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INNOVATIVE SUBSURFACE DRIP IRRIGATION CONFIGURATIONS ENHANCE WATER USE EFFICIENCY AND OLIVE PRODUCTIVITY IN SANDY SOILS

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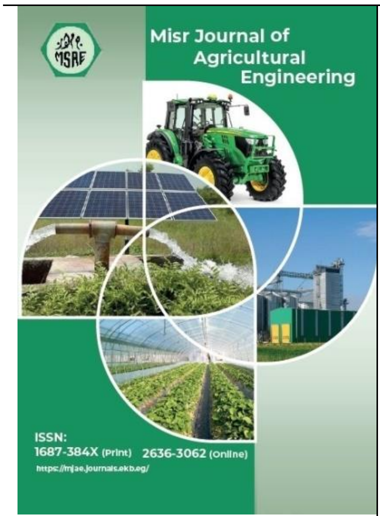


Keywords:
Fruit quality; Olive yield; Sandy soils; Subsurface drip irrigation; Water productivity

ABSTRACT

Efficient irrigation management is essential for sustainable olive production in semi-arid regions with sandy soils. This study evaluated three irrigation configurations—conventional surface drip, vertical subsurface drip, and inclined subsurface drip in terms of soil water distribution, crop yield, water productivity (WP), and fruit quality during the 2022–2023 seasons in Egypt. Soil moisture monitoring revealed that the inclined subsurface system provided the most favorable distribution, achieving deeper infiltration (up to 120 cm) and broader lateral spread compared to the vertical and surface systems. Crop yield analysis showed significant improvements under subsurface methods, with the inclined system producing the highest yields (17.9 and 21.9 ton/ha in 2022 and 2023, respectively), significantly outperforming the surface and vertical treatments. Water productivity followed a similar trend, increasing from 2.0 to 2.8 kg/m³ under the inclined configuration, compared to 1.1–1.6 kg/m³ for surface drip. Fruit quality attributes, including fruit, pulp, and seed weights, were also significantly enhanced under subsurface irrigation, with the inclined system consistently producing the largest fruits and heaviest pulp. These findings highlight the superiority of inclined subsurface drip irrigation in optimizing soil moisture dynamics, improving water use efficiency, and enhancing yield and fruit quality, thereby offering a promising strategy for sustainable olive production in arid and semi-arid environments.

INTRODUCTION

Water scarcity is one of the most pressing challenges facing agricultural systems worldwide, particularly in semi-arid regions such as Egypt. With limited freshwater resources and increasing competition for water, optimizing irrigation efficiency is essential for sustainable agricultural production. The need for water-saving irrigation practices is particularly urgent in the context of climate change, which, combined with population growth, intensifies pressure on agricultural productivity and resource management (Aboukeira et al. 2010).Therefore, innovative irrigation strategies, such as subsurface drip irrigation, which minimizes water loss through evaporation and runoff, are essential for sustaining agricultural productivity (Yang et al. 2023).

Drip irrigation, recognized for its ability to deliver water directly to the root zone, has emerged as a promising solution by reducing water losses due to evaporation and minimizing the wetted surface area compared to traditional irrigation methods, such as surface and sprinkler irrigation (Gallo Jr. et al. 2021). Subsurface drip irrigation (SDI), a variation of drip irrigation in which emitters are placed below the soil surface, further reduces evaporation and improves water use efficiency (Mohammed et al. 2020a). This method enhances the direct delivery of water and nutrients to the root zone, thereby minimizing runoff and percolation losses (El-Nesr et al., 2014).

Despite its advantages, uncertainties remain regarding the optimal configuration of SDI systems, particularly emitter design, spacing, and depth of installation. These factors influence the wetted soil volume, root zone moisture, and overall crop performance (Lamm et al. 2010; Sinobas et al. 2012). In regions like Egypt, where sandy soils dominate, this challenge is especially critical: sandy soils are characterized by high infiltration rates and low water-holding capacity, requiring careful management of wetted area and irrigation frequency to prevent both deep percolation losses and insufficient crop moisture (Yu et al. 2017).

Drip irrigation systems, particularly SDI, have been shown to enhance water productivity by targeting the root zone more effectively than surface systems (Martínez & Reca, 2014; Yang et al., 2020). However, performance depends heavily on emitter layout and water distribution in soil. Conventional surface drip systems often create limited and uneven wetted areas, leading to water inefficiency, especially in sandy soils (Reddy et al. 2018). Conversely, SDI systems deliver water and nutrients directly to the root zone, reducing evaporation and deep percolation losses (El-Nesr et al. 2014; Rodríguez-Sinobas et al. 2012).

Implementing water-saving designs for SDI, such as vertical and inclined configurations, could optimize water use and enhance agricultural sustainability in Egypt’s arid and semi-arid regions. The present study therefore evaluates the effectiveness of these innovative SDI designs in olive orchards in Egypt. Specifically, we compare conventional surface drip irrigation with vertical and inclined SDI systems, assessing their impact on water distribution, water productivity, crop yield, and fruit quality.

MATERIALS AND METHODS

Study Site and Experimental Design

The field experiment was conducted at farm of faculty of Agriculture, Benha University, Egypt (latitude: 30°21'44.65''N, longitude: 31°38'46.75''E and Altitude: 70.1 m - WGS84). The site represents typical Mediterranean semi-arid conditions, characterized by high summer temperatures, low annual rainfall, and sandy soil texture. The study was carried out on a commercial olive orchard (*Olea europaea* L.), cultivar *Picual*, cultivated for table olive production.

The trees were spaced at 5 × 5 m (equivalent to 400 trees ha^{-1}). The soil at the experimental site was classified as sandy, with low water-holding capacity (Fc = 20 %, WP = 8 %) necessitating precise irrigation management as presented in Table 1. The soil chemical properties are provided in Table 2. Irrigation water was sourced from a nearby irrigation canal and applied to meet 100% of the crop evapotranspiration (ETc), calculated using local weather data and standard FAO Penman-Monteith methodology(Allen et al. 1998).

Table 1: Soil physical and mechanical properties.

depth	Physical Properties					Mechanical properties			
	Bd (Mg m^{-3})	SP (%)	FC (%)	AW (%)	PWP (%)	sand %	Clay %	Silt %	Soil texture
0-30	1.5	43.4	22	14	10	76.38	16.08	7.54	sandy loam
30-60	1.55	41.5	18	10	6	71.9	18.74	9.36	sandy loam
60-90	1.6	39.6	19	11	7	75.24	15.22	9.54	sandy loam
90-120	1.6	41.5	21	13	9	75.83	15.76	8.41	sandy loam

Table 2: Soil chemical properties.

Depth	pH	EC	ESP	Cations milli equivalent /Liter				Anions milli equivalent /Liter			
cm		mS/cm		Ca	Mg	K	Na	Cl	SO_4	HCO_3	CO_3
(surface 0-30)	7.7	2.90	9.16	5.78	6.70	0.56	19.20	18.0	10.23	4	0
(30-60)	7.8	2.35	8.36	6.05	3.84	0.51	15.66	14.4	7.66	4	0
(60-90)	7.8	1.40	8.52	2.75	1.98	0.58	11.03	9.0	5.34	2	0
(90-120)	7.9	1.17	6.91	2.48	1.83	0.45	8.63	7.2	4.19	2	0

Irrigation Treatments

Three irrigation system configurations were evaluated in a randomized complete block design with three replications per treatment. Each experimental unit consisted of a minimum of five trees, with the central three used for data collection to minimize border effects. All treatments were managed to apply equal volumes of irrigation water, allowing for direct comparison of system performance based on emitter configuration and placement.

Figure 1 shows the irrigation treatments, which were as follows:

- **C: Surface Drip Irrigation (Conventional)**

This treatment served as the control. Two surface drip lines were installed along each tree row, with each tree receiving four online drippers (8 L h^{-1} each), for a total discharge of 32 L h^{-1} per tree. The drip lines were positioned 1 m from the tree trunk on either side, resulting in a 2 m spacing between the two drip lines per tree.

- **V: Vertical Subsurface Drip Irrigation**

Each 8 L h^{-1} surface dripper used in treatment C was replaced with two inline drippers delivering 4 L h^{-1} each. These were installed vertically into the soil profile, with the first emitter placed at a depth of 30 cm below the soil surface and the second at 60 cm, spaced 30 cm apart along the lateral line. The emitters were positioned near the active root zone to enhance sub-surface water delivery and reduce surface evaporation, as illustrated in Figure 1.

- **I: Inclined Subsurface Drip Irrigation**

Similar to treatment V, this treatment used two inline drippers (4 L h^{-1} each) per inclined drip line, totaling 32 L h^{-1} per tree. Each drip line was 60 cm in length and buried at a 45° inclination toward the tree trunk, starting 1 m horizontally from the trunk base. The first dripper was positioned at a depth of 30 cm, and the second at 60 cm below the soil surface. This inclined configuration was designed to improve both lateral and vertical water distribution within the root zone. Full installation details and dimensions are illustrated in Figure 1.

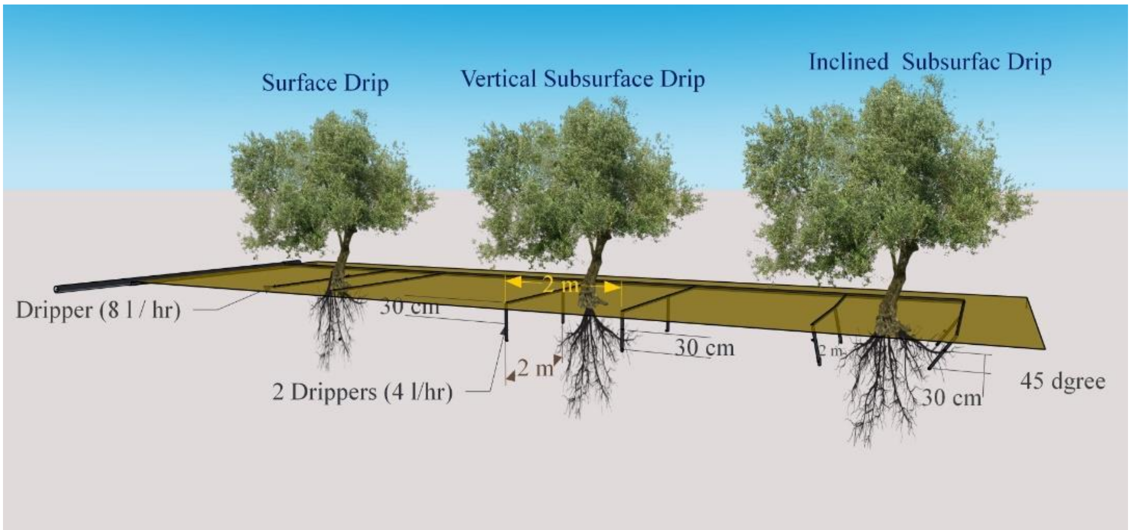


Fig. (1): Schematic diagram showing the layout of different drip lines below the soil surface.

Irrigation Scheduling and Monitoring

Irrigation was scheduled based on daily ETc values derived from local meteorological data, using reference evapotranspiration (ETo) and FAO 56 crop coefficient (Kc) values appropriate for olive trees. All treatments received equal irrigation volumes on each irrigation event to isolate the effect of system layout on water distribution and plant response.

Soil moisture was monitored using sensors (ML3 ThetaProbe Soil Moisture Sensor and HH2 Meter) installed at different depths (0–120 cm) and distances (0-100 cm) from the emitters to evaluate water distribution dynamics for each irrigation method.

The soil water thresholds—including soil water content at field capacity (SWC-FC), wilting point (SWC-WP), and readily available water (SWC-RAW)—as well as soil water balance (WB), applied water, and rainfall, are shown in Figure 2.

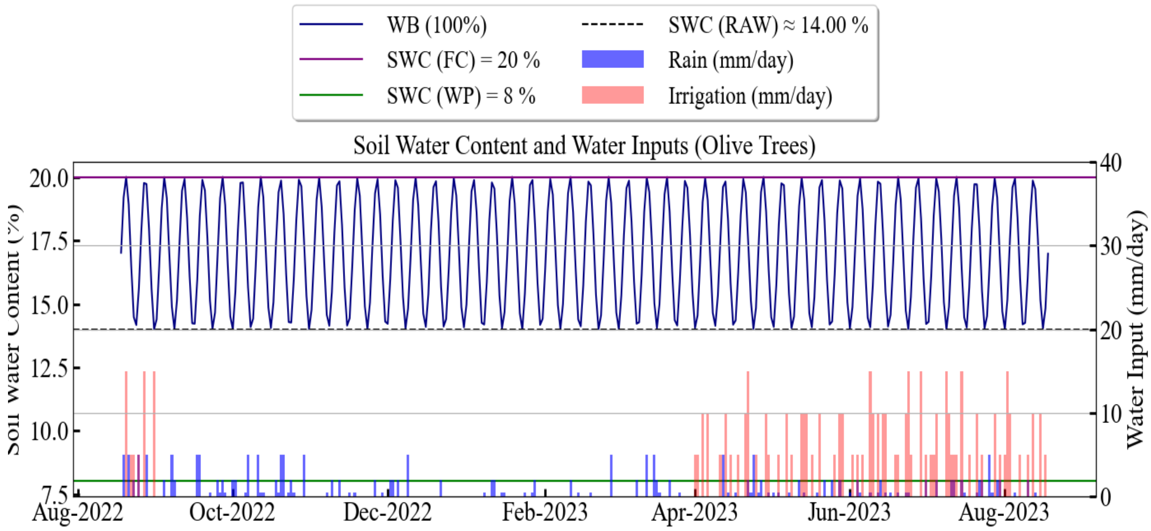


Fig. (2): The crop evapotranspiration mm/day, applied irrigation water related between soil water thresholds lines (field capacity Fc, Welting point Wp and Radial available line for olive trees.

Soil Water Distribution:

Determined using gravimetric and sensor-based measurements to characterize wetting patterns for each treatment.

Water Use Efficiency and Productivity:

Total irrigation water applied was recorded using flowmeters. Water productivity (WP) was calculated as the ratio of fruit yield (kg ha^{-1}) to the volume of irrigation water applied (m^3 ha^{-1}).

Fruit Yield: Total yield per hectare (ton ha^{-1}) was recorded at harvest by weighing fruits collected from sample trees.

Fruit Quality: Measured as the weight of 100 representative fruits (g) to assess the impact of irrigation treatments on fruit size. As the orchard was used for table olive production, oil content and quality analysis were not conducted.

Statistical analysis

All collected data were subjected to statistical analysis using analysis of variance (ANOVA) to determine the significance of treatment effects. Where significant differences were found, Tukey's Honestly Significant Difference (HSD) test was used for multiple comparisons among treatment means at a significance level of $p < 0.05$.

RESULTS AND DISCUSSION

RESULTS

Soil Water Distribution

The performance of the three irrigation systems was monitored over four measurement dates: 20 May 2022, 1 July 2022, 1 September 2022, and 25 January 2023, with soil water content tracked radially up to 100 cm from the tree trunk and vertically to 120 cm. Figure 3 shows contour plots illustrating the spatial and temporal dynamics of soil moisture distribution under each irrigation method.

The contour plots depict the distribution of soil water content, ranging from 12% (dark blue) to 46% (lite blue), across soil depths (0–120 cm) and horizontal distances from the tree. Three irrigation methods were compared: vertical drip, inclined drip, and surface control drip.

- Vertical Drip Irrigation: This system concentrated moisture directly beneath the emitter, particularly in the shallow layers (0–30 cm), with water content reaching 40–46%. As the distance from the emitter increased, moisture content decreased to 12–20%. Water penetration was limited to the upper and middle soil layers, with minimal effect beyond 60 cm. The vertical system improved water penetration in the 40–80 cm depth range, where moisture content remained higher compared to the surface drip method. While the lateral spread was moderate, the vertical system enhanced moisture uniformity in the root zone, especially during July and September 2022.
- Inclined Drip Irrigation: The inclined system provided the most favorable water distribution, with the 45° emitter angle facilitating both vertical infiltration and lateral spread. This resulted in a broad wetted volume reaching up to 120 cm in depth and extending radially beyond 80 cm. Moisture content in the top 30 cm remained between 35–40%, and water penetration reached deeper layers (30–60 cm). While the lateral spread was more uniform than the vertical system, it was still less extensive than the surface drip system. The inclined system consistently demonstrated effective hydration of the entire active root zone across all measurement dates, particularly in July and September 2022.
- Surface Control Drip Irrigation: The surface system exhibited the widest lateral spread, especially in the upper layers (0–30 cm), where moisture content remained between 35–40%. However, moisture levels decreased sharply in deeper layers (90+ cm), with values dropping to 12–18%. The surface system showed a shallow wetting pattern, primarily within 20–40 cm of the soil, with limited radial spread beyond 40 cm from the emitter. Infiltration into deeper layers remained poor, suggesting inefficient water use, with higher evaporative losses and less coverage of deeper root zones.

These findings highlight the importance of emitter configuration in optimizing soil moisture dynamics. The inclined subsurface drip system (I) was particularly effective in ensuring both vertical and horizontal water availability, making it the most efficient design for sandy soils and high evaporation conditions at the study site.

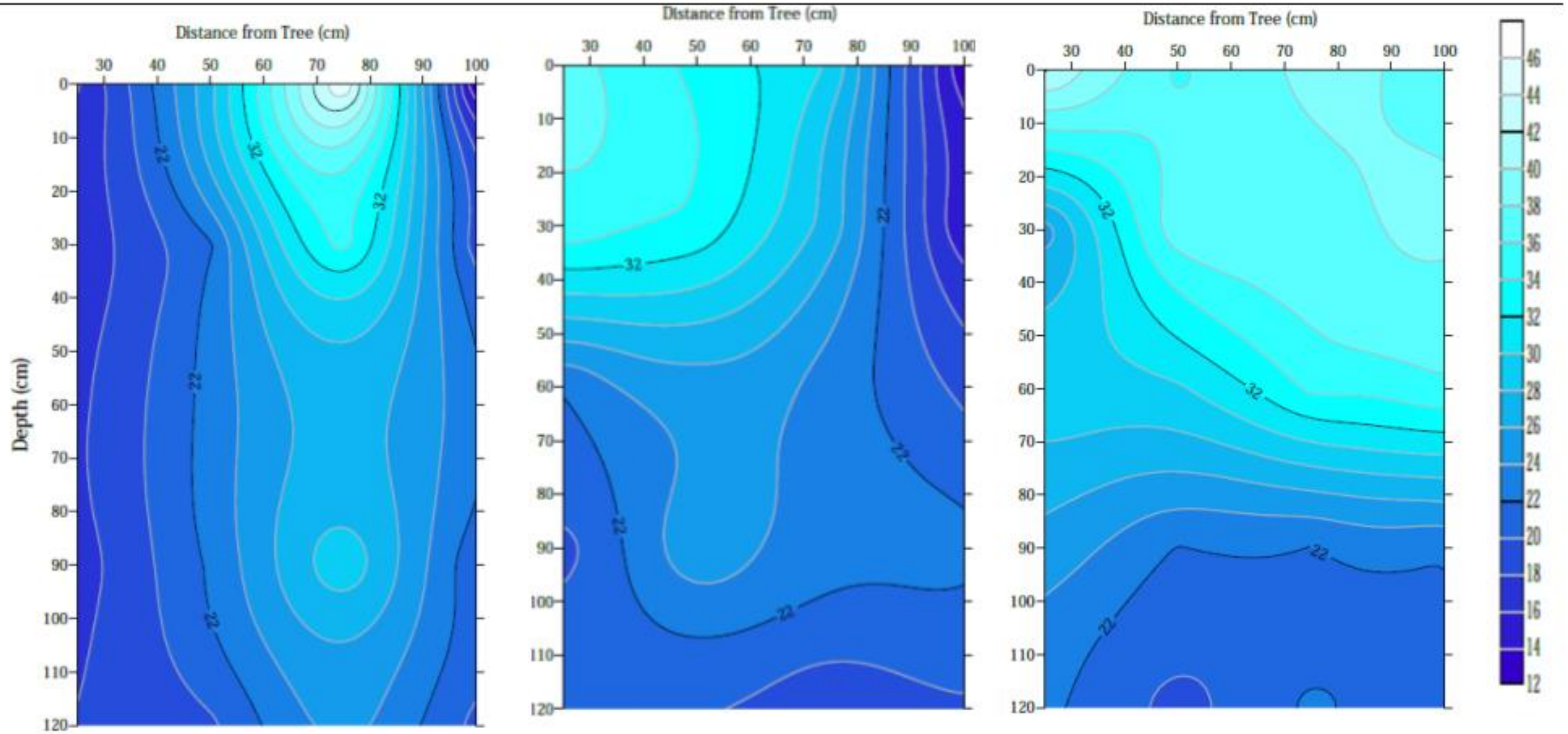
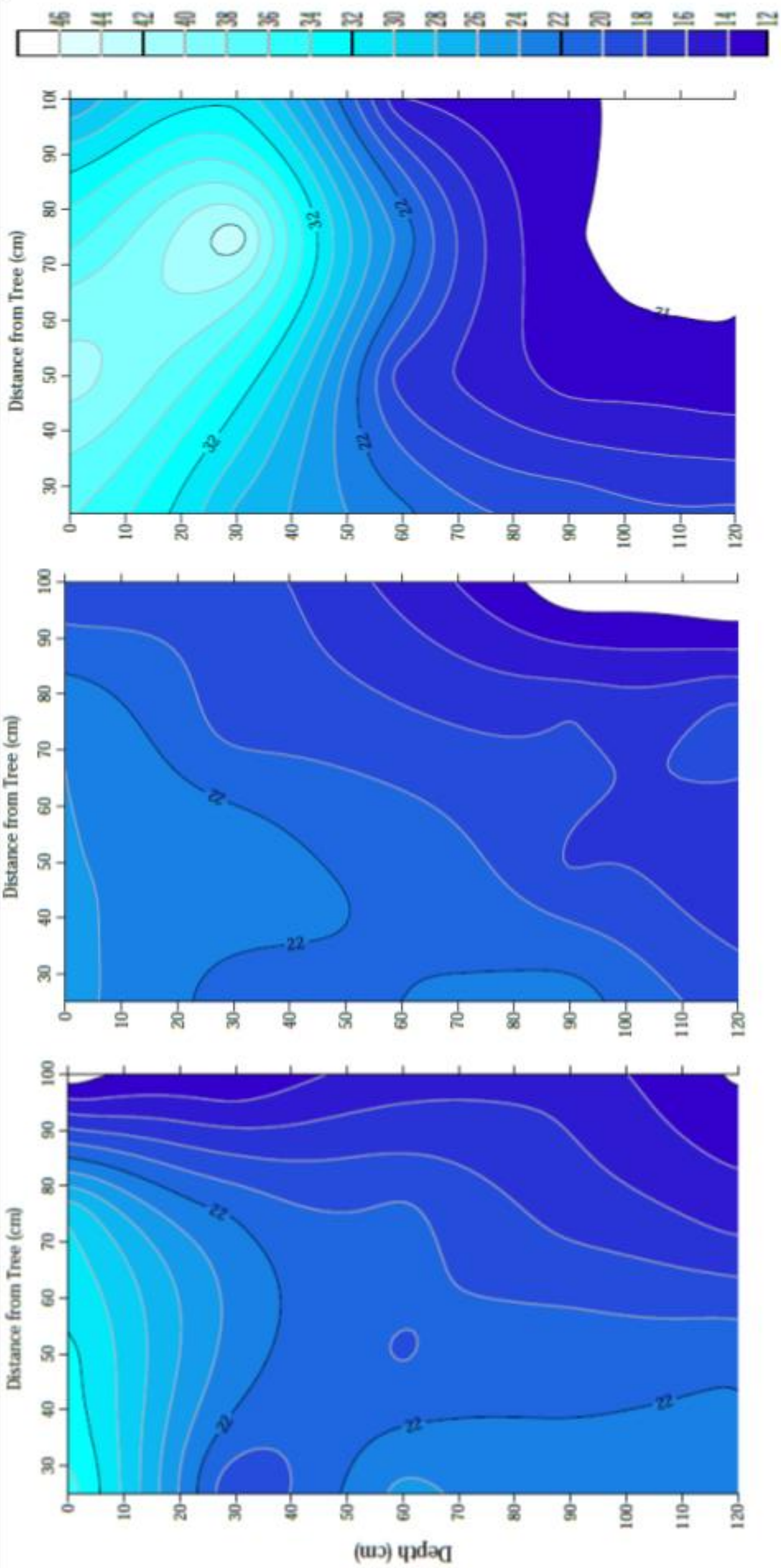
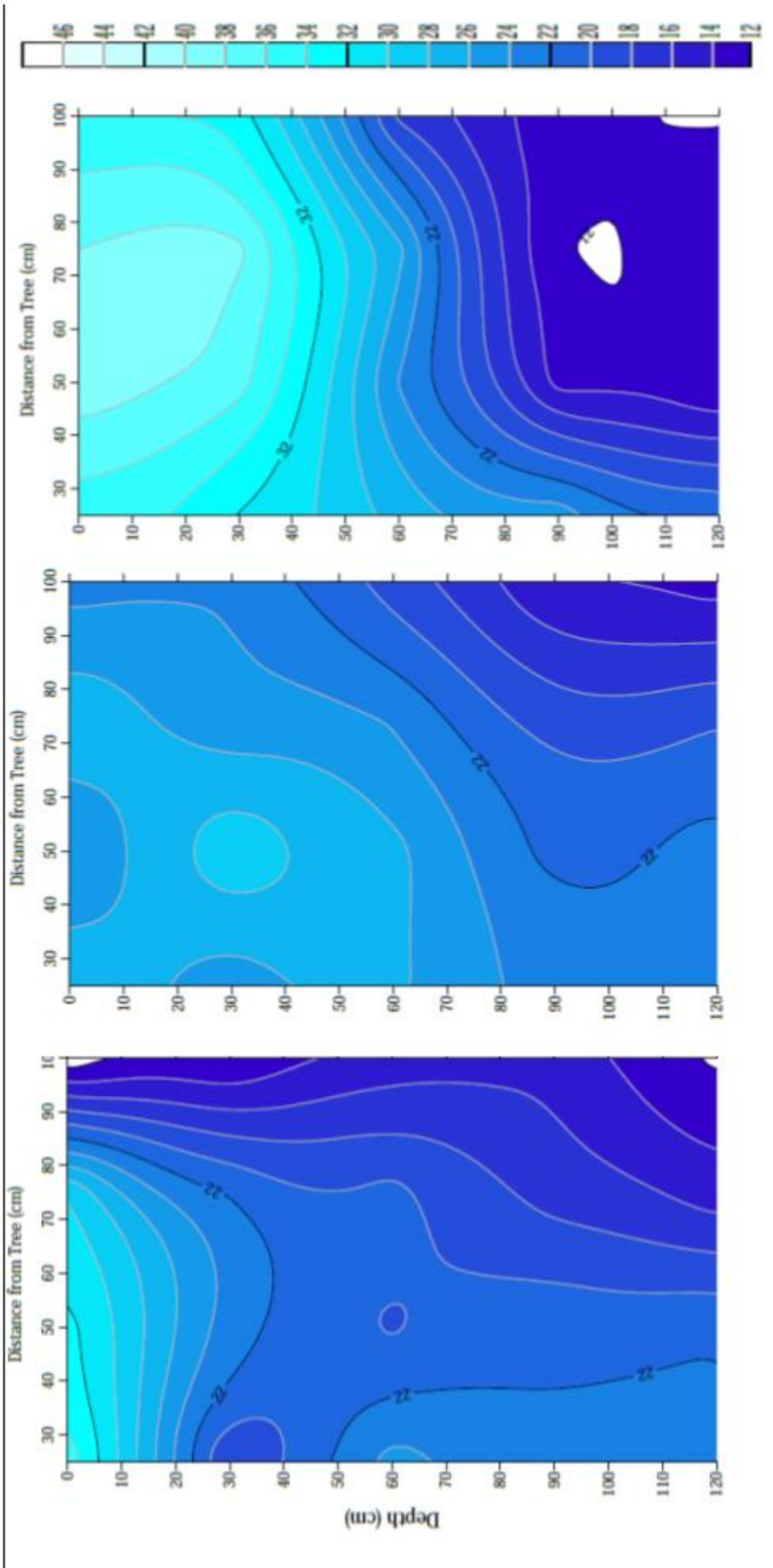
Date	Teniques		
	Surface drip line (c)	Vertical drip line (V)	Inclinad drip line (I)
20 May, 2022			

Fig. (3): Soil water distribution under surface, vertical and inclined drip lines.



1 July, 2022

Fig. (3): Cont.



1 September, 2022

Fig. (3): Cont.

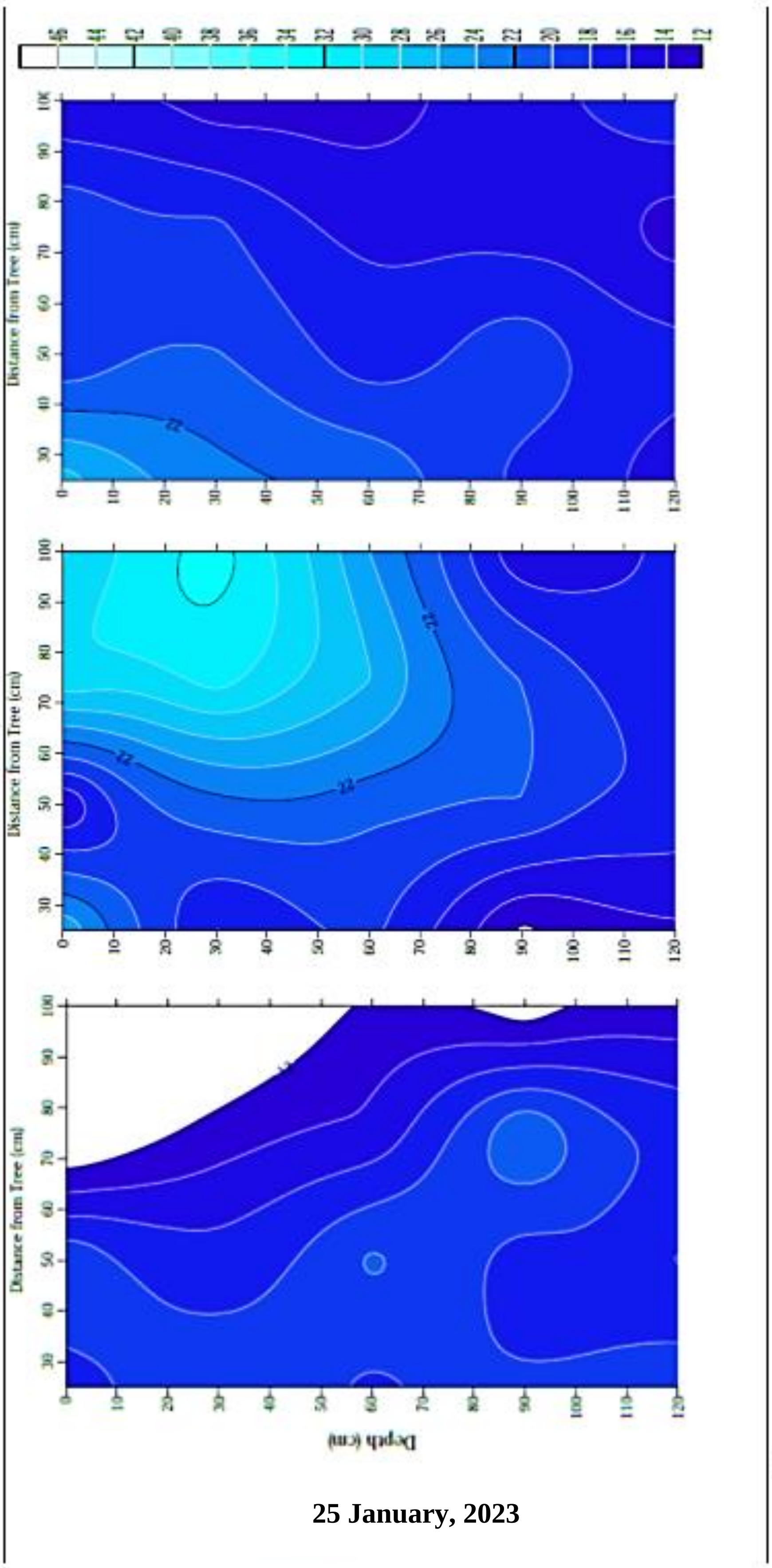

Distance from Tree (cm)
Distance from Tree (cm)
Distance from Tree (cm)
Depth (cm)
22
25 January, 2023

Fig. (3): Cont.

Crop Yield and water productivity (WP)

Crop yield data (ton/ha) were analyzed over two growing seasons (2022 and 2023) for three drip irrigation treatments: Drip, Vertical, and Inclined. The results, as depicted in the bar chart, demonstrate variation in production across years and irrigation treatments as shown in Figure 4.

For the Drip treatment, production in 2022 was significantly lower, averaging approximately 7.5 ton/ha, compared to 2023, where yield increased modestly to around 10.5 ton/ha. Similarly, the Vertical treatment yielded approximately 8.5 ton/ha in 2022, with a notable increase in 2023, reaching about 17.5 ton/ha. The Inclined drip system exhibited the highest yields, with production in 2022 at approximately 9 ton/ha and a substantial increase to 22 ton/ha in 2023.

Post-hoc pairwise comparisons using Tukey's Honest Significant Difference (HSD) test revealed significant differences in crop production between treatments. Specifically, the Inclined 2023 treatment exhibited the highest yield (21.9 ± 2.3 ton/ha), which was significantly higher than all other treatments. Inclined 2022 (17.9 ± 2.0 ton/ha) was also significantly higher than Drip 2022 (10.3 ± 2.1 ton/ha) and Vertical 2022 (11.5 ± 1.5 ton/ha). Additionally, Drip 2023 (12.1 ± 1.8 ton/ha) and Vertical 2023 (16.9 ± 2.4 ton/ha) yielded significantly higher production compared to their 2022 counterparts.

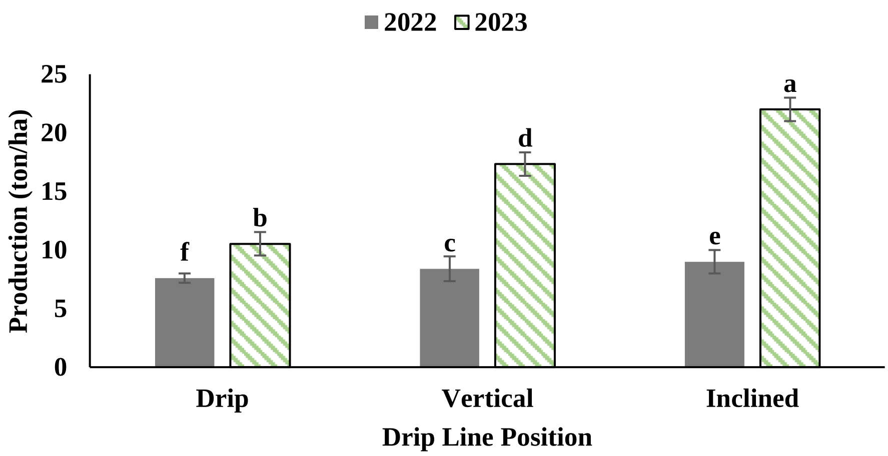


Fig. (4): Yield of three drip lines positions.

Water productivity (WP) was calculated for each treatment in both 2022 and 2023, with the results showing significant differences in water use efficiency across the drip line positions. All three irrigation treatments demonstrated an increase in WP values from 2022 to 2023 as shown in Figure 5.

For the Drip treatment, WP increased from 1.1 ± 0.2 kg/m³ in 2022 to 1.6 ± 0.2 kg/m³ in 2023. Similarly, Vertical irrigation showed an increase in WP, from 1.4 ± 0.3 kg/m³ in 2022 to 2.0 ± 0.3 kg/m³ in 2023. The Inclined system exhibited the greatest increase in WP, rising from 2.0 ± 0.3 kg/m³ in 2022 to 2.8 ± 0.4 kg/m³ in 2023.

The highest WP value was recorded for Inclined 2023, with a mean of 2.8 ± 0.4 kg/m³, significantly higher than all other treatments. Tukey’s HSD test identified Inclined 2023 as the highest-performing group (a), followed by Inclined 2022 (d), which was significantly greater than Drip 2022 (f) and Vertical 2022 (c). Additionally, Drip 2023 (b) and Vertical 2023 (e) showed significant differences in WP, further indicating the enhanced efficiency of subsurface irrigation methods.

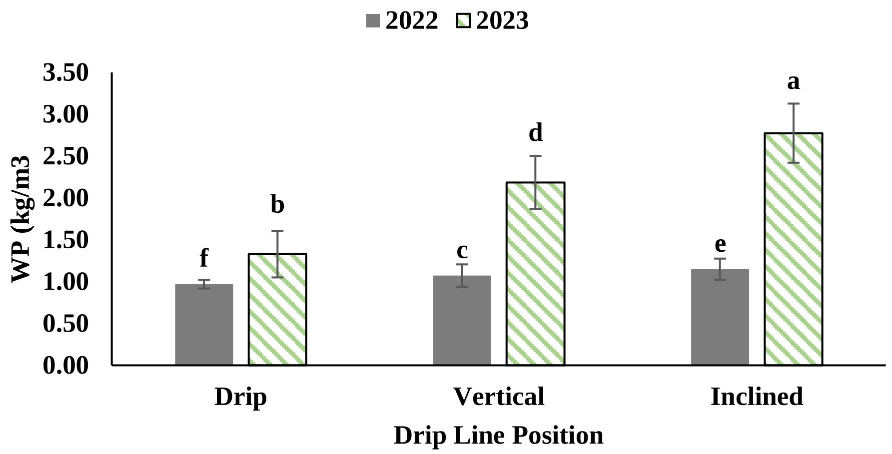


Fig. (5): Water productivity of three drip lines possessions.

Fruit Quality

The analysis of single fruit weight (g) across three drip line positions (Drip, Vertical, and Inclined) for the years 2022 and 2023 revealed significant differences between both drip line positions and years as shown in Figure 6.

In the Drip treatment, single fruit weight increased from 5.4 ± 2.6 g in 2022 to 7.4 ± 0.3 g in 2023. The Vertical treatment showed nearly stable fruit weight, with 7.5 ± 0.7 g in 2022 and 7.3 ± 0.7 g in 2023. The Inclined treatment demonstrated the highest fruit weights, increasing from 8.3 ± 0.6 g in 2022 to 8.8 ± 0.6 g in 2023.

Post-hoc pairwise comparisons using Tukey's Honest Significant Difference (HSD) test revealed significant differences among the treatment groups. Specifically, Inclined 2023 (a) had the highest single fruit weight, followed by Inclined 2022 (c), Vertical 2023 (b), and Vertical 2022 (d). Drip 2022 (f) had the lowest fruit weight, with significant differences from all other treatments.

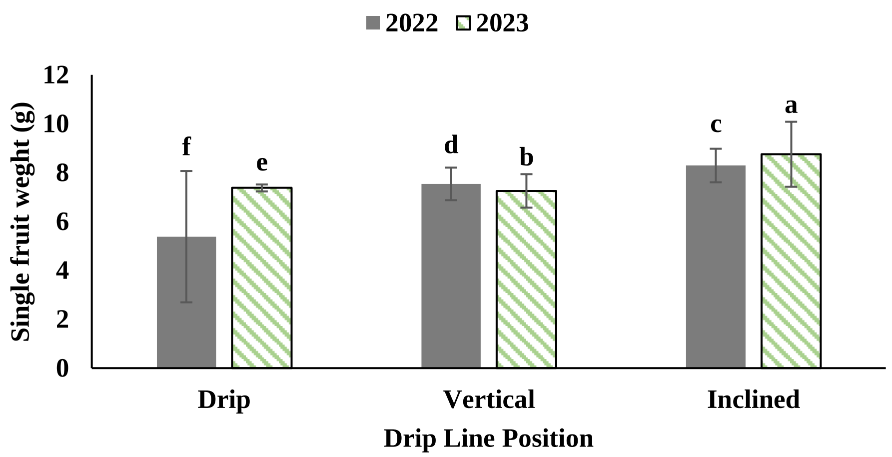


Fig. (6): fruit quality of three drip irrigation lines.

The analysis of pulp weight (g) across the three drip line positions for the years 2022 and 2023 also revealed significant differences. In the Drip position, pulp weight increased from 4.2 ± 0.5 g in 2022 to 5.3 ± 0.6 g in 2023. The Vertical position showed a similar increase, from 5.5 ± 0.6 g in 2022 to 6.5 ± 0.7 g in 2023. The Inclined treatment demonstrated the highest pulp weight, with Inclined 2022 producing 6.2 ± 0.5 g, and a significant increase to 7.8 ± 0.6 g in 2023 as shown in Figure 7.

Post-hoc Tukey's HSD test identified Inclined 2023 (a) as the treatment with the highest pulp weight, followed by Inclined 2022 (d), Vertical 2023 (b), and Vertical 2022 (e). Drip 2022 (f) had the lowest pulp weight, significantly differing from all other treatments.

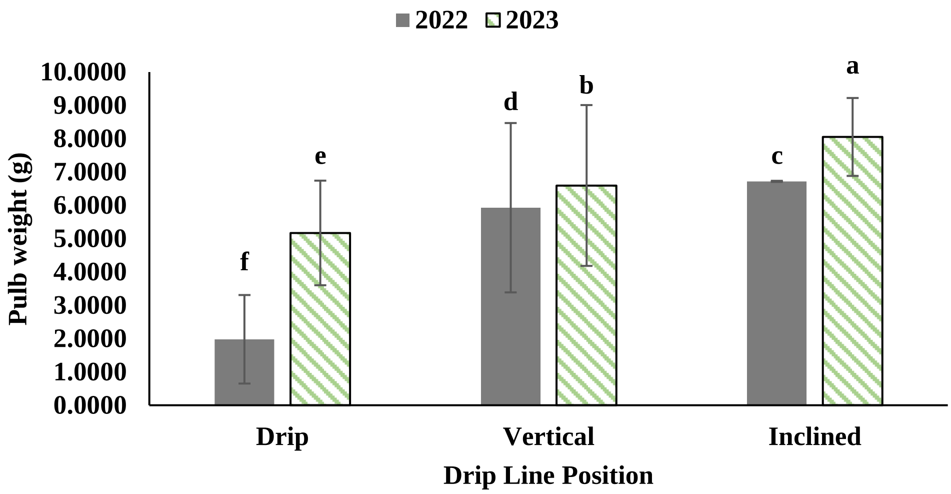


Fig. (7): pulp weight under three drip lines position.

Finally, the analysis of seed weight (g) across the three drip line positions for the years 2022 and 2023 revealed significant differences. In the Drip position, seed weight was 1.3 ± 0.1 g in 2022, with a slight increase to 1.4 ± 0.1 g in 2023. The Vertical position showed less variation, with 1.1 ± 0.1 g in 2022 and 1.2 ± 0.1 g in 2023. The Inclined treatment exhibited a more consistent seed weight, with 1.0 ± 0.1 g in 2022 and 1.1 ± 0.1 g in 2023 as shown in Figure 8.

Post-hoc Tukey's HSD test revealed that Drip 2023 (a) had the highest seed weight, followed by Vertical 2023 (b), Inclined 2023 (c), and Vertical 2022 (e). Inclined 2022 (f) showed the lowest seed weight, significantly differing from the other treatments.

DISCUSSION

The results of this study provide valuable insights into the impact of drip irrigation system design on soil water distribution, water use efficiency, fruit yield, and quality in olive orchards under arid conditions.

Soil Water Distribution and Irrigation Efficiency

Subsurface drip irrigation systems (V and I) demonstrated superior soil water distribution compared to the surface system (C). The Inclined system (I) achieved the most uniform horizontal and vertical water spread, followed by the Vertical system (V). In contrast, the Surface drip system (C) exhibited limited lateral spread and higher evaporative losses due to exposed wetted areas, leading to lower water use efficiency.

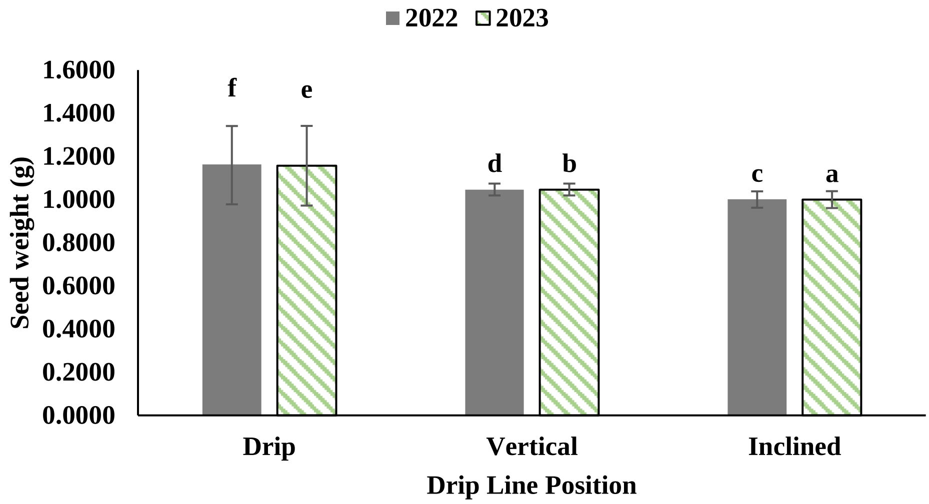


Fig. (8): seed weight under three different drip line positions.

The observed irrigation water savings under subsurface systems were substantial. Both the Vertical (V) and Inclined (I) systems reduced evaporation losses and enhanced water use efficiency. On average, subsurface systems saved approximately 10% of irrigation water compared to the surface method, while still replenishing full crop evapotranspiration (ETc). This improved performance can be attributed to more targeted water application directly within the root zone, thereby reducing surface evaporation. These findings are consistent with previous studies (Martínez-Gimeno et al. 2018), which emphasized the importance of minimizing exposed wet soil surfaces to improve water use efficiency in semi-arid environments. Subsurface drip irrigation systems significantly enhance water application efficiency compared to traditional surface methods by delivering water directly to the plant root zone, minimizing losses to evaporation and deep percolation (Wu et al. 2021).

Despite all systems applying the same irrigation volume (100% ETc), the Vertical subsurface system (V) exhibited superior water productivity. This result corroborates the findings of (Maisiri et al. 2005; Martínez-Gimeno et al. 2018) which highlight the enhanced water use efficiency achieved by subsurface drip irrigation compared to surface irrigation methods.

The Inclined system (I), while slightly less effective than the vertical configuration, facilitated enhanced horizontal spread, which is beneficial in soils with high infiltration rates this results in more uniform moisture distribution across the root zone.

Yield and Water Productivity

This section critically examines the agricultural output achieved in terms of crop yield and the efficiency of water utilization across various cultivation practices.

Both year and drip line position significantly influenced crop yield (ton/ha). The effect of year was particularly pronounced, as 2023 showed higher yields across all treatments. This was likely due to more favorable climatic conditions, including optimal rainfall and temperature, which are known to influence plant growth and crop productivity(Amare 2020). The drip line position further refined these outcomes, with specific placements potentially optimizing water delivery and nutrient uptake, thereby contributing to the observed yield variations (Mansour et al. 2019).

Specifically, Inclined 2023 produced the highest yield (21.9 ± 2.3 ton/ha), reflecting a significant increase in production compared to 2022.

The increase in fruit yield observed under the subsurface irrigation systems can be attributed to better soil moisture conditions around the active root zone, which facilitated improved water uptake and sustained physiological activity during periods of high atmospheric demand. These results support the work of (Wu et al. 2021)who found that subsurface drip irrigation can increase application efficiency by strategically delivering water directly to the root zone, thereby reducing deep percolation and evaporation losses.

The Vertical system (V) demonstrated an 18.42% increase in yield compared to the surface drip system (C), highlighting the limitations of conventional surface systems, particularly in sandy soils where water drains quickly below the root zone without adequate emitter placement. These findings are consistent with previous research on citrus and olive crops, where subsurface or increased emitter density resulted in higher yields and reduced unproductive water loss (Mohammed et al. 2020; Monteiro et al. 2014). Specifically, subsurface drip irrigation has been shown to significantly enhance date palm yield, concurrently minimizing water consumption and improving water use efficiency when contrasted with surface drip irrigation methods.

The Inclined system (I) consistently outperformed the other two configurations. The yield for Inclined 2022 (17.9 ± 2.0 ton/ha) was the highest for that year, and this trend continued in 2023, where the yield increased from 17.9 to 21.9 ton/ha. This suggests that the Inclined drip line configuration offers superior water distribution and is better adapted to the environmental conditions of 2023.

Fruit Quality and Marketability

Fruit size is a key determinant of market value in table olive production. The significant increase in the weight of 100 fruits under subsurface treatments indicates that improved water availability during critical fruit development stages positively influenced fruit caliber. These results are consistent with previous research highlighting that optimized irrigation, particularly subsurface drip systems, enhances fruit development and yield by ensuring consistent water availability directly at the root zone while minimizing surface evaporation (Martínez-Gimeno et al. 2018; Mohammed et al. 2020).

The Vertical subsurface system (V), which maintained a more uniform and deeper wetting pattern, likely provided more stable moisture availability, supporting consistent cell expansion during fruit growth. This is particularly crucial in sandy soils, where maintaining uniform moisture can be challenging with surface irrigation systems.

The Inclined system (I) consistently produced the largest fruit, with a marked increase in fruit size in 2023. This is likely due to the more efficient water distribution and better root zone hydration offered by the Inclined configuration, which supports improved nutrient uptake and fruit development. The Vertical system (V) showed moderate improvements, though it still produced smaller fruit compared to the Inclined system. The Drip system (C) consistently produced the smallest fruit, which suggests that it may not provide adequate water distribution for optimal fruit growth.

Seed and Pulp Quality

Both seed and pulp weights were significantly influenced by both the year and drip line position. The Inclined system (I) consistently produced the heaviest pulp and seed weights, likely due to more efficient water distribution, which enhanced nutrient uptake and supported optimal fruit growth. In contrast, the Drip system (C), despite showing improvements from 2022 to 2023, consistently produced the lowest pulp and seed weights, suggesting that this system does not provide the optimal moisture conditions for seed and pulp development.

The Vertical system (V) showed moderate improvements in pulp weight, though it still lagged behind the Inclined system (I) in terms of both pulp and seed weight. These findings are in line with previous studies, which suggest that efficient water distribution, particularly in subsurface systems, plays a crucial role in improving fruit quality metrics such as pulp and seed weight.

CONCLUSION

This study evaluated three drip irrigation systems; Inclined subsurface (I), Vertical subsurface (V), and Surface drip (C) in olive orchards under semi-arid conditions, focusing on soil water distribution, yield, fruit quality, and water productivity. The findings demonstrate that both irrigation design and environmental conditions strongly influence performance.

The Inclined system proved most effective, ensuring both deep and lateral soil wetting, which enhanced root zone hydration. As a result, it consistently achieved the highest yields, heaviest fruit and pulp, and superior water productivity, particularly in 2023. These outcomes highlight its potential as a highly efficient irrigation strategy for olives in water-limited environments.

The Vertical system provided moderate effectiveness, with better water distribution and yield than the Surface system, though its performance remained below that of the Inclined system. It offers a practical option where Inclined installation is less feasible. By contrast, the Surface drip system concentrated water near the soil surface, limiting deep penetration and reducing root access. Consequently, it produced the lowest yields, smallest fruit, and lowest water productivity, although seed weight was greatest under this system, while the Inclined system produced the lightest seeds.

Overall, the Inclined subsurface irrigation system emerged as the most efficient and balanced option, combining effective soil water distribution with improved yield and fruit quality. Future studies should examine long-term impacts across soil types and varieties, while also addressing economic feasibility and sustainability. Such research will support adoption of efficient irrigation strategies to enhance productivity under semi-arid conditions.

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تكوينات مبتكرة للري بالتنقيط تحت السطحي تعزز كفاءة استخدام المياه وإنتاجية الزيتون في الأراضي الرملية

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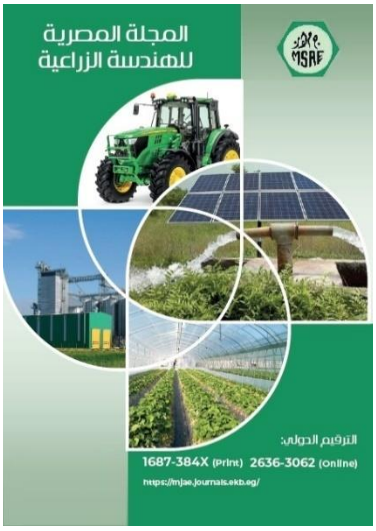
الملخص العربي

تعدّ الإدارة الفعّالة للري أمرًا أساسيًا لإنتاج الزيتون بشكل مستدام في المناطق شبه الجافة ذات التربة الرملية. وقد قيّمت هذه الدراسة ثلاثَ طرق ري: التنقيط السطحي التقليدي، والتنقيط تحت السطحي العمودي، والتنقيط تحت السطحي المائل، من حيث توزيع رطوبة التربة، وإنتاجية المحصول، وإنتاجية المياه (WP)، وجودة الثمار خلال موسمي ٢٠٢٢–٢٠٢٣ في مصر. أظهرت مراقبة رطوبة التربة أن نظام التنقيط تحت السطحي المائل قدّم أفضل توزيع للرطوبة، محققًا نفاذية أعمق (حتى ١٢٠ سم) وانتشارًا أفقيًا أوسع مقارنة بالنظامين العمودي والسطحي. وأظهرت تحليلات الإنتاجية تحسنًا ملحوظًا مع أنظمة الري تحت السطحي، حيث سجّل النظام المائل أعلى إنتاجية (١٧,٩ و٢١,٩ طن/هكتار في عامي ٢٠٢٢ و٢٠٢٣ على التوالي)، متفوقًا بشكل كبير على المعاملات السطحية والعمودية. وسارت إنتاجية المياه على نفس المنوال، إذ ارتفعت من ٢,٠ إلى ٢,٨ كجم/م³ مع نظام التنقيط المائل، مقارنةً بـ١,١–١,٦ كجم/م³ للتنقيط السطحي. كما تحسنت بشكل ملحوظ صفات جودة الثمار، بما في ذلك وزن الثمرة واللب والبذرة، في أنظمة الري تحت السطحي، حيث حقق النظام المائل باستمرار أكبر الثمار وأثقل اللب. وتؤكد هذه النتائج تفوّق الري بالتنقيط تحت السطحي المائل في تحسين ديناميكية رطوبة التربة، وزيادة كفاءة استخدام المياه، وتعزيز الإنتاجية وجودة الثمار، مما يجعله استراتيجية واعدة لإنتاج الزيتون المستدام في البيئات الجافة وشبه الجافة.



الكلمات المفتاحية:
جودة الثمار؛ انتاجية الزيتون؛ الأراضي الرملية؛ الري بالتنقيط تحت السطحي؛ إنتاجية المياه