii) increase soil organic matter - one of the ways to reduce the effects of salinity is to increase soil organic matter. Considering that the roots of pistachio trees are located at low depths in this irrigation method, organic matter should be placed by digging channels in the

Table 13. Comparison of production costs and income in the furrow and SDI per hectare (in dollars) (2022).

Irrigation method	Water supply costs*	Nutrition costs	The cost of controlling pests, weeds	Labor costs	Harvesting and processing costs	Total costs	Dry yield (kg ha^{-1})	Gross income	Net income	Water consumption (m^3 ha^{-1})	Water use efficiency (m^3 ha^{-1})
SDI	28.57	328.57	85.71	200	200	842.85	444	3298.28	2455.42	3000	0.14
Furrow	57.14	514.28	142.85	371.42	228.57	1314.28	484	3595.42	2281.14	6912	0.07

SDI, sub-surface drip irrigation. *Calculating the cost of water consumption is based solely on the electricity cost of the well pump motor.

root development zone on one side of the tree; iii) remove the topsoil containing a lot of salt - as explained earlier, high sodium levels in the soil surface layer had destroyed the soil structure. In this case, the best thing for the future is to remove this layer as much as possible from the orchard using agricultural equipment; iv) plow the soil deeply while avoiding damage to the drippers and drip tapes. It is recommended to plow the soil to a depth of at least 50 cm after removing the soil from the surface layer so that gas exchanges at lower depths are improved and water can ascend from the lower layers to the surface; toxic elements (sodium and chlorine) also move from the root zone to the soil surface layers; v) increase the frequency of foliar application to compensate for any nutrient deficiency; vi) as a result of the recent findings, particularly those from last year (2022), it seems necessary to continue the project in the future to clarify different trends.

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Online Supplementary Figures

Figure 1. Comparison of soil EC (dS m-1) in different soil layers between two irrigation methods (2022).

Figure 2. Uniform distribution of roots according to the area of soil moisture development in subsurface drip irrigation (2018).

Figure 3. In furrow irrigation, the roots start from the surface layer and reach the maximum density up to a depth of 50 cm in the soil, Feyzabad Pistachio Research Station Garden (2018).

Figure 4. Uniform vegetative growth without symptoms of nutrient deficiency or toxic elements, SDI method, Feyzabad Pistachio Research Station (summer of 2022) .

Figure 5. Measuring the height of the tree in subsurface drip irrigation, Feyzabad Pistachio Research Station (autumn of 2022).

Figure 6. Reproductive growth and fruiting in SDI method, Feyzabad Pistachio Research Station (2021).