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# Comparative analysis of precision, deficit, and drip irrigation for water efficiency in Iraq

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**Abstract:** Sustainable irrigation practices are critical for addressing the challenges of water scarcity and food insecurity in the face of climate change and growing global food demand. This study investigated the potential of precision irrigation (PI), deficit irrigation (DI), and drip irrigation (DRI) techniques to enhance crop productivity and water use efficiency (*WUE*) compared to conventional flood irrigation (CFI) in three distinct agroecological zones of Iraq. Field experiments were conducted using a randomised complete block design with wheat, maize, and rice crops. The results demonstrated that PI significantly increased crop growth parameters, grain yield, and *WUE* across all zones, with yield improvements of 33–38% and *WUE* increases of 46–51% in contrast with CFI. The DI and DRI treatments also outperformed CFI, albeit to a lesser extent. Remote sensing-derived vegetation indices strongly correlated with crop growth parameters and yield, while hydrological modelling revealed reduced evapotranspiration and surface runoff under the PI treatment. The sustainable irrigation practices resulted in substantial water savings of 20–30% compared to CFI. These findings highlight the importance of adopting efficient irrigation techniques, along with a holistic approach encompassing technological innovations, capacity building, and stakeholder engagement, to promote water-efficient agriculture and ensure food security in water-scarce regions.

**Keywords:** field experiments, food production, irrigation practices, water use efficiency

## INTRODUCTION

Water scarcity and food insecurity are two of the most pressing challenges facing the global community in the 21st century. As the global populace expands, the necessity for enhanced agricultural output is escalating swiftly, placing immense pressure on already stressed water resources (Zhang *et al.*, 2020). Climate change further exacerbates these challenges, with rising temperatures, altered precipitation patterns, and more frequent droughts and floods affecting agricultural productivity and water availability (Nhemachena *et al.*, 2020). In this context, the adoption of sustainable irrigation practices has emerged as a critical strategy for enhancing food security while promoting water conservation in agricultural landscapes.

Irrigation plays a vital role in global food production, with irrigated agriculture accounting for approximately 40% of the food supply (Wrachien de, Schultz and Goli, 2021; Schmitt, Rosa and Daily, 2022). However, traditional irrigation methods, such as flood and furrow irrigation, are often inefficient, leading to substantial water losses through evaporation, runoff, and deep percolation (Ambomsa, 2020). Moreover, the excessive application of water can result in soil salinisation, nutrient leaching, and groundwater depletion, further compromising the long-term sustainability of agricultural systems (Yin *et al.*, 2022). To address these challenges, researchers and practitioners have been exploring innovative irrigation techniques and water management strategies that can optimise water use efficiency (*WUE*) while maintaining or enhancing crop productivity.

Precision irrigation (PI) offers a promising solution, involving the targeted application of water specifically to the needs of individual plants or crop zones (Zinkernagel *et al.*, 2020). By using advanced sensors, remote sensing technologies, and data analytics, precision irrigation enables farmers to monitor soil moisture levels, vegetation hydration state, and climatic variables in real-time, allowing for the precise and timely delivery of water (Abioye *et al.*, 2020). This approach not only reduces water consumption but also improves crop quality and yields by minimising water stress and optimising nutrient uptake (Plett *et al.*, 2020; Wang *et al.*, 2021; Batool *et al.*, 2023).

Another strategy for enhancing water conservation in agriculture is deficit irrigation (DI), which involves the deliberate application of water below the full crop water requirements (Suna *et al.*, 2023). By carefully managing water stress during specific growth stages, DI can reduce water use while maintaining acceptable crop yields (Attia *et al.*, 2021). This approach has been successfully applied to a wide range of crops, including cereals, legumes, and fruit trees, demonstrating its potential for improving water productivity in water-scarce regions (Singh and Singh, 2021).

In addition to these irrigation techniques, the adoption of water-saving technologies, such as drip irrigation (DRI) and micro-sprinklers, can significantly reduce water losses and improve irrigation efficiency (Patel *et al.*, 2023). These technologies deliver water directly to the plant root zone, minimising evaporation and runoff losses and enabling the precise control of water application rates (Tiwari *et al.*, 2023). The integration of these technologies with soil moisture monitoring and weather forecasting systems can further optimise irrigation scheduling, ensuring that water is applied at the right time and in the right amount (Gu *et al.*, 2020).

Despite the proven benefits of sustainable irrigation practices, their widespread adoption remains limited due to various socioeconomic, institutional, and technological barriers (Chen, Hsieh and Shichiyakh, 2021). These include the high initial costs of implementing new technologies, limited access to information and training, and the lack of supportive policies and incentives (Dwijendra *et al.*, 2022; Skibko *et al.*, 2022; Ayubirad *et al.*, 2024). To overcome these challenges, a holistic approach to water and land development is needed, encompassing not only technological innovations but also capacity building, stakeholder engagement, and policy reforms.

The aim of this research is to explore the potential of sustainable irrigation practices for enhancing food security and water conservation in agricultural landscapes. By employing a combination of field experiments, remote sensing, and hydrological modelling, we aim to assess the effectiveness of PI, DI, and water-saving technologies in optimising *WUE* and crop productivity across diverse agroecological zones. The findings of this research will advance water-efficient agriculture by informing policy decisions and guiding the development of sustainable water management strategies. These strategies aim to ensure food security while safeguarding precious water resources for future generations.

## MATERIALS AND METHODS

### STUDY AREA

The investigation was implemented in three distinct agroecological zones located in Iraq, characterised by varying climatic conditions, soil types, and cropping systems.

The first study site, located in the semi-arid zone of the Al-Anbar Governorate (coordinates: 33.3486° N, 43.7695° E), experiences a mean yearly precipitation of 150 mm and is predominantly characterised by sandy loam soils. The primary crops grown in this area include barley, wheat, and legumes. The experimental field in this zone had a gentle slope of approximately 1–2%, with a slight inclination from north to south.

The second site, situated in the sub-humid zone of the Diyala Governorate (coordinates: 33.7717° N, 44.9430° E), receives an average annual rainfall of 300 mm and has predominantly silty clay loam soils. The main crops cultivated here are maize, tomato, and cucurbits. The experimental field in this zone was relatively flat, with a slope of less than 0.5% in any direction.

The third site, located in the humid zone of the Maysan Governorate (coordinates: 31.8359° N, 47.1443° E), experiences a mean yearly precipitation of 500 mm and is characterised by clay soils. The primary crops grown in this area are rice, date palm, and alfalfa. The experimental field in this zone had a very gentle slope of approximately 0.5–1%, with a slight inclination from east to west.

### EXPERIMENTAL DESIGN

At each study site, a randomised complete block design (RCBD) was utilised, incorporating three replicates of four distinct irrigation regimens. The irrigation treatments included: (1) conventional flood irrigation (CFI), serving as the control; (2) PI using soil moisture sensors and variable rate application; (3) DI with 70% of the full crop water requirements; and (4) DRI with 90% of the full crop water requirements. Each experimental plot measured 20×20 m, with a buffer zone of 5 m between plots to minimise edge effects.

The experiment was conducted over a full growing season for each crop: wheat (November to May, approximately 180 days), maize (April to August, approximately 120 days), and rice (May to September, approximately 135 days). These durations encompass the entire growth cycle from planting to harvest for each crop.

### CROP MANAGEMENT

The crops selected for the study included wheat (*Triticum aestivum* L.) in the semi-arid zone, maize (*Zea mays* L.) in the sub-humid zone, and rice (*Oryza sativa* L.) in the humid zone. These crops were chosen based on their economic importance and water requirements in the respective regions. The wheat variety used was 'Ibaa 99', while the maize variety was 'Baghdad 3' and the rice variety was 'Amber 33'. Crop management practices, including land preparation, sowing, fertilisation, and pest control, were carried out according to local recommendations and kept uniform across all treatments.

### IRRIGATION MANAGEMENT

In the CFI treatment, irrigation water was applied using traditional flood irrigation methods, with a fixed depth of 75 mm per application. Irrigation was applied throughout the entire growing season for each crop, starting from planting and continuing until the late grain-filling stage, approximately 10–14 days before harvest. The specific irrigation schedules were as follows:
- wheat: irrigation was applied for approximately 165 days, from November to late April;
- maize: irrigation was applied for approximately 105 days, from April to early August;
- rice: irrigation was applied for approximately 120 days, from May to late August.

Irrigation scheduling was based on visual observations of crop water stress and local farmer practices. In the precision irrigation (PI) treatment, soil moisture sensors (model: SM-150) were positioned at depths of 20, 40, and 60 cm in each plot. These sensors continuously monitored soil moisture levels, and irrigation was triggered when the average soil moisture in the root zone dropped below 50% of the field capacity. The amount of water applied varied based on the soil moisture deficit, ensuring precise and targeted irrigation. In the deficit irrigation (DI) treatment, irrigation water was applied at 70% of the full crop water requirements, estimated utilising the FAO Penman-Monteith method (Cai *et al.*, 2007). Irrigation scheduling was determined by the crop growth stages, with drought conditions experienced during the vegetative and late ripening stages. In the drip irrigation (DRI) treatment, a surface DRI system was utilised to deliver the irrigation water, positioning the emitters at intervals of 30 cm throughout the length of the crop rows. The system was designed to deliver 90% of the full crop water requirements, with irrigation scheduled based on the crop coefficients and reference evapotranspiration data.

### DATA COLLECTION

Soil moisture data were collected daily from the sensors installed in the PI treatment plots. Weather data, including solar radiation, wind speed, relative humidity, and temperature, were obtained from automatic weather stations (model: WS-GP1) installed at each study site. Crop growth parameters, such as plant height, leaf area index (*LAI*), and biomass, were measured at critical growth stages (vegetative, flowering, and maturity) using non-destructive methods. Plant height was measured using a measuring tape, while *LAI* was estimated using a plant canopy analyser (model: LAI-2200C). Biomass samples were collected from a 1×1 m quadrat in each plot, oven-dried at 70°C for 48 h, and then balanced to evaluate the dry matter content.

At harvest, crop yields were determined by manually harvesting the central 10×10 m area of each plot, excluding border rows. The harvested grains were threshed, cleaned, and weighed, and the moisture content was assessed employing a grain moisture meter (model: MC-7825G). Grain yields were adjusted to a standard moisture content of 14% for wheat and maize and 12% for rice. Water use efficiency (*WUE*) (in $kg \cdot m^{-3}$) was determined by the proportion of agricultural output to the aggregate water consumption (irrigation + rainfall) throughout the cultivation period.

### REMOTE SENSING AND HYDROLOGICAL MODELING

Remote sensing data, including Landsat-8 (30 m spatial resolution, 16-day revisit time) and Sentinel-2 (10 m spatial resolution, 5-day revisit time) satellite imagery, were acquired for each study site at key crop growth stages (emergence, vegetative, flowering, and maturity). The images were preprocessed to remove atmospheric effects and geo-referenced using ground control points. Indices of vegetation, including the normalised difference vegetation index (*NDVI*) and the enhanced vegetation index (*EVI*) were derived from the satellite data to assess crop health and vigour.

For each study site, a hydrological model known as the soil and water assessment tool (SWAT) was established using topographic, soil, land use, and climate data. The model was calibrated and validated using observed streamflow and soil moisture data (Aawar and Khare, 2020; Ayubirad and Ataei, 2024). The calibrated model was then used to simulate the impact of different irrigation treatments on water balance components, such as evapotranspiration, surface runoff, and groundwater recharge.

### STATISTICAL ANALYSIS

An analysis of variance (ANOVA) was performed on the collected data using the SAS statistical software package (ver. 9.4). The irrigation treatments were considered as fixed effects, while the replicates were treated as random effects. Means were separated using the Tukey's honest significant difference (HSD) test at a significance level of $P \leq 0.05$. Regression analyses were performed to examine the relationships between crop yields, *WUE*, and vegetation indices derived from remote sensing data.

## RESULTS AND DISCUSSION

### CROP GROWTH AND YIELD

The effects of different irrigation treatments on crop growth parameters and yield are presented in Table 1. In the semi-arid zone, the precision irrigation (PI) treatment significantly increased plant height, leaf area index (*LAI*), and biomass of wheat compared

**Table 1.** Effect of irrigation treatments on crop growth parameters and yield

| Treatment | Plant height (cm) | | *LAI* | | Biomass (Mg DM·ha$^{-1}$) | | Grain yield (Mg·ha$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|
| | mean value | *SE* | mean value | *SE* | mean value | *SE* | mean value | *SE* |
| **Semi-arid zone (wheat)** | | | | | | | | |
| CFI | 65.3 | ±3.2 b | 2.8 | ±0.2 b | 6.5 | ±0.4 b | 2.1 | ±0.1 c |
| PI | 78.6 | ±2.8 a | 3.5 | ±0.1 a | 8.2 | ±0.3 a | 2.8 | ±0.2 a |
| DI | 71.4 | ±3.6 ab | 3.1 | ±0.2 ab | 7.3 | ±0.5 ab | 2.4 | ±0.1 b |
| DRI | 74.2 | ±2.5 a | 3.3 | ±0.1 a | 7.8 | ±0.2 a | 2.6 | ±0.1 ab |
| **Sub-humid zone (maize)** | | | | | | | | |
| CFI | 180.5 | ±6.3 b | 3.6 | ±0.3 b | 12.4 | ±0.7 b | 4.5 | ±0.3 c |
| PI | 210.2 | ±5.1 a | 4.5 | ±0.2 a | 15.8 | ±0.5 a | 6.2 | ±0.2 a |
| DI | 195.7 | ±7.4 ab | 4.1 | ±0.4 ab | 14.1 | ±0.9 ab | 5.3 | ±0.4 b |
| DRI | 203.6 | ±4.9 a | 4.3 | ±0.1 a | 15.2 | ±0.4 a | 5.9 | ±0.1 ab |
| **Humid zone (rice)** | | | | | | | | |
| CFI | 85.2 | ±4.1 b | 4.2 | ±0.3 b | 10.6 | ±0.6 b | 3.8 | ±0.2 c |
| PI | 98.7 | ±3.5 a | 5.1 | ±0.2 a | 13.2 | ±0.4 a | 5.1 | ±0.1 a |
| DI | 92.4 | ±4.7 ab | 4.7 | ±0.4 ab | 11.9 | ±0.8 ab | 4.4 | ±0.3 b |
| DRI | 96.1 | ±2.9 a | 4.9 | ±0.1 a | 12.7 | ±0.3 a | 4.8 | ±0.1 ab |

Explanations: *LAI* = leaf area index, *SE* = standard error, DM = dry mater, CFI = conventional flood irrigation, PI = precision irrigation, DI = deficit irrigation, DRI = drip irrigation; means within columns and zones marked with different letters are significantly different at $p \leq 0.05$ according to Tukey's HSD test.
Source: own study.

to the conventional flood irrigation (CFI) treatment. The deficit irrigation (DI) and drip irrigation (DRI) treatments also showed improvements in these parameters, albeit to a lesser extent. Similar trends were observed for maize in the sub-humid zone and rice in the humid zone, with the PI treatment outperforming the other irrigation methods in terms of crop growth.

Grain yields followed a similar pattern, with the PI treatment resulting in the highest yields across all three zones (Tab. 1). In the semi-arid zone, the PI treatment increased wheat yield by 33% compared to the CFI treatment, while in the sub-humid and humid zones, maize and rice yields increased by 38 and 34%, respectively. The DI and DRI treatments also improved yields compared to the CFI treatment, but to a lesser degree than the PI treatment.

These results demonstrate the potential of PI to enhance crop growth and productivity in diverse agroecological zones. By providing plants with the optimal amount of water based on real-time soil moisture data, the PI treatment likely reduced water stress and improved nutrient uptake, leading to better crop performance (Zapata-García *et al.*, 2023). The DI and DRI treatments, while not as effective as PI, still outperformed the CFI method, highlighting the importance of adopting water-saving irrigation strategies in water-scarce regions (Kumar *et al.*, 2023).

## WATER USE EFFICIENCY

Figure 1 illustrates the *WUE* values for each irrigation treatment (CFI, PI, DI, and DRI) in the semi-arid, sub-humid, and humid zones. The highest *WUE* exhibited the PI treatment, followed by the DRI and DI treatments. In the semi-arid zone, the PI treatment increased *WUE* by 46% compared to the CFI treatment, while in the sub-humid and humid zones, the increases were 51 and 48%, respectively. The PI treatment consistently achieved the highest *WUE* across all zones, followed by the DRI and DI treatments. The CFI treatment had the lowest *WUE* in all zones.

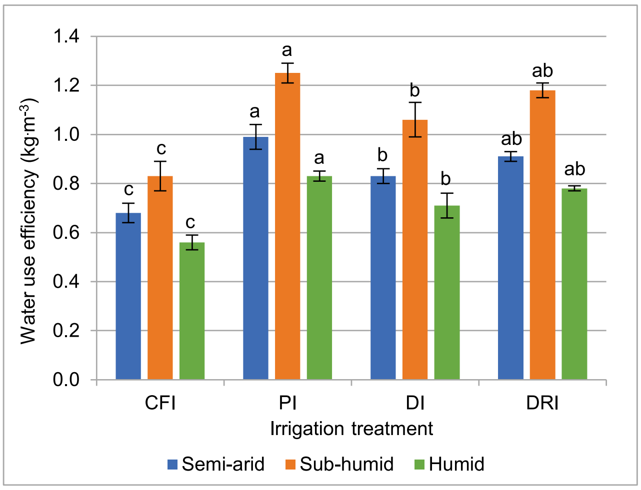


**Fig. 1.** Water use efficiency (*WUE*) for irrigation treatment in the semi-arid, sub-humid, and humid zones, error bars represent the standard error of the mean; mean values in bars with the same letter do not differ significantly at $p < 0.05$; source: own study

Table 2 presents the total amount of water applied (irrigation + rainfall) and the percentage of water saved compared to the CFI treatment. In the semi-arid zone, the PI, DI, and DRI treatments

**Table 2.** Total water applied and water savings under different irrigation treatments

| Treat-ment | Total amount of water and percentage of water saved | | | | | |
|---|---|---|---|---|---|---|
| | semi-arid zone (wheat) | | sub-humid zone (maize) | | humid zone (rice) | |
| | value (mm) | (%) | value (mm) | (%) | value (mm) | (%) |
| CFI | 450 | 0 | 600 | 0 | 1000 | 0 |
| PI | 360 | 20 | 480 | 20 | 800 | 20 |
| DI | 315 | 30 | 420 | 30 | 700 | 30 |
| DRI | 405 | 10 | 540 | 10 | 900 | 10 |

Explanations as in Tab. 1.
Source: own study.

reduced water application by 20, 30, and 10%, respectively, compared to the CFI treatment. Similar trends were observed in the sub-humid and humid zones, with the DI treatment achieving the highest water savings of 30% in both zones.

The higher *WUE* of the PI treatment can be attributed to its ability to precisely match water application with crop water requirements, minimising losses through evaporation, runoff, and deep percolation (Batool *et al*., 2023). The DRI and DI treatments also improved *WUE* compared to the CFI treatment, likely due to their water-saving properties and targeted application methods (Dwijendra *et al*., 2022).

These findings underscore the importance of adopting efficient irrigation practices to maximise crop production per unit of water consumed. In water-scarce regions like Iraq, where water resources are increasingly strained, improving *WUE* is crucial for ensuring food security and sustainable agricultural development (Canton, 2021).

## REMOTE SENSING AND HYDROLOGICAL MODELLING

The vegetation indices derived from remote sensing data showed strong correlations with crop growth parameters and yield (Tab. 3). In all three zones, *NDVI* and *EVI* exhibited significant positive correlations with *LAI*, biomass, and grain yield, indicating their potential as non-destructive tools for assessing crop performance (Attia *et al*., 2021).

The hydrological modelling results revealed that the PI treatment led to significant reductions in evapotranspiration and surface runoff compared to the CFI treatment (Tab. 4).

**Table 3.** Pearson correlation coefficients between vegetation indices and crop growth parameters

| Parameter | Pearson correlation coefficients | | |
|---|---|---|---|
| | semi-arid zone (wheat) | sub-humid zone (maize) | humid zone (rice) |
| *LAI* | 0.87** | 0.91** | 0.89** |
| Biomass | 0.82** | 0.88** | 0.85** |
| Grain yield | 0.79** | 0.86** | 0.83** |

Explanations: *LAI* = leaf area index, ** significant at $p \leq 0.01$.
Source: own study.

**Table 4.** Changes in water balance components under different irrigation treatments compared to CFI

| Treat-ment | Change components compared to CFI (%) | | | | | |
|---|---|---|---|---|---|---|
| | evapotran-spiration | | surface runoff | | groundwater recharge | |
| | value | *SE* | value | *SE* | value | *SE* |
| PI | –15 | ±2 | –40 | ±5 | +25 | ±3 |
| DI | –25 | ±3 | –30 | ±4 | +15 | ±2 |
| DRI | –20 | ±2 | –35 | ±4 | +20 | ±3 |

Explanations as in Tab. 1.
Source: own study.

The PI treatment also increased groundwater recharge, likely due to the reduced water losses and improved infiltration (Skibko *et al*., 2022). The DRI and DI treatments showed similar trends, although the effects were less pronounced than the PI treatment. These results highlight the potential of remote sensing and hydrological modelling to provide valuable insights into the impacts of different irrigation practices on crop growth and water balance components. By integrating these tools with field-based measurements, researchers and practitioners can develop more targeted and effective strategies for optimising *WUE* and crop productivity in agricultural landscapes (Canton, 2021).

In a study conducted in northwest China, authors compared drip irrigation with traditional furrow irrigation for cotton production (Liu *et al*., 2022). They reported a 19–24% increase in cotton yield and a 17–21% improvement in *WUE* under drip irrigation, which is consistent with our findings on the benefits of DRI across different agroecological zones. Similarly, Sharma *et al.* (2023) investigated the impact of drip irrigation on tomato production in India, observing a 32% increase in yield and a 56% improvement in *WUE* compared to surface irrigation methods.

The effectiveness of deficit irrigation strategies has been demonstrated in various climatic conditions. Regulated deficit irrigation in olive orchards in Spain were studied (Galindo *et al*., 2018), reporting water savings of up to 30% with minimal impact on yield, which aligns closely with our DI results. In a semiarid region of Brazil, a research found that deficit irrigation in cowpea cultivation led to water savings of 25–35% while maintaining acceptable yields, further supporting the potential of DI as a water-saving strategy in water-scarce regions (Freitas de *et al*., 2019).

Precision irrigation techniques have shown promise in diverse agricultural systems. In a study conducted in California, USA, authors utilised remote sensing and weather data to implement precision irrigation in almond orchards, achieving water savings of 20–25% compared to conventional irrigation practices (Goldstein *et al*., 2018). This corroborates our findings on the water-saving potential of PI across different crops and agroecological zones.

The integration of multiple irrigation strategies has also been explored in various contexts. A research combined drip irrigation with deficit irrigation techniques in a vineyard in northwestern China, reporting a 28% increase in water productivity and a 15% improvement in grape quality compared to conventional furrow irrigation (Zhang *et al*., 2021). This multi-faceted approach to irrigation management aligns with our study's exploration of different irrigation techniques and their potential for improving *WUE* and crop productivity.

It is important to note that the effectiveness of different irrigation methods can vary depending on soil type, climate, and crop characteristics. For instance, a research found that the benefits of drip irrigation were more pronounced in sandy soils compared to clay soils in southern India, highlighting the need for site-specific irrigation management strategies (Marimuthu *et al*., 2024). The economic feasibility of adopting advanced irrigation techniques has been a subject of research in various regions. Another research conducted a global assessment of the potential for expanding irrigated croplands, considering both biophysical and socioeconomic factors (Zagaria *et al*., 2023). Researchers emphasised the importance of considering local contexts and potential barriers to adoption when implementing new irrigation technologies.

Our study contributes to this growing body of literature by providing insights from three distinct agroecological zones in Iraq, a region where comprehensive irrigation studies have been relatively limited. The consistency of our findings with studies from diverse global contexts underscores the potential for sustainable irrigation practices to address water scarcity and enhance food security across different environmental conditions.

Despite the promising results, this study has some limitations that should be addressed in future research. These include the need for multi-year studies to assess the long-term effects of sustainable irrigation practices, the exploration of a wider range of crops and regions, the investigation of potential barriers to adoption, and the enhancement of remote sensing and hydrological modelling techniques. Future research should focus on these aspects to develop more comprehensive and sustainable water management strategies for diverse socioeconomic and environmental contexts.

## CONCLUSION

This study demonstrates the potential of sustainable irrigation practices to enhance food security and water conservation in diverse agroecological zones of Iraq. The key findings and implications are as follows:

- irrigation treatment effectiveness:
  - precision irrigation (PI) significantly improved crop growth, yield, and water use efficiency compared to conventional flood irrigation (CFI);
  - deficit irrigation (DI) and drip irrigation (DRI) also outperformed the traditional method, albeit to a lesser extent than PI;
- water use efficiency (*WUE*) and conservation:
  - PI increased *WUE* by 46–51% across all three agroecological zones;
  - DI achieved the highest water savings, reducing water application by 30% compared to CFI;
  - DRI resulted in 10% water savings while maintaining high crop productivity;
- crop yield improvements:
  - PI increased crop yields by 33–38% compared to CFI across all zones;
  - DI and DRI also improved yields, demonstrating the potential for water-saving irrigation strategies to maintain or enhance crop productivity;
- remote sensing and hydrological modelling:
  - vegetation indices derived from remote sensing data showed strong correlations with crop growth parameters and yield;
  - hydrological modelling revealed reduced evapotranspiration and surface runoff under PI treatment, along with increased groundwater recharge;
- implications for sustainable agriculture:
  - the study underscores the importance of adopting efficient irrigation practices to maximise crop production per unit of water consumed;
  - results highlight the potential for sustainable irrigation practices to address water scarcity challenges in regions like Iraq;
- recommendations:
  - promote the adoption of precision irrigation technologies where feasible, given their superior performance in improving *WUE* and crop yields;
  - encourage the implementation of deficit and drip irrigation as effective alternatives in areas where precision irrigation may not be practical;
  - integrate remote sensing and hydrological modelling tools in irrigation management to optimise water use and crop productivity.

## CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

## REFERENCES


Aawar, T. and Khare, D. (2020) "Assessment of climate change impacts on streamflow through hydrological model using SWAT model: a case study of Afghanistan," *Modeling Earth Systems and Environment*, 6(3), pp. 1427–1437. Available at: https://doi.org/10.1007/s40808-020-00759-0.

Abioye, E.A. *et al.* (2020) "A review on monitoring and advanced control strategies for precision irrigation," *Computers and Electronics in Agriculture*, 173, 105441. Available at: https://doi.org/10.1016/j.compag.2020.105441.

Ambomsa, A. (2020) "Role of drip irrigation system as increasing water use efficiency over furrow irrigation system," *Academic Research Journal of Agricultural Science and Research*, 8(3), pp. 252–262.

Attia, A. *et al.* (2021) "Evaluating deficit irrigation scheduling strategies to improve yield and water productivity of maize in arid environment using simulation," *Agricultural Water Management*, 249, 106812. Available at: https://doi.org/10.1016/j.agwat.2021.106812.

Ayubirad, M.S., and Ataei, S. (2024) "An efficient modal parameter identification method based on free vibration response and the energy sorted matrix pencil method," *IJRARE*, 11 (1), pp. 15–27. Available at: http://dx.doi.org/10.22068/ijrare.349.

Ayubirad, M.S., Ataei, S., and Tajali, M. (2024) "Numerical model updating and validation of a truss railway bridge considering train-track-bridge interaction dynamics," *Shock and Vibration*, 2024(1), 4469500. Available at: https://doi.org/10.1155/2024/4469500.

Batool M. *et al.* (2023) "Drought stress in *Brassica napus*: Effects, tolerance mechanisms, and management strategies," *Journal of Plant Growth Regulation*, 42(1), pp. 21–45. Available at: https://doi.org/10.1007/s00344-021-10542-9.

Cai, J. *et al.* (2007) "Estimating reference evapotranspiration with the FAO Penman–Monteith equation using daily weather forecast messages," *Agricultural and Forest Meteorology*, 145(1–2), pp. 22–35. Available at: https://doi.org/10.1016/j.agrformet.2007.04.012.

Canton, H. (2021) "Food and Agriculture Organization of the United Nations – FAO," in *The Europa directory of international organizations 2021*. London: Routledge, pp. 297–305.

Chen, T.-C., Hsieh, T.-S. and Shichiyakh, R.A. (2021) "Sustainable operation of surface-groundwater conjunctive use systems in the agricultural sector," *Journal of Water and Land Development*, 51, pp. 25–29. Available at: https://doi.org/10.24425/jwld.2021.139011.

Dwijendra, N.K.A. *et al.* (2022) "The effect of various irrigation technologies and strategies on water resources management," *Journal of Water and Land Development*, 53, pp. 143–147. Available at: https://doi.org/10.24425/jwld.2022.140790.

Freitas de, R.M. *et al.* (2019) "Water use of cowpea under deficit irrigation and cultivation systems in semi-arid region," *Revista Brasileira de Engenharia Agrícola e Ambiental*, 23, pp. 271–276. Available at: https://doi.org/10.1590/1807-1929/agriambi.v23n4p271-276.

Galindo, A. *et al.* (2018) "Deficit irrigation and emerging fruit crops as a strategy to save water in Mediterranean semiarid agrosystems," *Agricultural Water Management*, 202, pp. 311–324. Available at: https://doi.org/10.1016/j.agwat.2017.08.015.

Goldstein, A. *et al.* (2018) "Applying machine learning on sensor data for irrigation recommendations: revealing the agronomist's tacit knowledge," *Precision Agriculture*, 19, pp. 421–444. Available at: https://doi.org/10.1007/s11119-017-9527-4.

Gu, Z. *et al.* (2020) "Irrigation scheduling approaches and applications: A review," *Journal of Irrigation and Drainage Engineering*, 146(6), 04020007. Available at: https://doi.org/10.1061/(ASCE)IR.1943-4774.0001464.

Kumar, N. *et al.* (2023) "Resource conserving mechanization technologies for dryland agriculture," in A. Naorem and D. Machiwal (eds.) *Enhancing resilience of dryland agriculture under changing climate*. Singapore: Springer Nature Singapore, pp. 657–688. Available at: https://doi.org/10.1007/978-981-19-9159-2_33.

Liu, M. *et al.* (2022) "Optimal irrigation levels can improve maize growth, yield, and water use efficiency under drip irrigation in northwest China," *Water*, 14(23), 3822. Available at: https://doi.org/10.3390/w14233822.

Marimuthu, S. *et al.* (2024) "Harnessing rain hose technology for water-saving sustainable irrigation and enhancing blackgram productivity in garden land," *Scientific Reports*, 14(1), 18692. Available at: https://doi.org/10.1038/s41598-024-69655-2.

Nhemachena, C. *et al.* (2020) "Climate change impacts on water and agriculture sectors in Southern Africa: Threats and opportunities for sustainable development," *Water*, 12(10), 2673. Available at: https://doi.org/10.3390/w12102673.

Patel, A. *et al.* (2023) "Advances in micro-irrigation practices for improving water use efficiency in dryland agriculture," in A. Naorem and D. Machiwal (eds.) *Enhancing resilience of dryland agriculture under changing climate*. Singapore: Springer Nature Singapore, pp. 157–176. Available at: https://doi.org/10.1007/978-981-19-9159-2_10.

Plett, D.C. *et al.* (2020) "The intersection of nitrogen nutrition and water use in plants: New paths toward improved crop productivity," *Journal of Experimental Botany*, 71(15), pp. 4452–4468.

Schmitt, R.J.P., Rosa, L. and Daily, G.C. (2022) "Global expansion of sustainable irrigation limited by water storage," *Proceedings of the National Academy of Sciences*, 119(47), e2214291119. Available at: https://doi.org/10.1073/pnas.2214291119.

Sharma, V. *et al.* (2023) "Climatological approaches of irrigation scheduling for growing tomato crop under drip irrigation in subtropical region of Punjab," *Journal of Agrometeorology*, 25(4), pp. 565–570. Available at: https://doi.org/10.54386/jam.v25i4.2269.

Singh, H.P. and Singh, B. (2021) "Innovative approaches for enhancing water productivity in agriculture including horticulture," *International Journal of Innovative Horticulture*, 10(2), pp. 115–129.

Skibko, Z. *et al.* (2022) "Electricity supply to irrigation systems for crops away from urban areas," *Journal of Water and Land Development*, 53, pp. 73–79. Available at: https://doi.org/10.24425/jwld.2022.140782.

Suna, T. *et al.* (2023) "Enhancing agricultural water productivity using deficit irrigation practices in water-scarce regions," in A. Naorem and D. Machiwal (eds.) *Enhancing resilience of dryland agriculture under changing climate*. Singapore: Springer Nature Singapore, pp. 177–206. Available at: https://doi.org/10.1007/978-981-19-9159-2_11.

Tiwari, A.K. *et al.* (2023) "Sustainable water management in agriculture: irrigation techniques and water conservation," in M. Bauah *et al.* (eds.) *Research trends in agriculture science Vol. II*. Kolhapur, India: Bhumi Publishing, pp. 53–68.

Wang, H. *et al.* (2021) "Optimization of water and fertilizer management improves yield, water, nitrogen, phosphorus and potassium uptake and use efficiency of cotton under drip fertigation," *Agricultural Water Management*, 245, 106662. Available at: https://doi.org/10.1016/j.agwat.2020.106662.

Wrachien de, D., Schultz, B. and Goli, M.B. (2021) "Impacts of population growth and climate change on food production and irrigation and drainage needs: A world-wide view," *Irrigation and Drainage*, 70(5), pp. 981–995. Available at: https://doi.org/10.1002/ird.2597.

Yin, X. *et al.* (2022) "An interplay of soil salinization and groundwater degradation threatening coexistence of oasis-desert ecosystems," *Science of The Total Environment*, 806, 150599. Available at: https://doi.org/10.1016/j.scitotenv.2021.150599.

Zagaria, C. *et al.* (2023) "Potential for land and water management adaptations in Mediterranean croplands under climate change," *Agricultural Systems*, 205, 103586. Available at: https://doi.org/10.1016/j.agsy.2022.103586.

Zapata-García, S. *et al.* (2023) "Using soil water status sensors to optimize water and nutrient use in melon under semi-arid conditions," *Agronomy*, 13(10), 2652. Available at: https://doi.org/10.3390/agronomy13102652.

Zhang, D. *et al.* (2020). "Water scarcity and sustainability in an emerging economy: A management perspective for future," *Sustainability*, 13(1), 144. Available at: https://doi.org/10.3390/su13010144.

Zhang, T. *et al.* (2021) "Comparison of different irrigation methods to synergistically improve maize's yield, water productivity and economic benefits in an arid irrigation area," *Agricultural Water Management*, 243, 106497. Available at: https://doi.org/10.1016/j.agwat.2020.106497.

Zinkernagel, J. *et al.* (2020) "New technologies and practical approaches to improve irrigation management of open field vegetable crops," *Agricultural Water Management*, 242, 106404. Available at: https://doi.org/10.1016/j.agwat.2020.106404.