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Effect Of Smart Agriculture Practices On Yield And Crop Water Productivity Of Sweet Pepper

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Abstract
This study was conducted to evaluate the performance of sweet pepper (*Capsicum annuum L.*) under different irrigation levels and systems, with the aim of optimizing water use efficiency and improving crop productivity under field conditions in central Iraq. The field experiment was carried out in Al-Yusufiyah, Baghdad Governorate, using a randomized complete block design (RCBD) with a factorial arrangement of three irrigation levels (I1: 100%, I2: 75%, and I3: 50% of crop water requirement) and two irrigation systems (furrow and surface drip irrigation). The experimental plot covered an area of approximately 2000 m², and Modesto sweet pepper seedlings were transplanted and monitored over a 173-day growing season. Results showed that surface drip irrigation significantly reduced seasonal water consumption compared to furrow irrigation, with a 21% decrease at the same irrigation level. The highest water consumption was recorded under furrow irrigation (622 mm at I2), whereas the lowest was under drip irrigation (350 mm at I3). Surface drip irrigation improved plant height, stem thickness, and total yield, particularly under moderate water stress (I2). Plant height reached 110 cm under I1 and 103 cm under I2 in the drip system, with no significant differences between the two. Total yield peaked at 80 $t{\cdot}ha^{-1}$ under I1 in the drip system, which was not statistically different from I2 (76 $t{\cdot}ha^{-1}$), despite a substantial reduction in water input. Water use efficiency (WUE) was also significantly higher under drip irrigation, with values of 12.6, 15.4, and 13.7 $kg{\cdot}m^{-3}$ for I1, I2, and I3, respectively, compared to 9.4, 10.6, and 8.9 $kg{\cdot}m^{-3}$ under furrow irrigation. These improvements were attributed to better root zone moisture retention, enhanced nutrient availability, and reduced water losses through evaporation and deep percolation. The findings highlight the potential of surface drip irrigation, particularly at 75% irrigation level (I2), as a sustainable strategy for improving water productivity and maintaining high yields of sweet pepper under water-limited conditions. This is the first documented estimation of the seasonal water requirement of sweet pepper in central Iraq under open-field conditions.
Key word: Sweet pepper (*Capsicum annuum L.*); Surface drip irrigation; Furrow irrigation; Irrigation levels; Water use efficiency; Vegetative growth; Cumulative yield; Iraq; Sustainable water management

INTRODUCTION

The Food and Agriculture Organization (FAO) of the United Nations. It is a way of ecological friendly farming that will increase at the same time the productivity of the farm, increase the resilience of livelihoods and conserve the ecosystem within all agricultural outputs. Those sustainable practices toward zero net greenhouse gas emissions to food secure and the millennium development goals. An alternate definition to this is Ngara (2017) and Bouthalija (2020) which describes smart agriculture as Climate-Smart Agriculture (CSA) is the unified approach of horticulture as well as field crop production maximization alongside their sustenance for the conservation of natural resources for the sake of generations to attain food and economic security, respectively able to meet the country's long-term development needs also reclaimed National food and economic securities ensure economic development also horticultural and field crop production maximum under climatic variability guaranteeing food production through resource conservation. The application of smart agriculture technologies is a cost-effective method that enhances the efficiency of output. This becomes the most crucial measure in view of the trends in climate, increased pressure on available water, and non-expansion of arable land. The World Bank projects that the technologies will result in a 50% average crop productivity increase, mainly through efficient irrigation and soil fertility management, leading to environmentally sustainable and economically viable agricultural systems. The Climate-Resilient Agriculture CSA, as a sub-component of the latter, refers to the adjustment and mitigative measures in crop production as induced to suffer the adverse effects of changes in climatic conditions. It involves the management of strategic crops, livestock, and natural resource management to lower greenhouse gas emissions and sustain stable food production systems. In addition to sustainability goals, climate-sensible practices aim to make agriculture more climate-resilient against the background challenge of feeding the increasing world population (Bell et al., 2018; Sarker et al., 2019; Jabbar et al., 2020; Crawford et al., 2023; Al-Rawi and Bahia, 2024). Horticultural crops are greatly affected by the vagaries of climate, among them, sweet pepper (*Capsicum annuum* L.). Annual global production is estimated at 35.9 million metric tons with an average yield of 17.9 tons per hectare, and it ranks second after potatoes among the most widely grown vegetable crops. Sweet pepper is very sensitive to water stress at its different critical phenological stages, such as flowering and fruit set; at that time both water deficiency and water excess at this surface can drastically reduce the yield. Where surface irrigation is the prevailing method, it often wastes water and does not maximize the crop yield. The focus is now on deficit water applications, although information related to the effects of the water-stress related to the diverse water regimes on the yield and quality of sweet pepper is deficient. Therefore, timing of watering comes out as a central part in reaping good results by growing sweet pepper in a major way under water-deprived conditions. Bell pepper, a yearly veggie belonging to the Solanaceae clan, abounds in vital vitamins and comes in various shades of color such as green, red, yellow, and orange all possessing a taste profile that is sweet (non-hot).

Objectives of the Study

1. To estimate the seasonal water consumption of sweet pepper cultivated under different sustainable management systems, comparing the effects of surface drip irrigation and furrow irrigation at varying irrigation levels and planting methods.
2. To identify the optimal irrigation water requirements for maximizing plant growth, yield, and water use efficiency of sweet pepper, under varying irrigation strategies and cultivation methods, while adhering to sustainable agricultural management principles.

MATERIALS AND METHODS

Study Site and Soil Characteristics

The field experiment was conducted in the Al-Muhammadiyah District, within the Al-Yusufiyah Subdistrict of Baghdad Governorate, Iraq. The site is geographically located at 44°13′34.5″ E longitude and 33°02′19.8″ N latitude, at an elevation of 34.2 meters above sea level. The soil at the experimental location is classified as clay loam, with a field capacity (θfc) of 0.265 cm^3/cm^3 and a permanent wilting point (θwp) of 0.162 cm^3/cm^3. Additional soil properties include an electrical conductivity (EC) of 2.86 dS/m, pH of 7.21, organic matter content of 7.21 g/kg soil, and carbonate mineral content of 222 g/kg. These parameters were determined following the procedures outlined by Black et al. (1965).

Experimental Design and Treatments

The study was structured as a factorial experiment within a random complete block design (RCBD), incorporating two main factors:

1. **Irrigation System**
   a. Furrow irrigation with conventional planting methods
   b. Surface drip irrigation with double-line terrace planting
2. **Irrigation Levels**
   a. I1: Full irrigation when 35% of available soil water is depleted (considered the control treatment)
   b. I2: 75% of the control irrigation level
   c. I3: 50% of the control irrigation level

These factors were arranged such that irrigation levels were assigned to the main plots, and irrigation systems were nested within subplots, resulting in a total of 18 experimental units (3 irrigation levels × 2 systems × 3 replicates). Treatment means were compared using the Least Significant Difference (LSD) test at a 0.05 probability level, and T-tests were used to analyze the effect of planting method across all measured traits.

Field Implementation

The experiment was conducted on a plot measuring approximately 2000 m². Minimal soil disturbance was practiced in land preparation, using a rotary tillage machine (secondary tillage equipment of Turkish origin) to a depth of 0.20 m, in alignment with conservation tillage principles. Modesto sweet pepper seedlings were transplanted from the nursery on March 25, 2024, at the six-true-leaf stage, and harvesting was completed on September 15, 2024. Plant spacing was carefully implemented as follows:

1. Under the drip irrigation system: 0.40 m between rows and 0.40 m between individual plants
2. Under the furrow irrigation system: 0.70 m spacing between lines

Figure 1 includes photographic documentation of the field implementation.

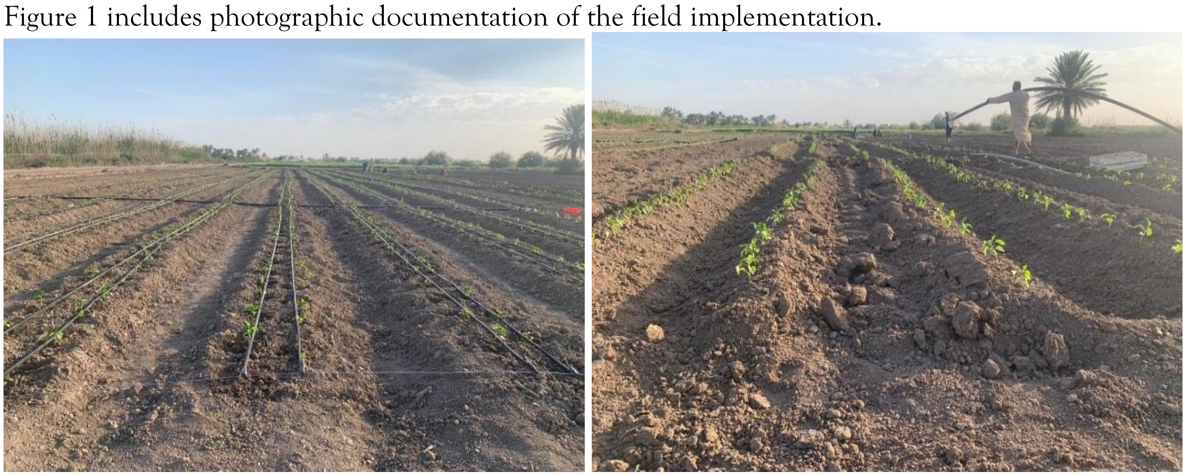

Figure 1. Selected Field Application Images.

The irrigation pipelines, which transport water from the storage tank to the different experimental treatments, were evaluated for hydraulic performance. Discharge rates under varying operating pressures were measured and analyzed according to the standards set by the United States Department of Agriculture (USDA), which are commonly used to calculate the hydraulic energy of water movement through pipes and to estimate pressure losses across the system. To assess the uniformity and distribution consistency of water application within the field plots, the Christiansen Uniformity Coefficient (CU) was applied, as described by Christiansen (1942). This coefficient remains one of the most widely used and reliable indicators for evaluating the performance of on-farm irrigation distribution systems (Equation 1).

$$CU = \left(1 - \frac{\sum |X|}{D_{ac}\, n}\right) \times 100 \qquad (1)$$

Where:

CU = Christiansen Uniformity Coefficient (expressed as a percentage)

$\sum|D_x - D_{av}|$ = Sum of the absolute deviations of the individual water depths (D_x) at each measurement location from the average depth (D_{av}) across the irrigated area
n = Number of measurement points for water depth across the field surface
D_{av} = Average total depth of water applied over the field surface (mm)

Another key index used to assess the performance of drip systems is the Distribution Uniformity (DU) of the lowest quartile, which reflects deep percolation losses together with the economic efficiency of water. This index is most preferred in showing how well water is distributed within the irrigated zones, more so in surface drip irrigation. The DU coefficient concentrates on the lowest 25% of water depth applied that gives the dimension of the areas which receive the least amount of irrigation, and is given by the equation below according to Anderson et al. (1978):

$$DU\left(\frac{1}{4}\right) = \left(\frac{D_{iq}}{D_{ac}}\right) \times 100 \qquad (2)$$

Where:
$DU_{1/4}$ = Distribution Uniformity of the lowest quartile (expressed as a percentage)
D_{iq} = Average depth of water applied in the lowest one-quarter of the field (mm)
D_{av} = Average total depth of water applied to the entire area (mm)

This coefficient is mostly used to express the efficiency of water distribution in drip irrigation systems. It is more specifically used with respect to the objective of decreasing deep percolation loss and improving the economic water utilization efficiency. In addition to the above, the emitter flow variation coefficient is another parameter to show the hydraulic performance of lateral lines in a drip-irrigation system. This variation is calculated from the hydraulic characteristics of the system and is expressed by the following equation proposed by Wu and Gitlin (1974).

$$q_{Var} = \left(\frac{(q_{Max} - q_{Min})}{\bar{q}}\right) \qquad (3)$$

Where:
q_v = Emitter flow variation coefficient (dimensionless)
q_{max} = Maximum emitter discharge ($L \cdot h^{-1}$)
q_{min} = Minimum emitter discharge ($L \cdot h^{-1}$)
$\bar{q}$ = Average emitter discharge ($L \cdot h^{-1}$)

This coefficient (q_v) indicates the evenness of water distribution along the laterals in a drip system. A lower value of q_v shows better hydraulic performance and higher emitter discharge uniformity. The equation proposed by Wu and Gitlin (1974) is widely used for the design and assessment of systems in both laboratory and filed applications.Apart from the uniformity of distribution and variation in emitter discharge, there are several other parameters to assess the efficiency of an irrigation system, among which one very critical parameter is the Application Efficiency (AE) as described by Schneider et al (2000). It is the percentage of applied water that infiltrates below the effective root zone which the plant can uptake. In simple words, it is the relationship between the amount of water stored in the root zone and the total volume of water applied. Thus, AE for a drip irrigation system can be represented in the subsequent equation:

$$Ea = \frac{V(1 - D_d)}{3600 \times Q_t \times T_a} \qquad (4)$$

Where:
AE (Ea) = Application Efficiency (%)
V = Volume of irrigation water required to replenish the root zone (liters)
Dd = Theoretically allowable depletion of soil moisture (mm)
Qt = Discharge rate of the drip irrigation pipe ($L \cdot s^{-1}$)
Ta = Total irrigation time (hours)
This equation allows for the quantification of how effectively the irrigation water is utilized by the plant within the root zone. It serves as a key performance metric in evaluating the operational efficiency of surface drip irrigation systems. Based on the evaluation of the hydraulic performance parameters, the surface drip irrigation system was operated at a regulated pressure of 100 kPa, which remained stable throughout the experiment. For the furrow irrigation system, the uniformity assessment and water distribution were conducted under an operating pressure of 200 kPa, ensuring consistent conditions across comparative treatments. Soil moisture content was evaluated using GS3 sensors. After giving the five times irrigation when 35% of the available water depletion, we apply the irrigation treatment, the irrigation treatments were applied (the control treatment when 35% of the available water depletion) and the treatment of 75% and 50% of the control treatment. Irrigation was carried out by adding the depth of water needed to reach the moisture content at field capacity (Allen et al., 1998) (equation 5).

$$d = \left(\theta_{fc} - \theta_w\right) \times D \qquad (5)$$

Where:
d = Depth of added water (mm)
$\boldsymbol{\theta}_{fc}$ = Volumetric soil moisture at field capacity ($cm^3\ cm^{-3}$)
$\boldsymbol{\theta}_{w}$ = Volumetric soil moisture content before irrigation ($cm^3\ cm^{-3}$)
D = Soil depth equivalent to the effective rooting depth (mm)

To evaluate the hydraulic performance of the surface drip irrigation system, several tests were conducted to measure emitter discharge rates and distribution uniformity. Results indicated that an operating pressure of 50 kPa yielded the most favorable hydraulic characteristics for drip irrigation. In contrast, the furrow irrigation system demonstrated optimal performance when operated at a pressure of 200 kPa. In addition to hydraulic evaluations, key agronomic measurements were recorded throughout the growing season. These included:

1. Plant height (cm)
2. Stem diameter (mm)
3. Number of fruits per plant
4. Total yield ($ton \cdot ha^{-1}$)

Total yield was calculated by collecting the yield data from each experimental unit, determining the production per unit area, and subsequently converting the value to yield per hectare for standardized comparison.

$$Total\ Yield = \frac{hectare\ area \times experimental\ unit\ yield}{experimental\ unit\ area} \qquad (6)$$

Calculate water productivity according to Aleen et al., (1998) (equation 7).

$$WUE_c = \frac{Yield}{ETc} \qquad (7)$$

Where:
WUEc = Water productivity (kg m^{-3})
Yield = Total yield (kg ha^{-1})

RESULTS AND DISCUSSION

Table 1 presents the water balance components and seasonal water consumption values for sweet pepper cultivated under furrow and surface drip irrigation systems across three irrigation levels. The findings indicate that the highest seasonal water use (622 mm) occurred under the furrow irrigation system during a 173-day growth period, while surface drip irrigation reduced total consumption to 493 mm, representing a 21% reduction. Under the furrow irrigation system commonly practiced by Iraqi farmers in open-field sweet pepper cultivation the water consumption across irrigation levels I1, I2, and I3 reached 808 mm, 622 mm, and 437 mm, respectively. In comparison, the surface drip irrigation system showed lower consumption at the same irrigation levels, with values of 635 mm, 493 mm, and 350 mm, respectively. Notably, this study represents the first quantitative estimation of sweet pepper water requirements under open-field conditions in central Iraq. The application of surface drip irrigation significantly contributed to reducing surface soil evaporation, leading to a more efficient use of applied water. By delivering water directly to a targeted soil zone beneath the emitters, this system enhanced root proliferation, improved water uptake efficiency, and maintained optimal soil moisture levels within the effective root zone. Furthermore, the localized wetting pattern reduced evaporative and deep percolation losses, thereby increasing soil water storage efficiency and overall water use efficiency (WUE). Despite requiring a higher number of irrigation events, the total volume of applied water was substantially lower under the drip system, affirming its potential for water conservation and improved crop performance in arid and semi-arid environments. Figure 2 presents the impact of different irrigation systems and levels on plant height of sweet pepper. The data reveal significant differences in plant height across irrigation levels within both furrow irrigation and surface drip irrigation systems. Under the furrow irrigation system, plant height decreased significantly from 109 cm (I1) to 102 cm (I2) and further to 80 cm (I3) as water stress increased and the applied irrigation depth declined. A similar trend was observed under the drip irrigation system, where plant height declined from 110 cm (I1) to 103 cm (I2) and 85 cm (I3). However, the difference between I1 and I2 treatments was not statistically significant under either irrigation system. Figure 3 illustrates the effect of irrigation stress on stem diameter, which showed a notable reduction with decreased irrigation levels. Under furrow irrigation, stem thickness declined from 2.93 mm at I1 to 2.74 mm at I2 and 2.21 mm at I3. Similarly, under surface

Table 1: The seasonal consumption values of sweet pepper under furrow and surface drip irrigation systems

Irrigation Systems	Treatments	Growth days	Rainwater depth (mm)	Irrigation water depth (mm)	Water consumption ETa (mm)	Amount of water used (m^3/ha)
furrow irrigation	I1	173	65	743	808	8080
	I2	173	65	557	622	6220
	I3	173	65	372	437	4370
Mean		173	65	557	622	6220
surface drip irrigation	I1	173	65	570	635	6350
	I2	173	65	428	493	4930
	I3	173	65	285	350	3500

Mean	173	65	428	493	4930
			CV	0.17	

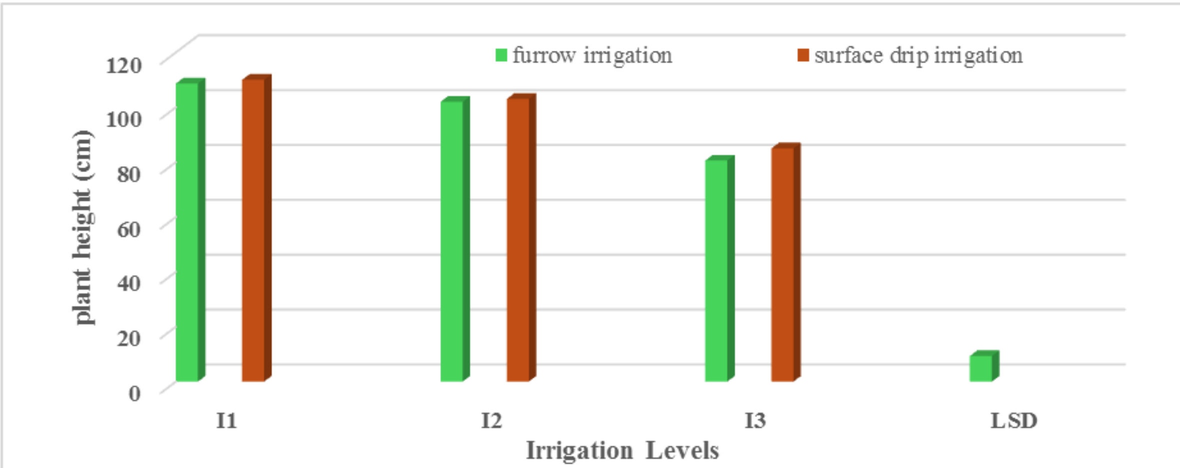

Figure 2. The plant height of sweet pepper under different irrigation levels and two irrigation systems (furrow and surface drip irrigation).

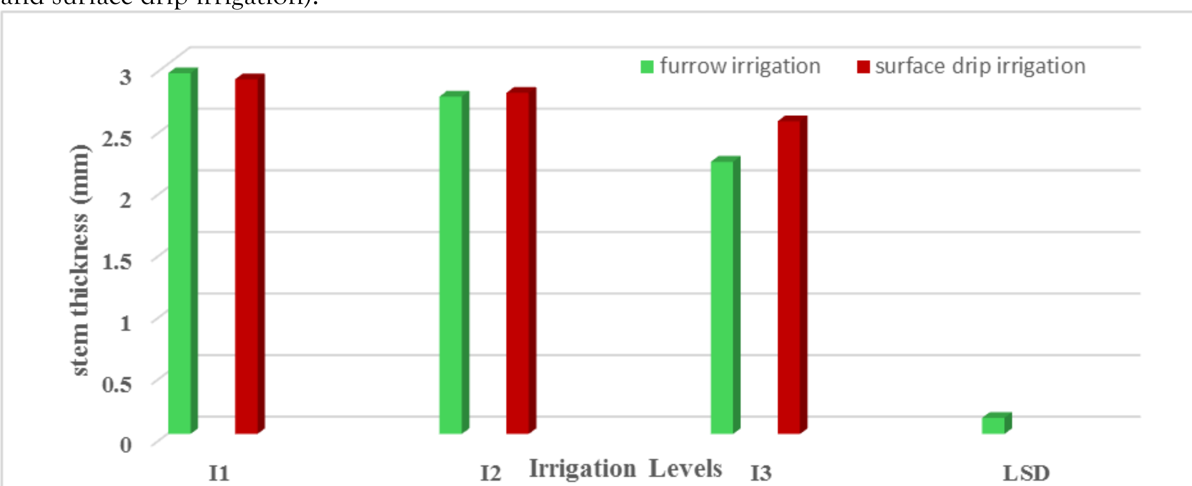

Figure 3. Stem thickness of sweet pepper plants under different irrigation levels and two irrigation systems (furrow and surface drip irrigation).

drip irrigation, values decreased from 2.90 mm to 2.77 mm and 2.54 mm for the same respective treatments. This reduction is likely due to changes in the soil–plant water balance, which negatively impacted nutrient uptake and translocation from leaves to stems, ultimately affecting overall plant growth and architecture. The observed improvement in vegetative growth parameters under surface drip irrigation can be attributed to more favorable moisture conditions in the root zone. This, combined with the efficient application of mineral fertilizers, enhanced nutrient availability and uptake. Furthermore, the precise and localized application of water near the emitter zone minimized losses through evaporation and deep percolation, thereby improving soil water retention and water use efficiency. Physiological processes in plants are highly sensitive to irrigation timing, placement, and management. Variations in these factors influence vegetative growth indicators, largely due to their role in amino acid synthesis, which is directly tied to protein formation. Consequently, plant protein content is closely linked to soil moisture availability. In addition, leaf development and expansion critical for photosynthesis are modulated by both growth hormones and nutrient uptake, particularly nitrogen and potassium. Thus, improved irrigation management not only enhances vegetative growth but also supports higher photosynthetic rates, resulting in increased assimilation production, dry matter accumulation, and ultimately, fruit development. As shown in Figure 4, the highest cumulative yield of sweet pepper was recorded under the I1 treatment (control), reaching 80 Ton ha^{-1} and 76 Ton ha^{-1} under drip irrigation and furrow irrigation, respectively. These two values were not significantly different from each other. Yield declined considerably under water stress conditions. Under furrow irrigation, cumulative yield dropped to 66 Ton ha^{-1} (I2) and 39 Ton ha^{-1} (I3), while under drip irrigation it decreased to 76 Ton ha^{-1} (I2) and 48 Ton ha^{-1} (I3). Interestingly, there was no significant difference between I1 and I2 treatments in total yield under the drip system, despite the lower seasonal water consumption in I2 (493 mm) compared to I1 (635 mm). This suggests that I2 may represent a more water-efficient strategy, maintaining high productivity with reduced water input. The positive response of cumulative yield to better moisture availability may be attributed to multiple factors, including enhanced protein synthesis, protoplasmic activity, and cell division and expansion. Adequate soil moisture promotes the growth of vegetative organs, increases leaf area index, and stimulates the accumulation of dry biomass. Morphological improvements under optimal water management are closely associated with enhanced photosynthetic activity and efficient nutrient use, leading to higher total assimilate production, improved fruit filling, and consequently, increased marketable yield (Al-Lami et al., 2023; Shahadha and Wendroth, 2025).

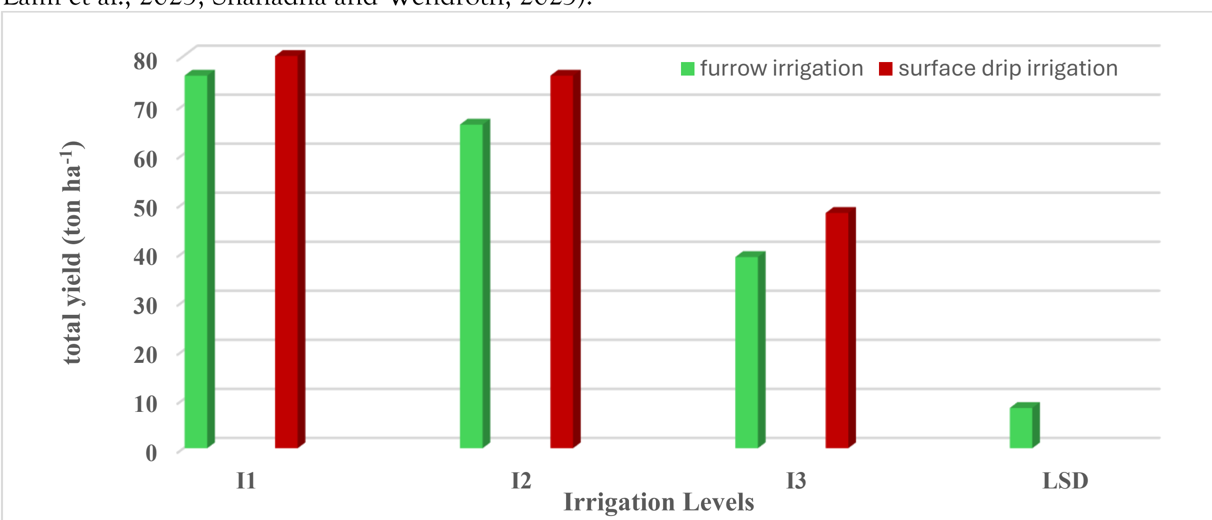

Figure 4. Cumulative yield of sweet pepper under different irrigation levels and two irrigation systems (furrow and surface drip irrigation).

Figure 5 shows the crop water use efficiency (CWUE) of sweet pepper in kilograms per cubic meter of irrigation water (kg m^{-3}) under both furrow and surface drip irrigation systems at three irrigation levels. The treatments differed highly significantly ($P < 0.01$) in all aspects. The surface drip system used water more productively than the furrow method in all aspects. The CWUE values for drip irrigation were 12.6, 15.4, and 13.7 kg m^{-3} for levels I1, I2, and I3, respectively, and 9.4, 10.6, and 8.9 kg m^{-3} for the same levels under furrow irrigation. In this study, results are providing evidence in support of the statement that drip irrigation multiplies water use efficiency, especially under the condition of moderate water stress (I2). The drip-treated plots gave higher productions with a lower net total water application and with lowered frequency of irrigation, indicating better biomass water conversion. The improvements in CWUE noted could be because of accurate water application, minimal loss through evaporation and deep percolation, and improved moisture availability around the root zone of the crop, which collectively led to increased yield without a corresponding increase in water use. This, therefore, indicates the role of scheduling of irrigation and application efficiency in working towards the achievability of sustainable production under the constraints of available water resources (Khrbeet et al., 2019; Dawod et al., 2024; Jabbar and Ati, 2025; Ati et al., 2025a,b).

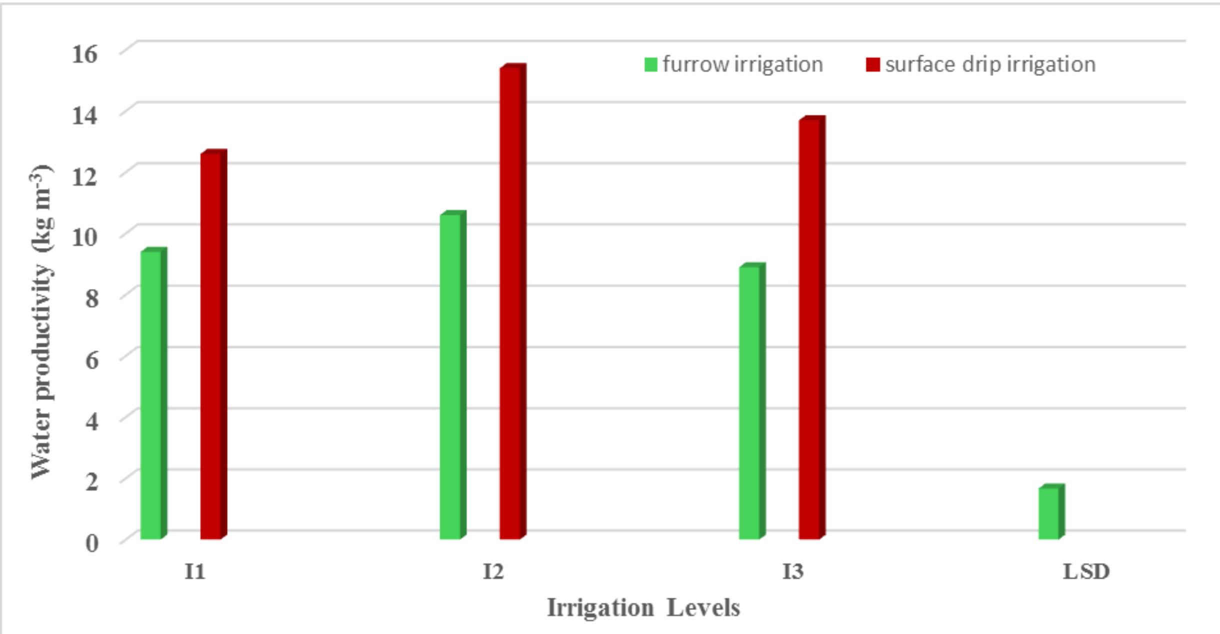

Figure 5. Water use efficiency of sweet pepper under different irrigation levels and two irrigation systems (furrow and surface drip irrigation).

CONCLUSION

Results obtained from this experiment proved that both the irrigation system and water application levels significantly influenced the growth, yield, and water use efficiency of sweet pepper under open field. Surface drip irrigation was superior to furrow irrigation in optimizing water use, reducing losses, and improving vegetative and yield performance. The irrigation level of I2 gave the most efficient strategy in the reduction of water consumed for significantly maintaining high levels of yield. Results also show that the increases in plant height, stem diameter, and cumulative yield obtained under drip irrigation reflect the efficiency of this system in providing more uniform and targeted water distribution as well as in enhancing soil moisture retention and nutrient availability in the root zone. It is a system as low in performance as the furrow irrigation system which is known and has been used by the farmer for a long time in the locality. The study also proved that the practice of deficit irrigation could be an alternative in managing the irrigation schedule to improve water use efficiency without loss in yield water use efficiency without loss in yield. These findings have paramount importance in the specific conditions of arid and semi-arid climates of central Iraq when water scarcity is a major constraint, coupled with the importance of making farming systems more water use efficiency. Therefore, the use of the surface drip irrigation system is recommended to adopt 75% as a sustainable approach towards water saving, improvement in soil-plant relationship and productivity of sweet pepper under field conditions.

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