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Research Article

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Evaluating surface and subsurface drip irrigation efficiency and maize grain yield in central Iraq

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Abstract

This field study was conducted at six selected agricultural sites in Baghdad and Babil Governorates in central Iraq , comprising three sites in each governorate .

The study sites were characterized by varying climatic conditions, with daily evaporation rates ranging from 3.5 to 6.5 mm day⁻¹. Soil properties and irrigation water sources also varied among the sites. Irrigation water salinity ranged from 0.78 to 1.8 dS m⁻¹, while soil salinity reached 3.3 dS m⁻¹ at the Baghdad site. Soil textures varied among silty clay, silty clay loam, and loam. These variations provided an opportunity to evaluate the performance of subsurface drip irrigation (SDI) and surface drip irrigation (DI) under diverse soil conditions and irrigation water qualities.

The results generally demonstrated the superiority of subsurface drip irrigation (SDI) over surface drip irrigation (DI) in terms of grain yield and water use efficiency. Grain yield under SDI ranged from 8.55 to 11.87 t ha⁻¹, with an overall mean of approximately 9.63 t ha⁻¹, whereas grain yield under DI ranged from 8.44 to 9.93 t ha⁻¹, with a mean of approximately 9.02 t ha⁻¹. Babil 2 recorded the highest grain yield under both irrigation systems, reaching 11.87 t ha⁻¹ under SDI compared with 9.93 t ha⁻¹ under DI representing an increase of approximately 19.74% in favor of SDI. The subsurface system also outperformed DI at Baghdad 1, Baghdad 2, Baghdad 3 , Babil 1 , and Babil 3 , indicating a positive yield response to SDI across most of the conditions evaluated in the study.

Regarding water use efficiency (WUE) SDI also exhibited superior performance compared with DI across all study sites. Water use efficiency under SDI ranged from 1.98 to 2.20 kg m⁻³ compared with 1.73 to 1.90 kg m⁻³ under DI.

This superiority indicates that subsurface drip irrigation was more efficient in converting available water into crop production, particularly at sites where pronounced differences in grain yield were observed between the two irrigation systems.

With respect to soil volumetric water content (VWC) the results showed a clear degree of similarity between the two irrigation systems at most sites. Values under SDI ranged from 0.21 to 0.28 $\text{cm}^3 \text{cm}^{-3}$ whereas those under DI ranged from 0.20 to 0.28 $\text{cm}^3 \text{cm}^{-3}$. Equal VWC values were recorded under both systems at some sites, such as Babil 2, where the volumetric water content reached 0.24 $\text{cm}^3 \text{cm}^{-3}$ under both irrigation treatments.

This similarity indicates that both irrigation systems were capable of maintaining an adequate soil moisture level, with relatively small differences in favor of SDI at some sites. However, similarity in soil volumetric water content does not necessarily imply similar irrigation-system performance, as more pronounced differences were observed in grain yield and water use efficiency.

The results also indicated an association between irrigation-system performance and soil properties and irrigation water quality. SDI achieved high performance at the Babil sites, particularly Babil 2, which recorded the highest grain yield and water use efficiency, with relatively low irrigation water salinity of 0.78 dS m^{-1} . In contrast, SDI also performed well at Baghdad 3 despite the relatively high soil salinity of 3.3 dS m^{-1} where grain yield reached 9.65 t ha^{-1} compared with 9.15 t ha^{-1} under DI. These findings demonstrate that irrigation-system efficiency is influenced not only by the method of water application but also by soil properties, irrigation water quality, salinity levels, and the prevailing environmental conditions at each study site.

Based on the findings of this study, subsurface drip irrigation (SDI) demonstrated a clear advantage over surface drip irrigation (DI) in terms of grain yield and water use efficiency while maintaining relatively similar soil moisture levels. This performance may be attributed to the delivery of water closer to the active root zone, which can reduce surface water losses and direct evaporation while improving the plant's utilization of the applied water. Therefore, SDI represents a promising irrigation option for improving irrigation water use efficiency and enhancing crop productivity under the climatic conditions prevailing in central Iraq. However, soil characteristics,

irrigation water quality, and salinity levels should be carefully considered when designing and operating subsurface drip irrigation systems.

Keywords

Maize ; Surface Drip Irrigation ; Subsurface Drip Irrigation ; Grain Yield; Water Use Efficiency ; Volumetric Water Content ; Irrigation System;

1. Introduction

Water represents one of the most important constraints to agricultural production, particularly in arid and semi-arid regions characterized by high evaporative demand, limited rainfall, and increasing pressure on water resources .

Efficient irrigation water management has become essential for achieving food security and sustaining agricultural production under climate change and increasing competition for water resources. The Food and Agriculture Organization (FAO) reports that more than 60% of the world's irrigated lands are located in areas experiencing high or very high water stress, while climate change is expected to increase evaporative demand by 20–30% by 2050, further emphasizing the need for more efficient irrigation systems that improve water delivery to crops and its management within the root zone (FAO, 2026).

The importance of this issue is particularly evident in Iraq, where the agricultural sector relies heavily on surface water resources , particularly the Tigris and Euphrates Rivers . Over recent decades, Iraq has shifted from a state of relative water security toward increasing water stress as a result of several factors, including declining water resources, climate change, increasing water demand, and the deterioration of water and soil quality in some areas. The Food and Agriculture Organization indicates that more than 90% of water use in Iraq is associated with agricultural irrigation, making improvements in agricultural water productivity one of the most important approaches to addressing water scarcity and strengthening food security (FAO, 2025).

The need to improve water-use efficiency is particularly important for cereal production , including maize (*Zea mays* L.) which is one of the major strategic crops used for food, feed, and various industrial purposes. Maize productivity is strongly affected by water availability throughout its different growth

stages; therefore, irrigation management , including the timing and amount of applied water, represents a major factor determining both crop productivity and water-use efficiency.

A recent review showed that maize responds positively to improved irrigation systems and that drip irrigation can increase crop productivity and improve irrigation water-use efficiency compared with several conventional irrigation methods (**Ray et al., 2024**).

Drip irrigation is considered a modern irrigation technology designed to deliver water directly and frequently to the root zone, thereby reducing losses associated with surface runoff and non-uniform water distribution. However, the efficiency of drip irrigation depends not only on the method of water application but also on the position of the drip lines relative to the soil surface, soil properties, evaporation rate, irrigation water quality, and crop water requirements. Accordingly, a distinction can be made between surface drip irrigation (DI), in which the drip lines are placed on the soil surface, and subsurface drip irrigation (SDI) , in which the drip lines are installed below the soil surface in close proximity to the root zone.

Subsurface drip irrigation possesses several characteristics that may provide advantages under hot and arid conditions .

Placing the water source below the soil surface reduces the exposure of the wetted zone to direct evaporation from the soil surface

. It may also improve water distribution within the root zone and increase the efficiency with which applied water is utilized. Studies investigating maize under subsurface drip irrigation have shown that irrigation amount and system management directly influence evapotranspiration and grain yield, and that yield response is associated with the amount of water available within the root zone. Recent experimental evidence further supports the potential superiority of subsurface irrigation in terms of crop productivity and water-use efficiency.

A global analysis encompassing 61 independent field studies conducted in arid and semi-arid environments provided more direct evidence comparing subsurface drip irrigation with surface drip irrigation. The study found that subsurface drip irrigation increased water-use efficiency by 15.0% and crop productivity by 9.9%, while reducing average soil salinity by 3.6% compared with surface drip irrigation. The study also indicated that these responses

varied according to crop type, climate, soil type, and irrigation water salinity (**Zhang et al., 2026**).

A field study conducted in saline soil demonstrated that drip irrigation resulted in the formation of a salt-leaching zone around the emitters. Controlling the amount and distribution of applied water improved soil moisture conditions, reduced water losses, and enhanced water-use efficiency and grain yield (**Wang et al., 2023**).

The efficiency of subsurface drip irrigation cannot be evaluated independently of soil properties. Soil texture and structure influence the rate and direction of water movement, the extent of the wetted zone, and the retention and distribution of water within the root zone. Consequently, the response to surface and subsurface drip irrigation may differ among sandy, clayey, and silty-clay soils. Irrigation water salinity may also affect salt movement within the root zone and the plant's ability to absorb water.

Therefore, integrating irrigation method with soil properties and water quality is an important component in evaluating irrigation-system performance.

Recent studies on water and salt movement under drip irrigation have emphasized the importance of investigating the spatial and vertical distribution of soil moisture and salinity when assessing system efficiency (**Wang et al., 2023**).

Recent studies have indicated that the relationship between water consumption and maize productivity depends largely on evapotranspiration and water availability within the root zone, and that improved irrigation management can increase productivity per unit of water used (**Kukal et al., 2024**).

In maize studies specifically, comparisons among different irrigation systems have demonstrated that irrigation method and water-supply level can substantially affect plant growth and grain production. Zhao et al. (2022) found that maize productivity was affected by both irrigation level and irrigation method, and that subsurface drip irrigation produced higher yields than conventional surface irrigation under the conditions of their study, with a clear interaction between irrigation and fertilization management in influencing crop growth and productivity.

The comparison between surface and subsurface drip irrigation is particularly important in Iraq because differences among agricultural sites are not limited to climate and evaporation rate but also include soil type, irrigation-water sources, and salinity levels. An Iraqi field study conducted in Babil Governorate found that different irrigation systems affected maize growth, productivity, and water productivity, and that subsurface drip irrigation treatments were among the superior treatments in terms of water-use efficiency. These findings provide local evidence supporting the potential application of this technology under Iraqi soil conditions (**Al-Aridhee & Mahdi, 2022**).

A recent study conducted across three Iraqi agro-environmental regions compared precision irrigation technologies, deficit irrigation, drip irrigation, and flood irrigation. The results showed that improved irrigation technologies outperformed conventional irrigation in terms of crop productivity and water-use efficiency, with water savings ranging from 20–30% under some treatments. These findings support the importance of evaluating modern irrigation technologies across different Iraqi environments rather than relying on results obtained from a single location (**Jumintono et al., 2024**).

The Food and Agriculture Organization has emphasized the importance of adopting modern technologies and improving water management efficiency, while also supporting programs aimed at modernizing irrigation systems and promoting agricultural practices capable of adapting to climate change in Iraq. Despite the increasing number of studies addressing subsurface drip irrigation, the magnitude of its response relative to surface drip irrigation may vary considerably according to environmental conditions, irrigation management, soil properties, and water quality.

Therefore, findings obtained from a single environment cannot be directly generalized to all agricultural sites. This highlights the need for multi-site comparative studies that integrate irrigation method with the environmental factors associated with system performance, particularly evaporation rate, soil texture and structure, irrigation-water source, and salinity.

2. Materials and Methods

2.1 Research Methodology

The study aimed to conduct a quantitative comparative analysis of the results of published field experiments investigating surface drip irrigation (DI) and

subsurface drip irrigation (SDI) for yellow maize under different Iraqi environmental conditions. The study evaluated response trends in grain yield, water use efficiency, and soil moisture content, and interpreted the variation in results in relation to soil and climatic characteristics and irrigation-water salinity.

The study included an analysis of field data obtained from six experiments distributed across two major agricultural governorates: Baghdad Governorate (three sites: Baghdad 1, Baghdad 2, and Baghdad 3) and Babil Governorate (three sites: Babil 1, Babil 2, and Babil 3). These sites differed in soil characteristics, irrigation-water sources and salinity levels, and daily evaporation rates, as follows:

1. Study Site Characteristics

- **Sites in Baghdad Governorate:**

- **Baghdad 1 and Baghdad 2:** The experiments were conducted in alluvial silty clay soil and used the Tigris River as the source of irrigation water. Water salinity ranged from **0.8–1.8 dS m⁻¹**, while daily evaporation rates ranged from **5.2–6.8 mm day⁻¹**.
- **Baghdad 3:** The experiment was conducted in sedimentary loam soil, with a soil salinity of **EC = 3.3 dS m⁻¹**. The evaporation rate ranged from **3.5–6.5 mm day⁻¹**.

- **Sites in Babil Governorate:**

- **Babil 1, Babil 2, and Babil 3:** All experiments were conducted in silty clay loam soil and used the Hilla River (Shatt al-Hillah) as the irrigation-water source. Irrigation-water salinity was relatively low, ranging from **0.78–1.6 dS m⁻¹**, with daily evaporation rates ranging from **5.2–6.55 mm day⁻¹**.

2. Studied Parameters

The data from the selected experiments were extracted and classified, with measurement units standardized and the data reorganized into a unified database to facilitate quantitative comparisons between DI and SDI systems.

The following variables were included:

1. **Grain Yield:** measured in **t ha⁻¹**.
2. **Water Use Efficiency (WUE):** measured in **kg m⁻³**.
3. **Volumetric Soil Moisture Content:** measured in **cm³ cm⁻³**.
4. **Environmental and Hydrological Factors:** including daily evaporation rate (**mm day⁻¹**), irrigation-water and soil salinity (**dS m⁻¹**), and soil texture and origin.

2.2 Study Scope

The study included field studies investigating the response of yellow maize (*Zea mays* L.) to surface drip irrigation and subsurface drip irrigation under Iraqi agricultural conditions.

- **Crop:** Yellow maize (*Zea mays* L.).
- **Comparison:** Surface drip irrigation (DI) and subsurface drip irrigation (SDI).
- **Study locations:** Babil and Baghdad (Abu Ghraib).

For the purpose of interpreting variations among the results, the available information regarding the experimental location, soil type, irrigation-water quantity, irrigation scheduling, and operational conditions of the irrigation system was recorded.

2.3 Data Collection and Organization

Numerical data were extracted from tables and published results in the original studies. The primary comparison was limited to treatments that could be directly associated with the DI and SDI systems. Measurement units were standardized to **t ha⁻¹** for grain yield and **kg m⁻³** for water use efficiency.

2.4 Calculation Indicators

2.4.1 Irrigation Water Use Efficiency

Irrigation water use efficiency (IWUE) was calculated according to the following equation:

$$\text{IWUE} = Y / W_a$$

where:

- **IWUE:** Irrigation water use efficiency (kg m⁻³)
- **Y:** Grain yield (kg ha⁻¹)
- **W_a:** Amount of irrigation water applied (m³ ha⁻¹)

2.4.2 Irrigation Water Saving Percentage

The percentage of irrigation water saved when using SDI compared with DI was calculated as follows:

$$\text{WS\%} = [(W_{a,\text{DI}} - W_{a,\text{SDI}}) / W_{a,\text{DI}}] \times 100$$

where:

- **W_{a,DI}:** Amount of irrigation water applied under the DI system.
- **W_{a,SDI}:** Amount of irrigation water applied under the SDI system.

2.4.3 Percentage Increase in Grain Yield

The percentage increase in grain yield resulting from the use of SDI compared with DI was calculated as follows:

$$YI\% = [(YSDI - YDI) / YDI] \times 100$$

where:

- **YI:** Percentage increase in grain yield (%).
- **YSDI:** Grain yield under the SDI system.
- **YDI:** Grain yield under the DI system.

2.4.4 Comparison Among Study Sites

A quantitative comparison between the DI and SDI systems was conducted across the study sites to determine the direction and magnitude of the yellow maize response in terms of grain yield, irrigation water use efficiency, and water savings where data were available. The magnitude of the response was also compared between Babil and Baghdad. Differences were interpreted in relation to soil characteristics, climatic conditions, growing season, crop variety, irrigation-water quantities, and operational conditions of the irrigation system.

2.4.5 Statistical Analysis

Because the data used in this study represented published results from independent experiments with different experimental designs and environmental conditions, the quantitative analysis was limited to comparisons of published means and the calculation of differences and percentages of yield increase or water savings.

Descriptive and inferential analyses were used to identify and demonstrate the response trends of the DI and SDI systems across the study sites and to determine the superiority of SDI over DI.

3. Results and Discussion

3.1 Grain Yield (t ha^{-1})

The field results demonstrated an overall superiority of the subsurface drip irrigation (SDI) system over the surface drip irrigation (DI) system across all study sites in Baghdad and Babylon Governorates.

- **Yield levels:** Grain yield under SDI ranged from **8.55 t ha^{-1}** at Baghdad 1 to **11.87 t ha^{-1}** at Babylon 2, with an overall mean of **9.61 t ha^{-1}** . In comparison, grain yield under DI ranged from **8.44 t ha^{-1}** at Baghdad 1 to **9.93 t ha^{-1}** at Babylon 2, with an overall mean of **8.86 t ha^{-1}** .
- **Highest yield response:** The highest grain yield was recorded at Babylon 2, characterized by silty clay loam soil and fresh irrigation water with an electrical conductivity of **0.78 dS m^{-1}** . Grain yield reached

11.87 t ha⁻¹ under SDI compared with **9.93 t ha⁻¹** under DI, representing a relative increase of **19.54%** in favor of SDI. Babylon 3 also exhibited a pronounced response, with an increase of **14.54%** in grain yield under SDI compared with DI.

The observed superiority of SDI in grain yield can be attributed to the direct and regulated supply of water within the effective root-zone, which helps maintain favorable soil moisture conditions and reduces water stress during critical physiological growth stages. This finding is consistent with the comprehensive analysis of crop productivity and trade-offs under subsurface irrigation reported by **Zhang et al. (2026)**. It is also supported by **Irmak (2024)**, who indicated that precise water delivery through SDI can improve photosynthetic performance and crop yield. Furthermore, the present findings under Iraqi conditions are consistent with those reported by **Abdul-Razak et al. (2016)** and **Ali et al. (2017)**, who demonstrated the superior yield performance of subsurface drip irrigation compared with surface drip irrigation under local soil and climatic conditions.

3.2 Water Use Efficiency (WUE; kg m⁻³)

The water use efficiency results demonstrated the ability of SDI to maximize crop yield per unit of applied water.

- **Field values:** SDI consistently showed higher water use efficiency across all study sites, with values ranging from **1.98 kg m⁻³** at Baghdad 2 to **2.20 kg m⁻³** at Babylon 3, with an overall mean of **2.10 kg m⁻³**. In contrast, WUE under DI ranged from **1.73 kg m⁻³** at Baghdad 3 to **1.90 kg m⁻³** at Baghdad 1 and Babylon 3, with an overall mean of **1.81 kg m⁻³**.

The consistently higher WUE under SDI, particularly under the high evaporative demand conditions recorded at the study sites, including a maximum evaporation rate of **6.80 mm day⁻¹** at Baghdad 2, can be attributed primarily to the reduction of direct soil-surface evaporation and the more efficient delivery of irrigation water to the crop root zone. This mechanism improves the proportion of applied water available for crop transpiration and, consequently, increases water productivity.

These findings are consistent with **FAO (2025)** reports concerning improved agricultural water management and water productivity in Iraq. They are also in agreement with **Ray et al. (2024)** and **Kukal (2024)**, who emphasized the importance of reducing non-beneficial evaporative losses in improving crop water-use efficiency. Furthermore, the present results are consistent with the

findings of **Jumintono et al. (2024)** and **Mahdi and Al-Aridhee (2022)** regarding the potential of precision irrigation systems to improve water use efficiency under Iraqi environmental conditions.

3.3 Volumetric Soil Moisture Content ($\text{cm}^3 \text{ cm}^{-3}$)

Measurements of volumetric soil moisture content showed relatively similar and stable moisture conditions between the two irrigation systems at the sampling locations.

- **Moisture stability:** Volumetric soil moisture content under SDI ranged from **0.21 to 0.28 $\text{cm}^3 \text{ cm}^{-3}$** , with a mean of **0.235 $\text{cm}^3 \text{ cm}^{-3}$** , whereas values under DI ranged from **0.20 to 0.28 $\text{cm}^3 \text{ cm}^{-3}$** , with a mean of **0.23 $\text{cm}^3 \text{ cm}^{-3}$** . Identical values were recorded for the two irrigation systems at Baghdad 2 (**0.227 $\text{cm}^3 \text{ cm}^{-3}$**), Baghdad 3 (**0.28 $\text{cm}^3 \text{ cm}^{-3}$**), and Babylon 2 (**0.24 $\text{cm}^3 \text{ cm}^{-3}$**).

The close numerical similarity between the two irrigation systems indicates that both systems maintained adequate soil moisture conditions at the time of measurement. However, the more important distinction may lie in the dynamic pattern of moisture distribution and retention within the wetted soil profile.

Wang et al. (2023) reported that subsurface irrigation can maintain more stable capillary water distribution and favorable moisture conditions around the root zone for longer periods between irrigation events. This behavior is also consistent with the findings of **Oudah and Al-Kellabi (2023)** concerning the influence of irrigation methods on water uptake and moisture stability within the root zone.

3.4 Interaction with Soil Salinity, Irrigation Water Salinity, and Soil Texture

The performance of the irrigation treatments varied according to the physical and chemical characteristics of the study sites.

- The **silty clay loam soils** at the Babylon sites exhibited an excellent yield response to SDI when irrigated with water from the Shatt Al-Hillah, characterized by an electrical conductivity of **0.78–0.79 dS m^{-1}** . This response may be attributed to the relatively high water-holding capacity of these soils and their favorable balance between water retention and capillary movement.
- Despite the relatively higher soil salinity at Baghdad 3, where soil electrical conductivity reached **$\text{EC} = 3.3 \text{ dS m}^{-1}$** and the soil texture was **loam**, SDI reduced the impact of osmotic stress and produced a grain yield of **9.65 t ha^{-1}** , compared with **9.15 t ha^{-1}** under DI. Water use

efficiency also reached **2.13 kg m⁻³** under SDI compared with **1.73 kg m⁻³** under DI.

The improved performance of SDI under saline conditions can be attributed to the spatial redistribution of dissolved salts with the movement of irrigation water toward the outer margins of the wetted bulb, thereby reducing direct salt accumulation within the most active portion of the root zone. This interpretation is consistent with the findings of **Wang et al. (2023)** and **Zhang et al. (2026)**, who reported that subsurface drip irrigation can influence salt redistribution and reduce salt accumulation within the immediate root-zone under variable salinity conditions.

Table 1. Hydrological and Yield Characteristics of Surface and Subsurface Drip Irrigation Systems across Different Locations in Baghdad and Babylon Governorates

Study Site	Water Source and Salinity	Soil Texture and Structure	Water use efficiency (kg m ⁻³) DI	Water use efficiency (kg m ⁻³) SDI	Volumetric moisture content (cm ³ /cm ³) DI	Volumetric moisture content (cm ³ /cm ³) SDI	Grain yield (ton ha ⁻¹) DI	Grain yield (ton ha ⁻¹) SDI	Evaporation mm day ⁻¹
Baghdad 1	Tigris River, 0.8–1.2 dS m ⁻¹	Alluvial, Silty Clay	1.90	2.15	0.20	0.21	8.44	8.55	5.2 - 5.8
Baghdad 2	Tigris River, 1.8 dS m ⁻¹	Alluvial, Silty Clay	1.75	1.98	0.22	0.22	8.50	9.05	6.0 - 6.8
Baghdad 3	Soil EC = 3.3 dS m ⁻¹	Sedimentary, Loam	1.73	2.13	0.28	0.28	9.15	9.65	3.5 - 6.5
Babil 1	Shatt Al-Hilla, 1.2–1.6 dS m ⁻¹	Silty Clay Loam	1.85	2.10	0.21	0.22	8.68	8.88	5.5 - 6.2
Babil 2	Shatt Al-Hilla, 0.78 dS m ⁻¹	Silty Clay Loam	1.75	2.05	0.24	0.24	9.93	11.87	5.2 - 6.5
Babil 3	0.79 dS m ⁻¹	Silty Clay Loam	1.90	2.20	0.21	0.22	8.46	9.69	5.2 - 6.5

3.5 Methodological Levels of Results Analysis (Descriptive, Inferential, and Probabilistic Inductive Analysis)

The analysis of the results in this study was based on three complementary methodological levels: **descriptive analysis, inferential analysis, and probabilistic inductive analysis**. These levels were adopted to progress from presenting the characteristics of the data and identifying their general trends to testing the statistical significance of differences between the irrigation treatments, and subsequently interpreting the recurrence of the observed patterns in light of the available experimental evidence. This methodological integration provides a more comprehensive interpretation of the results, whereby the analysis is not limited to describing the numerical differences between **subsurface drip irrigation (SDI)** and **surface drip irrigation (DI)**, but also extends to assessing the statistical strength of these differences and their consistency across the different experimental sites.

3.5.1 Descriptive Analysis

Table 2 presents the main descriptive statistical indicators for the studied variables across the six study sites, including the arithmetic mean (**Mean**), standard deviation (**SD**), and the minimum and maximum values (**Min–Max**).

Table 2. Descriptive Analysis of the Studied Variables

variable	Kind og irrigation	Mean $\pm$ SD	Min	Max
Evaporation (mm day⁻¹)	—	5.39 $\pm$ 0.94	3.5	6.55
Grain Yield (ton ha⁻¹)	SDI	9.61 $\pm$ 1.22	8.55	11.87
	DI	8.86 $\pm$ 0.58	8.44	9.93
WUE (kg m⁻³)	SDI	2.10 $\pm$ 0.08	1.98	2.20
	DI	1.81 $\pm$ 0.09	1.73	1.90
VWC (%)	SDI	0.235 $\pm$ 0.024	0.21	0.280
	DI	0.227 $\pm$ 0.028	0.20	0.280

Grain Yield:

The subsurface drip irrigation (SDI) system demonstrated a clear numerical superiority, with a mean grain yield of **9.61 t ha⁻¹**, compared with **8.86 t ha⁻¹** under surface drip irrigation (DI), representing a descriptive increase of **8.01%**. The highest grain yield for both irrigation systems was recorded at **Babil 2**, reaching **11.87 t ha⁻¹** under SDI and **9.93 t ha⁻¹** under DI.

Water Use Efficiency (WUE):

The SDI system showed superior water use efficiency, with a mean value of **2.10 kg m⁻³**, compared with **1.81 kg m⁻³** for DI, representing a descriptive increase of **16.02%**. The highest WUE under SDI was recorded at **Babil 3**, reaching **2.20 kg m⁻³**, whereas the DI values varied within a relatively narrow range of **1.73–1.90 kg m⁻³**.

Volumetric Water Content (VWC):

The SDI system maintained a slightly higher mean volumetric water content (**0.235 cm³ cm⁻³**) than the DI system (**0.227 cm³ cm⁻³**), corresponding to a descriptive difference of **3.52%**.

The results also indicated a high degree of similarity and stability in soil moisture levels between the two irrigation systems at most study sites, particularly **Baghdad 2, Baghdad 3, and Babil 2**.

Evaporation Rate:

Daily evaporation across the study sites ranged from **3.50 to 6.55 mm day⁻¹**, with an overall mean of **5.39 mm day⁻¹**.

3.5.2 Inferential Analysis

Table 3. Results of the Paired t-Test Comparing SDI and DI Systems (df = 5)

المتغير	SDI Mean	DI Mean	Mean Diff. (SDI-DI)	Change (%)	t-value (df=5)	P-value	Significance
Grain Yield (ton ha ⁻¹)	9.61	8.86	+0.75	+8.01	2.316	0.068	ns
WUE (kg m ⁻³)	2.10	1.81	+0.29	+16.02	7.406	0.0007	+++
VWC (cm ³ cm ⁻³)	0.235	0.227	+0.008	+3.52	1.826	0.127	ns

Note: ns = not statistically significant at $P < 0.05$; *** = $P < 0.001$.

Grain Yield

Grain yield increased by **0.75 t ha⁻¹ (+8.01%)** in favor of the **SDI** system. Although the difference did not reach the conventional level of statistical significance at the **5% significance level (P = 0.068)**, a positive trend in favor of SDI was observed. This result indicates a potentially meaningful agronomic benefit of SDI in improving grain yield; however, further studies with larger sample sizes would be required to determine whether this trend reaches statistical significance.

Water Use Efficiency (WUE)

The paired t-test revealed a **highly statistically significant difference (P = 0.0007)** in favor of the subsurface drip irrigation (**SDI**) system, with a mean difference of **0.29 kg m⁻³**, corresponding to a **16.02%** increase compared with DI. This result provides strong statistical evidence that SDI significantly improved water use efficiency compared with surface drip irrigation across the study sites.

Volumetric Water Content (VWC)

The SDI system showed a small, statistically non-significant increase in volumetric water content ($P = 0.127$) of $0.008 \text{ cm}^3 \text{ cm}^{-3}$, corresponding to a **3.52%** increase compared with DI. This result indicates that SDI maintained soil moisture conditions comparable to, or slightly higher than, those observed under DI within the root zone at the time of sampling.

Revised Statistical and Agronomic Conclusion

The inferential analysis provides strong statistical evidence that the use of subsurface drip irrigation (**SDI**) significantly improves **water use efficiency (WUE)** compared with surface drip irrigation (**DI**). This statistically significant improvement was accompanied by a positive, although not statistically significant, trend in grain yield. The observed field advantage of SDI may be associated with reduced direct soil-surface evaporation and improved maintenance of soil moisture within the active root zone.

Overall, the inferential results indicate that the principal statistically supported benefit of SDI in the present study was the improvement in **water use efficiency**, whereas the observed increase in grain yield represents a positive agronomic trend that warrants further investigation using a larger number of experimental units.

3.5.3 Probabilistic Induction and Interpretation of Experimental Evidence

The inductive approach of the thinker **Muhammad Baqir al-Sadr** was adopted to identify the underlying cause of the superiority of subsurface drip irrigation (**SDI**) over surface drip irrigation (**DI**) across the six experimental sites, based on the accumulation of evidence and the identification of the objective effect. According to his methodological approach, as the conditions associated with an experimental phenomenon become more diverse while the outcome remains consistent, the probability that the observed association is merely coincidental decreases, while the objective probability of a causal relationship increases, eventually leading to subjective certainty regarding the scientific law (**Al-Sadr, 2008**).

Based on this experimental reasoning, the repeated superiority of **SDI** across all six study sites, despite variations in soil texture (ranging from silty clay loam to loam), differences in irrigation-water and soil salinity (**0.78 to 3.3 dS m⁻¹**) and variation in evaporation rates (**3.50 to 6.55 mm day⁻¹**), represents an accumulation of positive evidence against random coincidence and supports the

existence of a causal relationship. This interpretation is reflected through the following three lines of evidence:

- **Volumetric Water Content (VWC):** The data demonstrated a consistently favorable moisture response under **SDI** across the study sites. At **Baghdad 3**, the highest recorded volumetric water content reached **$0.28 \text{ cm}^3 \text{ cm}^{-3}$** under both SDI and DI, while SDI showed a higher moisture level at other sites, such as **Baghdad 2**, where the values were **$0.21 \text{ cm}^3 \text{ cm}^{-3}$** under SDI compared with **$0.20 \text{ cm}^3 \text{ cm}^{-3}$** under DI. The underlying mechanism may be attributed to the direct application of water within the active root zone and the reduction of direct evaporation from the soil surface.
- **Grain Yield:** A consistent superiority of **SDI** was observed across all six study sites. The highest grain yield was recorded at **Babil 2**, reaching **11.87 t ha^{-1}** under SDI compared with **9.93 t ha^{-1}** under DI. This response may be attributed to maintaining more favorable moisture conditions around the active root zone, thereby reducing water stress and facilitating nutrient uptake.
- **Water Use Efficiency (WUE):** The **SDI** system showed a consistent and statistically significant superiority in water use efficiency, with **$P < 0.001$** . The highest WUE was recorded at **Babil 3**, reaching **2.20 kg m^{-3}** under SDI compared with **1.90 kg m^{-3}** under DI. At **Baghdad 1**, WUE reached **2.15 kg m^{-3}** under SDI compared with **1.90 kg m^{-3}** under DI. This improvement may be attributed to reduced non-beneficial water losses through evaporation while maintaining or improving crop productivity.

According to the principles of **Al-Sadr's inductive methodology**, if the observed superiority in water use efficiency were merely a coincidental occurrence or the result of a random factor, the probability of SDI outperforming DI in all six study sites without exception could, under the simplifying assumption of equal and independent probabilities, be expressed as: $(1/2)^6 = 1/64$

which corresponds to approximately **1.56%**.

This reasoning is further supported, within the framework of Al-Sadr's methodology, by the fact that the observed pattern did not occur within a single homogeneous environment. Rather, the consistency of the result was observed across six environments differing in soil texture, ranging from silty clay loam to loam, as well as in salinity levels (**$0.78\text{--}3.3 \text{ dS m}^{-1}$**) and evaporative

conditions. This represents what is referred to in inductive reasoning as **variation in cases and conditions**, which helps reduce the likelihood that the observed superiority is attributable solely to incidental environmental factors. Based on the generative stage of probability theory, the reduction in the assumed probability of coincidence to approximately **1.56%** increases the evidential support for the causal hypothesis (**causal relationship**).

Accordingly, the accumulation of objective probabilistic evidence provides increasing confidence in the interpretation that the subsurface water-delivery pattern contributes directly to reducing non-beneficial water losses and improving water use efficiency.

Based on the foregoing, the integration of the three analytical levels is considered more appropriate than relying on any single level independently, as each level performs a distinct methodological function that complements the other two. **Descriptive analysis** contributed to identifying the general trends in the data and the initial differences between the two irrigation systems.

Inferential analysis enabled the statistical significance of these differences to be evaluated and helped determine whether the observed differences could be attributed to the irrigation treatment within the limits of the available data.

Probabilistic inductive analysis, in turn, was used as an interpretive framework for examining the accumulation of experimental evidence and the consistency of the observed trends across different sites and environmental conditions, thereby supporting the scientific interpretation of the results.

Accordingly, the study adopted an integrated methodological sequence beginning with **descriptive analysis**, followed by **inferential analysis**, and then **inductive interpretation of the accumulated experimental evidence**. This sequence provides a logical transition from describing the phenomenon and identifying its general trends, to statistically testing the observed differences, and finally to interpreting the consistency of these findings across different experimental environments.

Therefore, probabilistic induction should not be regarded as a substitute for statistical testing or as a means of establishing causality with absolute certainty. Rather, it serves as a **supportive interpretive level** whose evidential value increases when consistent experimental trends are repeatedly observed under diverse conditions. Through this integration, the final interpretation is based on the convergence of descriptive evidence, inferential evidence, and the accumulation of experimental observations, providing a stronger and more balanced basis for interpreting the superiority of subsurface drip irrigation

(SDI) over surface drip irrigation (DI) within the scope and limitations of the present study.

Table 4. Aggregated Comparison of Productivity and Water-Use Efficiency Indicators between Surface and Subsurface Drip Irrigation Systems across the Study Sites.

Location	Irrigation Type	Grain Yield (ton ha ⁻¹)	Water Use Efficiency (kg m ⁻³)	Volumetric Soil Moisture ((cm ³ cm ⁻³)
Baghdad 1	SDI	8.55	2.15	0.21
	DI	8.44	1.90	0.20
Baghdad 2	SDI	9.05	1.98	0.22
	DI	8.50	1.75	0.22
Baghdad 3	SDI	9.65	2.13	0.28
	DI	9.15	1.73	0.28
Babylon 1	SDI	8.88	2.10	0.22
	DI	8.68	1.85	0.21
Babylon 2	SDI	11.87	2.05	0.24
	DI	9.93	1.75	0.24
Babylon 3	SDI	9.69	2.20	0.22
	DI	8.46	1.90	0.21
Baghdad Average	SDI	9.08	2.09	0.237
	DI	8.70	1.79	0.233
Babylon Average	SDI	10.15	2.12	0.227
	DI	9.02	1.83	0.220
Overall Average	SDI	9.61	2.10	0.235
	DI	8.86	1.81	0.227

Note: SDI stands for Subsurface Drip Irrigation and DI stands for Drip .Irrigation

4. Conclusions

1. The **SDI system** demonstrated a descriptive superiority in yellow maize grain yield across the six locations, with grain yield being higher under SDI than under DI at all locations. However, the overall difference in yield did not reach statistical significance at the 0.05 level according to the paired analysis.
2. SDI showed superior **water use efficiency (WUE)** at all locations, with a mean WUE of approximately **2.10 kg m⁻³**, compared with **1.81 kg m⁻³** under DI, representing an increase of **16.02%**. The results of the paired

test, using the corrected original values, indicated a statistically significant difference at the 0.05 level.

3. The superiority of SDI in terms of **volumetric water content (VWC)** was not consistent across all locations. VWC values varied among locations, while the values were equal at **Babylon 2**. Therefore, the superiority of SDI in VWC cannot be generalized to all locations.
4. The SDI system demonstrated high **operational efficiency** in areas with high daily evaporation rates by applying water directly into the soil.
5. The SDI system demonstrated considerable effectiveness in managing **highly saline areas** by displacing salts away from the effective root zone.

5. Recommendations

1. It is recommended to expand the application of **subsurface drip irrigation (SDI)** for yellow maize production in the central and southern regions of Iraq to take advantage of its water-saving and productivity benefits.
2. Additional field studies should be conducted to determine the **optimum lateral burial depth** and emitter spacing according to the characteristics of loamy and clay soils.
3. **Improvement of irrigation scheduling:** Programmed irrigation schedules based on **reference evapotranspiration (ET_o)** and soil volumetric water content should be adopted to ensure maximum water-use efficiency under the SDI system.
4. Future research should investigate **leaching requirements** and salt accumulation patterns around emitters when irrigation water with moderate or high salinity is used.
5. **Governmental and extension support** should be provided to farmers to reduce the initial costs of establishing SDI networks and to train them in the maintenance of subsurface emitters to prevent clogging caused by root intrusion.

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