Enhancing Water Productivity in Pepper Cultivation under Drip and Sprinkler Irrigation Scheduling using Sustainable Farming Practices

Alaa S. Ati, Hadeel A. Wahaib and Kusay A. Wheib

Abstract: *This research aimed at assessing how different irrigation methods and types of tillage influenced hot pepper (Capsicum frutescens L.) water productivity, growth characteristics and yields grown under sustainable agricultural management in Bagdad's Al Yousifiya region. The research project was undertaken as a field experiment throughout the 2025 growing season with a split-plot arrangement in randomized complete block design (RCBD) with three replications. The irrigation methods studied were two surface drip irrigation methods along with sprinkler irrigation, and the tillage types studied were cold or conventional tillage and warmer or reduced tillage. All irrigation scheduling was based upon 35% depletion of available moisture.*

According to the results there were significant differences found in plant growth, total yield and water productivity between each treatment. The best results were found to be from the combination of reduced tillage together with drip irrigation, where plant height was 86 cm, number of branches was 8 branches plant^{-1} and the total yield was 4165 Mg ha^{-1}, whereas the opposite was true for the conventional tillage with sprinkler irrigation yielding the least. The efficiency of water used for drip irrigation in conjunction with reduced tillage reached 5.21 kg m^{-3} and sprinkler irrigation in conjunction with conventional tillage producing 2.50 kg m^{-3}. In addition, less irrigation water has been applied to the drip irrigation method when compared to the sprinkler irrigation method thus indicating the drip

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irrigation method uses water more efficiently in situations where there is a limited water supply compared to the sprinkler irrigation method.
According to the results of the study, incorporating drip irrigation along with reduced tillage will lead to greater water productivity as well as increased pepper yield in dry and semi-dry climates. Hence, it is recommended that sustainable irrigation scheduling and conservation tillage be implemented to optimize water management in agriculture and improve the productivity of crops.

Keywords: Drip irrigation; sprinkler irrigation; water productivity; sustainable agriculture; reduced tillage; conventional tillage; Capsicum frutescens L. (pepper); irrigation scheduling; water use efficiency

Introduction

Water scarcity is one of the top challenges facing global agricultural sustainability, especially arid and semi-arid regions of land where agriculture relies heavily upon efficient irrigation management practices. The increased competition among all users of scarce fresh water supplies, when combined with the effects of climate change and the growth in global population, has created a heightened urgency for developing irrigation systems that provide higher yields of production while conserving our precious fresh water supplies (Ayada *et al,* 2024; Franco-Navarro *et al.,* 2025; Chen *et al.,* 2025). Iraq is one of the countries that is experiencing decreased water availability because of reduced flow into its rivers, rising air temperatures and continued use of inefficient traditional methods of irrigation making it very important for Iraq to develop systems that utilize water conservation technology to sustain agricultural production.

Iraq's pepper (*Capsicum frutescens* L.) is widely regarded as an economically important vegetable crop grown in many parts of the world because of its high nutritional value, strong market demand and versatility for use in the food industry. However, adequate soil moisture throughout pepper's growing season is essential for maximum plant growth, fruit production, and yield, therefore maintaining consistent water availability is critical to producing good yields of peppers. Improving efficiency and optimizing the amount of water used for irrigation are key factors to consider when growing peppers under limited water conditions.

Drip irrigation and sprinkler irrigation are modern irrigation systems that greatly improve both water application efficiency and decrease the amount of water lost compared to the traditional surface irrigation systems. Drip irrigation is generally known for being able to supply water directly to the root zone with very little evaporation and deep percolation; therefore, it has greater water productivity and improved crop performance, as shown by (Schneider *et al.,* 2020; Colak *et al.,* 2021). On the other hand, sprinkler irrigation provides an evenly distributed amount of water over the soil surface, however, it may have higher evaporation losses than drip irrigation in hot climates.

Soil physical characteristics, including its ability to retain and drain water and create roots, are strongly influenced by how we cultivate land. Conventional tillage can temporarily enhance soil loose particles creation; however, conventional tillage can than lead to faster loss of soil moisture, and to a continuing deterioration of the structure of the soil over time. Reduced form of tillage can therefore increase the soil's ability to produce clumps; that in turn can reduce evaporation of water from the soil surface and increase the ability of the soil to maintain moisture within the root zone, therefore, increasing crop productivity with little or no irrigation support (Dawod *et al.,* 2024; Shahadha and Wendroth, 2025).

Water productivity is one of the most widely used indicators for evaluating water use efficiency in agriculture because it represents a relationship between the crop yield and the water used for irrigation. Increasing water productivity is a key agro-strategic goal within sustainable agriculture, especially in areas experiencing continuous water shortages (Ati *et al.,* 2017; Michelon *et al.,* 2020; Absanto, 2025). There are many studies that demonstrate that implementing conservation tillage practices and using efficient irrigation systems can improve crop yields and water usage efficiencies, while also reducing total water needed for irrigation.

The objective of this research is to investigate the influence of two different kinds of irrigation systems, drip and spray; two methods of tillage, conventional tillage and reduced tillage; and the various combinations of these two factors on the growth characteristics, yield, and water efficiency of pepper crops grown in Baghdad, Iraq. The aim of the research is to ascertain the optimum agronomic practices that will enhance the efficiency of using water in agriculture and contribute to sustainable crop production in areas with limited water availability.

Materials and Methods

Experimental Site

The experiment was carried out on a field owned by a farmer in the Al-Bu Amer area of the Al-Yousifiya district, south Baghdad, Iraq, in 2025. This area has a semi-arid to arid climate with high summer temperatures and low annual rainfall amounts. The farm was previously studied to establish the composition and character of the soil using regular laboratory tests according to Black *et al*. (1965a, b). The soil type was classified as clay-loam (CL) with measurements of 250 g kg^{-1} sand, 400 g kg^{-1} silt, 350 g kg^{-1} clay. The pH of the soil was found to be at an average of 7.65. Also, the soil had a level of organic matter content equal to 11.92 grams per kg of soil. The amount of calcium carbonate in the soil was 285 grams per kg. The amount of soil nutrients found were as follows: available nitrogen-46 ppm; phosphorus-32 ppm; and potassium-266 ppm. Finally, the percentage of stable aggregates present in the soil was determined to be 37.82% - as shown in Table 1.

Table (1): Physical and chemical properties of the experimental soil before planting

Sand	Silt	Clay	Texture class	EC dS m^{-1}	pH	OM	$CaCO_3$	N	P	K	θFC	θWP	Stable Aggregate %
g kg^{-1} soil						g kg^{-1} soil		Available (ppm)			cm^3 cm^{-3}		
250	400	350	CL	2.13	7.65	11.92	285	46	32	266	0.336	0.190	37.82

Experimental Design and Field Management

This field experiment utilized a Randomized Complete Block Design (RCBD) and was analyzed using a Split-Plot Design approach, to provide for two experimental factors of comparison. The main plot experimental factor was comprised of the different irrigation systems used, which were surface drip type versus fixed sprinkler type irrigation. Irrigation scheduling took place on each irrigation system when there was a depletion of 35% of the available moisture in the soil profile.

The modified plot system incorporated the tillage management systems into the study as a sub-plot factor. The conventional tillage of 25 cm deep was accomplished with a disc plow followed using disc harrows for leveling the soil, and reduced till was completed with spring cultivators. Therefore, there were four possible treatment combinations with three replicates, which leads to 12 experimental units total (2 × 2 × 3). All experimental units were 100 m² (20 m × 5 m) and had seven rows of a mattress throughout the area of the unit. A buffer zone of 1.0 m was established between neighboring units to eliminate the possibility of treatment interference. Additionally, there was a longitudinal distance of 10 m at each end of the experimental unit to allow for stable machinery and operation at uniform speeds for all field practices. Analysis of variance was conducted using SAS statistical analysis program (SAS, 2018).

On 25 March 2025, seedlings of the hybrid hot pepper (*Capsicum frutescens* L.) type "Impala" produced by the French company Clause were transplanted into the field with a 0.4 m spacing between plants. Harvesting of the hot pepper slips commenced on 20 May and ended on 15 November 2025, having been in production for a total period of 236 days.

This research used two types of watering systems in a farm setting: surface drip and fixed sprinkler, both with oscillating sprayers that release 1000 liters of water per hour. Performance tests were performed for each of the irrigation systems to evaluate the output of both types as well as the consistency of water delivery across the field of both systems. Various water pressures between 50 and 150 kPa were evaluated for the surface drip system; the sprinkler systems were tested with pressures between 100 and 175 kPa. A mechanical pressure gauge with a range of 0 - 1000 kPa was used to determine water pressure throughout this study.

The surface drip irrigation method was tested with a working pressure of 50 kPa, while the sprinkler system tested with 175 kPa, resulting in the highest level of water distribution uniformity; therefore, both tests were performed by recording water pressure and evaluating the performance of the emitters and the sprinklers. Illustrations of various field application images associated with the experimental layout are exhibited in Figure 1.

Irrigation Scheduling and Water Consumption

Irrigation (Allen *et al.,* 1998) scheduling was determined according to the available water content (AW), which was calculated from the difference between the volumetric soil moisture content at 33 kPa water tension representing field capacity (θ_{fc}) and the volumetric soil moisture content at 1500 kPa water tension representing permanent wilting point (θ_{wp}), according to the following equation:

$$A_{W}= \theta_{fc} - \theta_{wp} \qquad (1)$$

Where:
AW = available water content in soil ($cm^3\ cm^{-3}$)
θ_{fc} = volumetric soil moisture content at field capacity ($cm^3\ cm^{-3}$)
θ_{wp} = volumetric soil moisture content at permanent wilting point ($cm^3\ cm^{-3}$)

Figure 1. Some field application images of the experimental setup and irrigation systems used during the field experiment.

Calculation of Applied Water Depth

The depth of applied irrigation water (Evett *et al.,* 2020) was calculated based on the difference between the volumetric soil moisture content at field capacity (θ_{fc}) and the volumetric soil moisture content before irrigation (θ_w), multiplied by the effective root zone depth (D), according to the following equation:

$$d = (\theta_{fc} - \theta_w) \times D \qquad (2)$$

Where:
d = depth of applied water (mm).
θ_{fc} = volumetric soil moisture content at field capacity ($cm^3\ cm^{-3}$).
θ_w = volumetric soil moisture content before irrigation ($cm^3\ cm^{-3}$).
D = soil depth, which represents the effective root zone depth (mm).

The depth of applied water was calculated when 35% of the available water was depleted, and irrigation was continued until the soil moisture content reached field capacity. Soil samples collected from the field were dried using a Kenwood Microwave Oven, model MW940, to determine the moisture content of soil samples.

Growth and Yield Parameters

Plant Height (cm)

Plant height was measured at the final maturity stage using a measuring tape. The measurement was taken from the soil surface at the stem base up to the highest point of the plant.

Number of Branches (branch plant^{-1})

The average number of branches per plant was calculated for randomly selected plants from each experimental unit.

Total Yield (Mg ha^{-1})

Total yield was determined from the cumulative fruit weight harvested from each experimental unit and then converted to hectare basis according to the following equation:

$$\text{Total Yield} = \frac{Yield\ of\ experimental\ unit \times Hectare\ area}{Experimental\ unit\ area} \qquad (3)$$

Water Productivity (kg m^{-3})

Water productivity (WUEf) was calculated according to (Allen *et al.* ,1998; Colak *et al.,* 2021) using the following equation:

$$WUEf=\frac{Yield}{Applied\ Water} \tag{4}$$

Where:
WUEf = water productivity (kg m^{-3}).

Yield = total yield (kg ha^{-1}).

Applied Water = amount of applied irrigation water (m^3 ha^{-1}).

Results and Discussion

Water Balance Components of Hot Pepper Irrigation Treatments

The results presented in Table 2 indicate clear differences among irrigation systems and tillage treatments regarding irrigation water depth, crop water consumption (ETa), and total amount of water used during the growing season. Drip irrigation treatments generally required lower amounts of irrigation water compared with sprinkler irrigation treatments.

Under drip irrigation, reduced tillage recorded the lowest irrigation water depth (800 mm), water consumption (876 mm), and total water used (8760 m^3 ha^{-1}), whereas traditional tillage under the same irrigation system required higher water quantities, reaching 1015 mm irrigation depth and 10910 m^3 ha^{-1} of applied water. The mean values for drip irrigation were 908 mm for irrigation water depth, 984 mm for ETa, and 9840 m^3 ha^{-1} for total applied water.

On the other hand, treatments using sprinkler irrigation used more water than any of the other irrigation methods evaluated. Sprinkler irrigation under traditional tillage used the most water for all measurements, with 1190 mm of irrigation water depth, 1266 mm of water consumed, and 12660 m^3/ha of total water used. Reduced tillage under sprinkler irrigation resulted in lower water usage than traditional tillage; specifically, the irrigation water depth and water consumed were 850 mm and 926 mm, respectively, resulting in 9260 m^3/ha of total water used. The average values for the sprinkler irrigation treatments were 1020 mm for irrigation water depth, 1096 mm for ETa, and 10960 m^3/ha for total water applied.

Improved soil moisture conservation because of practicing reduced tillage is believed to have contributed to the decreased amount of water applied to crops. Evaporation loss due to surface water evaporation has also decreased because of reduced tillage practices. Lastly, the physical characteristics of soil have improved through this conservation practice, which allows for increased water retained in the root zone where plants grow. As well, when using drip irrigation versus sprinkler irrigation for providing irrigation water, the delivery of the irrigation always occurs directly to the root zone of the plant and very little of the irrigation water is lost through either evaporative or runoff processes.

The results of this study indicate that combining drip irrigation with minimum tillage has decreased the need for irrigation water and improved overall water use efficiency, in arid and semi-arid agricultural conditions.

Table 2. Water balance components of hot pepper irrigation treatments

Irrigation Systems	Treatment	Growth day	Rainwater depth (mm)	Irrigation water depth(mm)	Water consumption ET a (mm)	Amount of water used(m3/ha)
Drip Irrigation	Traditional tillage	236	76	1015	1091	10910
	Reduced tillage	236	76	800	876	8760
Mean		236	76	908	984	9840
Sprinkler Irrigation	Traditional tillage	236	76	1190	1266	12660
	Reduced tillage	236	76	850	926	9260
Mean		236	76	1020	1096	10960
CV					0.19	

Irrigation systems and tillage practices both significantly affected the total amount of water needed to irrigate hot pepper crops, the amount of water needed for evaporation, and the total amount of water consumed during the growing season as shown in Table 2. The results of this research provide evidence that drip irrigation systems use considerably less irrigation water than sprinkler irrigation systems because drip irrigation delivers water directly to the root zone where there are little to no losses due to evaporation, run-off or deep percolation. These findings are consistent with a study by (Schneider *et al.,* 2020; Absanto, 2025) which found that drip irrigation reduces water loss and improves water use efficiency when used to irrigate vegetable crops compared to traditional irrigation methods.

Based on the findings of the study, Reduced Tillage under Drip Irrigation produced the lowest Irrigation Water Depth (800 mm), Evapotranspiration Value (876 mm), and Total Water Applied (8760 m^3 ha^{-1}), while Traditional Tillage under Sprinkler Irrigation produced the highest values: 1190 mm for Irrigation Water

Depth, 1266 mm for ETa and 12660 m^3 ha^{-1} for Total Water Applied. Results suggest reduced tillage effectively contributes to preserving soil moisture and therefore reduces the demand for irrigation. Reduced tillage also decreases soil disturbance, maintains soil aggregates, and decreases evaporation from the soil surface; these factors lead to increased soil moisture retention and more efficient use of irrigation water (Dawod *et al.,* 2024; Shahadha and Wendroth, 2025).

The increased amount of water utilized with sprinkler irrigation has been linked to increased evaporation loss due to the wetting of the total soil surface along with the exposure of the drop of water to high temperatures and air movement during irrigation events. In arid and semi-arid climates, sprinkler systems suffer from relatively low application efficiency due to evaporation losses from the atmosphere, particularly during high temperature and low relative humidity seasons (Allen *et al.,* 1998; Evett *et al.,* 2020). Drip irrigation provides more suitable soil moisture conditions for plant roots and minimizes non-productive water loss, therefore resulting in lower irrigation needs and greater efficiency of irrigation.

According to the study's findings, the reduced amount of irrigation water needed by both irrigation systems was due to the change in tillage methods. The volume of water used in drip irrigated systems decreased from 10910 to 8760 m^3 ha^{-1} when switched from traditional tillage to reduced tillage. The volume of water needed for irrigating sprinkler systems also decreased when switching from traditional to reduced tillage, going from 12660 m^3 ha^{-1} to 9260 m^3 ha^{-1} during the same period. Based on improved soil structure from reduced-till practices, it is likely that the decreased amount of water required for both types of irrigation systems can be attributed to better infiltration rates and greater moisture retention capabilities associated with reduced tillage systems. In a similar study by (Ati *et al.*, 2017; Chen *et al.,* 2025; Franco-Navarro *et al.,* 2025), conservation tillage practices were shown to have improved soil moisture retention properties, which resulted in increased agricultural productivity when there is limited water available for irrigation.

The combination of reduced tillage and the use of a drip irrigation system is the most effective in conserving water and crop water consumption when comparing various treatments. Thus, these results emphasize how important it is to integrate new irrigation technologies with sustainable soil management practices to achieve higher efficiency from irrigated agriculture and to support sustainable agricultural production using limited water resources.

Effect of Irrigation Systems and Tillage Practices on Plant Height, Number of Branches, and Total Yield

According to the data in Table 3, the differences in irrigating systems and tillage practices had a profound effect on the growth of hot peppers, including height and branch quantity and yield. All metrics showed there were significant differences in observed growth and yields attributable to the interaction between the method of irrigation and the tillage used.

For both irrigation systems, reduced tillage treatments had the highest plant heights: 86 cm for both drip and sprinkler systems. For the same systems, traditional tillage treatments had lower average heights of 80 cm and 81 cm respectively. The average height was 83 cm for the drip irrigation system and 84 cm for the sprinkler irrigation system. Based on these data, reduced tillage improves moisture retention in the soil, as well as creating better conditions for root development and nutrient absorption, thus increasing vegetative growth.

The number of branches per plant exhibited similar patterns throughout the two irrigation systems. Tillage treatment type had a marked effect on the number of branches; reduced tillage had the greatest number (8 branches plant^{-1}) when compared to traditional tillage (6 branches plant^{-1}) in both instances. The average branch count was 7 branches plant $^{-1}$ for both tillage systems. Reduced tillage may have enhanced branch formation due to increased water availability from reduced moisture stress around the root zone, which in turn, enhanced plant and canopy development.

Regarding overall yield, the highest yield recorded (4165 Mg ha^{-1}) occurred with drip irrigation in conjunction with reduced tillage and the lowest yield recorded (2975 Mg ha^{-1}) occurred with sprinkler irrigation together with conventional tillage. An intermediate yield (3243 Mg ha^{-1}) resulted from drip irrigation with conventional tillage and sprinkler irrigation with reduced tillage produced a yield of 3885 Mg ha^{-1}. The average total yield from drip irrigation is greater (3704 Mg ha^{-1}) than the average total yield from sprinkler irrigation (3430 Mg ha^{-1}). Therefore, drip irrigation is a more effective method for increasing crop yields than sprinkler irrigation.

According to the LSD values at the 0.05 level, irrigation systems and tillage treatments had significant differences in terms of all parameters measured and the interactions therein. Therefore, we conclude that the combination of drip irrigation and a reduction in tillage is an effective combination for enhancing the vegetative growth of and the yield of pepper plants when limited water availability will occur.

Table 3. Effect of irrigation systems and tillage practices on plant height (cm), number of branches plant^{-1}, and total yield (Mg ha^{-1})

Irrigation Systems	Treatment	Plant Height (cm)	Branches plant^{-1}	Total Yield Mg ha^{-1}
Drip Irrigation	Traditional tillage	80	6	3243
	Reduced tillage	86	8	4165

Mean		83	7	3704
Sprinkler Irrigation	Traditional tillage	81	6	2975
	Reduced tillage	86	8	3885
Mean		84	7	3430
LSD 0.05 Irrigation System		0.89	0.05	30.99
LSD 0.05 Tillage		1.33	0.11	20.41
LSD 0.05 Irrigation System × Tillage		2.35	0.18	55

The data in Table 3 show that irrigation type and tillage method have a statistically significant effect on plant height, total branch count per plant, and total yield of hot pepper crops. The improvement in the physiological characteristics of the plants that grew the best under the reduced tillage treatments was probably due to improved soil physical characteristics, and the amount of moisture retained surrounding the roots in the soil. Because when there is less disturbance created in the soil by using reduced tillage methods; therefore, the soil structure and aggregates are protected which allows for more efficient infiltration and holding of water within the soil; therefore, allowing for more root growth and more efficient nutrient uptake by the plant roots. The same or similar results have been described by (Dawod *et al.*, 2024) who noted that conservation tillage systems improve the hydraulic characteristics of the soil and promote crop growth when irrigated.

Both methods of irrigation and reduced tillage produced plant heights that were much higher than that of traditional tillage as illustrated by the maximum value of 86 cm recorded on both systems when using a reduced tillage method. The increase in plant height associated with reduced tillage is likely due to increased water availability and less moisture stress experienced by vegetation during vegetative growth. There is adequate moisture in the soil to allow for increased cell elongation, increased photosynthate production, and increased nutrient transportation in the plant tissue, which promotes increased vegetative growth. The findings of this study are consistent with those reported by (Ati *et al.* ,2017; Colak *et al.,* 2021; Michelon *et al.,* 2020) who noted that improved water management practices had a very positive impact on the growth and yield of crops grown in areas where water is limited.

Plants had more branches when grown in both farming systems. For example, plants had 8 branches plant^{-1} under reduced tillage vs 6 branches plant^{-1} using conventional tillage. Both soil moisture and nutrient uptake have been shown to play an important role in branch formation. It is likely that reduced tillage resulted in better soil moisture levels with less evaporation between rainfall events leading to better vegetative branching and canopy growth. Increased branching is an important growth trait, as it increases leaf area and photosynthetic efficiency ultimately leading to increased yield.

The greatest amount of total crop yield was produced by using drip irrigation along with reduced tillage (4165 Mg/ha), while the lowest amount of total crop yield came from the combination of traditional tillage with sprinkler irrigation (2975 Mg/ha). Drip irrigation's ability to deliver water with high degrees of irrigation efficiency (coefficient of uniformity) and to provide water directly to the root zone of the crop while minimizing evapotranspiration and surface losses may be two important contributors to its superior yield performance. In addition, the use of drip irrigation will provide plants with optimal soil moisture levels around their roots, reducing water stress during sensitive stages of the crop (blossoming, fruit set, and fruit development). Similar findings were observed by (Martins *et al.,* 2026), who documented that drip irrigation enhanced the growth, yield, and water productivity of lettuce relative to the other irrigation types.

Sprinkler irrigation can cause decreased yields because of increased evaporation, as well as loss of efficiency in the way that water is distributed during hot weather. In addition, with traditional NE tillage practices, water will be lost through evapotranspiration, resulting in less plant access to available moisture. (Allen *et al.* ,1998; Shahadha and Wendroth, 2025; Chen *et al.,* 2025) have shown that maintaining sufficient moisture in the plant's effective root zone is critical to the physiological functions of crops and maximizing agricultural production.

There is a clear interaction between drip irrigation systems and reduced tillage indicating that implementing efficient forms of irrigation in conjunction with sustainable practices for managing the soil will help to maximize the efficiency of these two technologies to improve plant growth and yield due to improved conservation of water in the soil, decreased loss of irrigation water from the environment as well as maintaining favorable conditions in the soil for plant growth. Thus, drip irrigation plus reduced tillage provides an excellent approach to enhance corn yields and water use efficiency in arid and semi-arid regions of the world.

Effect of Irrigation Systems and Tillage Practices on Water Productivity

As evidenced by Figure 1, significant variation in water productivity values exists for irrigated systems as well as for tilling methods. The interaction of both the irrigation method and tilling system were highly significant in determining the water productivity values. The highest water productivity value of 5.21 kg m^{-3} under drip irrigation in conjunction with reduced tillage practices was significantly higher than the 4.57 kg m^{-3} value reported for sprinkler irrigation using reduced tillage. Both traditional tillage practice values of 3.20 and 2.50 kg m^{-3} for drip irrigated and sprinkler irrigated, respectively, were significantly less than those corresponding water productivity values for reduced tillage practices.

Drip irrigation has proven to be more superior than Flood Irrigation due to its greater irrigation efficiency and its ability to put all the applied water directly into the root zone of crops while minimizing evaporation, runoff, and deep percolation losses from the applied water. By maintaining optimal soil moisture conditions surrounding the root of the crop, water uptake efficiency is improved, and better physiological performance is achieved; therefore, a greater yield per unit of water is obtained. (Martins *et al.,* 2026) also reported similar results when they indicated that drip irrigation greatly improved crop performance and water productivity even under limited water supply.

Both irrigation systems have benefited from the economic and environmental impact of reduced tillage on water productivity. Improved water retention in the soil, increased soil aggregation, and the reduction of evaporation from the soil have all contributed to this increase. The use of conservation tillage has traditionally enhanced the hydraulic properties of the soil, while helping to keep the root zones of crops in an optimal moisture state which, in turn, contributes to higher levels of crop use of water (Dawod *et al.,* 2024).

Sprinkler systems, when irrigated using conventional methods of tilling, create a lower level of water productivity, possible due to high levels of water lost due to evaporation, because of the larger surface area that is wetted when sprinkler irrigation occurs; the higher temperatures and wind that are also present may produce more loss due to evaporation. Traditional tillage practices can also create increased moisture loss from the soil through increased soil disturbance and reduced aggregate stability, which can ultimately lead to a decrease in the amount of water used by crops for growth.

The LSD value of 0.14 kg m^{-3} shows that there were statistically different between treatments, indicating that integrating drip irrigation and reduced tillage are effective methods to improve water productivity. The findings support how sustainable irrigation management used in conjunction with conservation tillage methods can greatly improve agriculture's efficiency of using water and help support production of crops in each area when climate conditions are arid or semi-arid (Ati *et al.,* 2017; Allen *et al.,* 1998; Evett and Tolk, 2022).

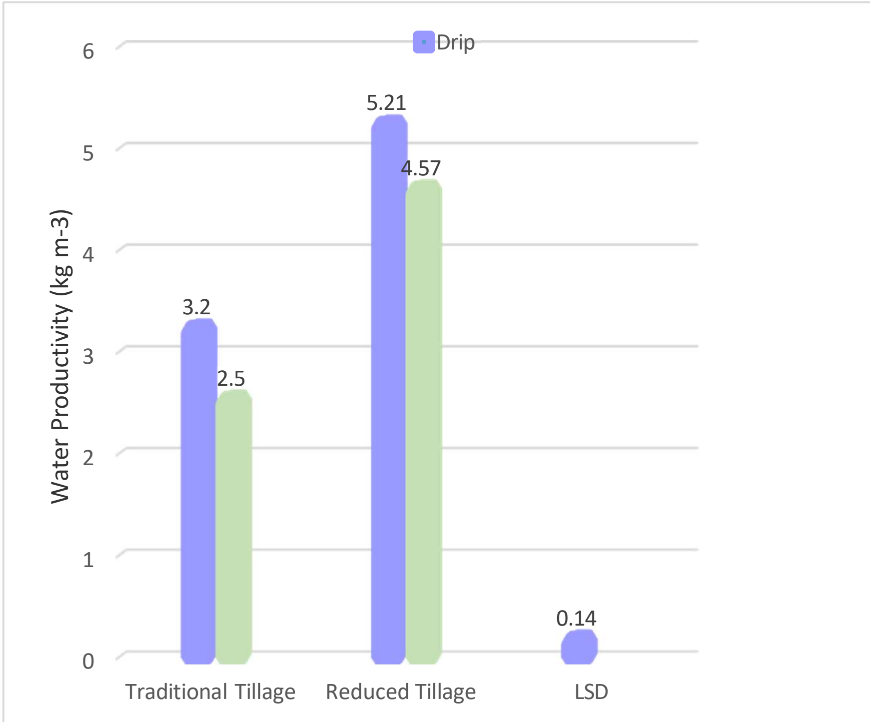

Figure 1. Effect of irrigation systems and tillage practices on water productivity (kg m⁻³).

Figure 1 clearly shows a positive correlation between water productivity and all the methods of irrigation used in the experiment. The method of irrigation that achieved the maximum amount of water productivity (5.21 kg m^{-3}) utilized drip irrigation in conjunction with reduced tillage. The minimum amount of water productivity (2.50 kg m^{-3}) was achieved using sprinkler irrigation along with traditional tillage practices. From this data, we can infer that using a combination of drip irrigation and reduced tillage would have greater contributions to increase the volume of water used efficiently when compared to sprinkler irrigation and traditional tillage practices when used in arid or semi-arid environments. (Abdulrazzaq *et al*., 2018; Franco-Navarro *et al.,* 2025; Chen *et al.,* 2025; Absanto, 2025).

Drip irrigation has increased the overall productivity of water because this type of irrigation is very efficient at supplying water directly to the root zone of a crop, thus resulting in minimal evaporation, runoff, or deep percolation losses. Therefore, drip irrigation creates a relatively uniform distribution of moisture around the root zone, while reducing non-productive water losses, resulting in a greater proportion of the water applied to the crop being used to grow and produce a crop's yield. In addition, according to (Allen *et al.,* 1998; Evett & Tolk, 2022), drip irrigation has provided significantly higher levels of water productivity and crop yield than other irrigation systems.

Tillage reduction contributed significantly to increased water productivity in both irrigation methods used. The increased water productivity was likely related to less disturbance of the soil and more aggregation of the soil, thereby conserving moisture in the soil. Practices that conserve tillage reduce evaporative loss of moisture from the soil surface and increase the amount of moisture that enters, stays in, and can be accessed by crops (Dawod *et al.,* 2024). In addition, reduced tillage improves root growth and makes more efficient use of nutrients due to better physical characteristics found in the soil after tilling.

Sprinkler irrigation has been shown to result in poor water productivity, particularly when combined with traditional tillage methods. One possible reason for the reduced water productivity may be that a larger area of the soil is affected by water evaporation, which causes water to evaporate before entering the root zone where it is utilized by the plant. In addition, increased soil disturbance and breakdown of soil aggregates due to traditional tillage methods increases the rate of soil moisture depletion and decreases the ability of plants to effectively use available water. Allen *et al.* (1998) report that excessive evaporation from agricultural production systems and insufficient techniques for conserving soil moisture lower the productivity of irrigation systems.

The findings that there were significant differences among the various treatments; indicated by the LSD value (0.14 kg m^{-3}), demonstrated that the combination of drip irrigation and reduced tillage has a positive impact on the productivity of water use. In other words, this study supported that if you integrate modern irrigation systems with sustainable soil management practices, you will significantly increase the amount of crop produced per unit of water applied; this has implications on areas where there is a lack of available water. In addition, (Ati *et al.*, 2017; Schneider *et al.,* 2020; Salman and Wheib, 2023; Liu *et al*., 2026) stated that through efficient irrigation management coupled with conservation agricultural systems, it is possible to improve productivity from an environmental perspective as well as from an economic perspective while utilizing limited water resources.

Conclusions

This study has demonstrated that the use of different Irrigation Systems and Tillage Practices caused major differences in the amount of Water Used, the amount of Plant Growth Achieved, the amount of Total Yield Achieved by the Plants, and the Water Productivity, which is measured as the ratio of total yield of the plant to the number of gallons of water used to produce that yield on the hot Pepper Crop grown under the Environmental Conditions of Baghdad, Iraq. Using Drip Irrigation instead of using Sprinkler Irrigation for Irrigation of this Crop will produce a greater reduction in the irrigation water required and an overall reduction in the amount of water used by this Crop, thus demonstrating that Drip Irrigation is the best choice for Sustainable Agricultural Production when Water is Limited; using Reduced Tillage Practices also recommended as it will help to maintain soil moisture management and improve soil physical characteristics which then aids in producing Plant Growth.

Drip irrigation with reduced tillage provided the best overall performance of any treatment measured in this study by providing the most pronounced and positive benefits for both plants and crop productivity through improved plant growth characteristics as well as total yields and water use efficiency (through increased crop yields per unit area compared to traditional tillage practices). The maximum total crop yield for drip-driven irrigation with reduced tillage was found to be 4165 Mg ha^{-1}, while the maximum water use efficiency for the same treatment combination was 5.21 kg m^{-3}. By comparison, sprinkler-driven irrigation with traditional tillage provided the lowest total crop yield and water use efficiency. These data demonstrate that the ability to combine effective irrigation systems and conservation tillage practices will provide substantial increases in irrigation efficiency and enhance crop yield per unit of water applied.

The research concluded that adopting sustainable irrigation scheduling, along with reduced tillage practices, is an important strategy for increasing agricultural water productivity and supporting sustainable crop production for farmers in arid regions or for farmers who operate under conditions of limited rainfall.

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